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Underground Astroparticle Physics at SNOLAB

Submission to the NSERC GSC-19 Long Range Planning Committee

Ad hoc Committee[†]

Nov 29th, 2005.

[†]Contributions from: M. Boulay (Queen's), M. Chen (Queen's), F. Duncan (SNOLAB), J. Farine (Laurentian), A. Hallin (Queen's), A. Noble (Queen's), A. McDonald (Queen's), D. Sinclair (Carleton), C. Virtue (Laurentian), V. Zacek (Montreal)

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1. Overview of the Science: Astroparticle Physics in the Spotlight

Astroparticle physics is a field with deeply significant connections. Subatomic physics at the smallest scales is connected to our understanding of the Universe at the largest scales. Experiments at low energies probe physics at the high energy scales of grand unification. Particle physics experimental techniques are applied to tackle the most puzzling astrophysical questions. The fundamental nature of these connections attracts students and researchers to this field and captures the fascination of the broader public.

Many scientific developments led to the birth of this new field. These include experimental leaps in observational cosmology, the discovery of neutrino oscillations (new physics beyond the Standard Model), new astronomical observations using high energy particles, and revolutionary theoretical ideas connecting particle properties to the geometry of space-time. Scientists and science policy makers around the world have begun charting the research directions of this field. As an example, in the US an inter-agency study was commissioned by the National Research Council of the National Academies to identify the most important questions in this field and to make recommendations on research strategy for tackling these questions. The report that was produced in 2002, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century,* lays out these profound questions in physics and astrophysics:

1. What is the dark matter?
2. What is the nature of the dark energy?
3. How did the universe begin?
4. Did Einstein have the last word on gravity?
5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. Are there new states of matter at exceedingly high density and temperature?
9. Are there additional spacetime dimensions?
10. How were the elements from iron to uranium made?
11. Is a new theory of matter and light needed at the highest energies?

A specific element of the third question is:

3b. Why is the Universe made of matter and not antimatter and how did this asymmetry arise?

and a related element of the tenth question is:

10b. What role do neutrinos play in supernova explosions and how does this process affect the synthesis of heavy elements?

In that report, the committee in the US stated that high priority should be given to constructing a deep underground laboratory. Experiments and research in a deep underground lab can address elements of the first, third, fifth, seventh and tenth questions in their list.

As host to the SNO experiment and the SNOLAB facility, Canada has a unique and leading role in the world as we wrestle with these questions. It is unique because the deepest underground laboratory that exists in the world is SNOLAB. As Canadian scientists and science policy makers prepare our road map for research in subatomic physics, we can prepare to be leaders in this field because of the opportunities that SNOLAB provides and because of the research experience developed from SNO.

The physics program for SNOLAB includes:

- the search for dark matter particles, perhaps the leading question in the field and the first of the *Eleven Questions* in the US report;
- understanding fundamental particle properties (with their corresponding impact on cosmology) by using low energy measurements such as double beta decay to probe higher energy scale physics;
- precision neutrino and stellar physics with low energy solar neutrinos, an astroparticle connection that probes particle physics using the particle most likely to reveal surprises – the neutrino;
- detection of neutrinos from a galactic supernova, revealing the inner workings of a supernova and examining the influence of neutrino physics on the supernova environment and processes, and vice versa.

This research program puts SNOLAB in the spotlight in this field – the astroparticle physics experiments being developed for SNOLAB go straight to the heart of the matter and probe some of the most fundamental questions in astroparticle physics. An overview of the "big picture" goals of this physics program follows, with greater details to be found in later sections.

Double beta decay measurements promise to demonstrate whether neutrinos are Dirac or Majorana particles. Next generation experiments have the potential to measure the absolute scale of neutrino masses to as low as 20 meV. Coupled with the neutrino mass differences determined by neutrino oscillation measurements, this would provide information on all the neutrino masses and potentially their mass hierarchy. Cosmology currently provides an upper limit to the mass of the neutrino. With an experimental determination of neutrino mass coming from double beta decay or from direct neutrino mass measurements (e.g. tritium endpoint), one could potentially turn the situation around, with the neutrino energy density in the Universe known and now helping to constrain cosmology and remove present covariances in the cosmological models.

Neutrino mass schemes that accommodate Majorana neutrinos are considered natural; the see-saw mechanism connects the small value of the neutrino mass to the GUT scale and this is seen theoretically as an appealing concept. Majorana neutrinos introduce additional complex phases in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix. These complex phases (or the simple Dirac phase, if large enough) introduce the possibility of CP violation in the lepton sector. Here lies an interesting connection. The baryon asymmetry in the Universe, the fact that there is more matter than antimatter, requires a CP violating process. The observed CP violation in the quark sector is experimentally observed to be well-described by the straightforward complex phase of the CKM matrix. Unfortunately, this level of CP violation, observed in the K and B systems, is insufficiently large to produce the observed baryon number asymmetry of the Universe. Leptogenesis proposes that a large CP violation in the lepton sector, plus GUT lepton-quark couplings, ultimately generates the observed baryon number asymmetry. Thus, determining the CP violating phases in the PMNS matrix and determining if additional Majorana phases are involved is an important question.

Physics beyond the Standard Model has been revealed by neutrino oscillations. The Standard Model proposed that neutrinos were massless, and that lepton flavour was a conserved quantity. The Standard Model also has the postulate of lepton flavour universality, and provides the couplings strengths of neutrinos to the weak bosons. With the observation of neutrino oscillations, two of the Standard Model postulates have fallen. How about the other neutrino-related postulates and inputs? How well do neutrinos fit in the Standard Model? As an example, one can ask if lepton flavour universality is as well-demonstrated for neutrinos as for charged leptons. Neutrinos are at the front line in pushing back the boundaries of the Standard Model.

There have been significant discoveries with solar neutrinos, but more physics remains to be explored. By exploring low energy solar neutrinos, precision measurements are possible that test fundamental neutrino properties and interactions. The MSW effect that enhances neutrino oscillations due to interactions with matter is understood, yet there is no direct evidence for it from existing solar neutrino experiments including SNO (although the best-fit oscillation parameters for solar neutrinos depend upon MSW). By making measurements of the survival probability of low energy solar neutrinos, one probes the details of the strength of the neutrino-matter interaction. This will provide direct evidence for the MSW effect and this turns out to have great sensitivity to new, higher order physics. New physics that could affect the neutrino-matter interaction and that could be revealed by future, precision low energy solar neutrino experiments include non-standard neutrino couplings, mass-varying neutrinos, admixtures of sterile neutrinos, and CPT violation.

With concordance in cosmological observations, including the cosmic microwave background anisotropy measurements, large-scale structure studies using galaxy surveys and weak-lensing, and Type 1a supernova measurements, the matter density in the Universe is now thought to be about 30% of the total (critical) energy density. Big bang nucleosynthesis and the observed ratio of light element abundances in the Universe also tell us that the baryon energy density is only about one-tenth of the total matter content. Thus, roughly 25% or more of the matter density that exists in the Universe is "dark" and is non-baryonic. Structure also tells us that this dark matter was non-relativistic, or "cold" when it thermally decoupled. The leading candidate for cold dark matter is a massive particle that has yet to be discovered. Cosmological arguments (and observational constraints) suggest that the interaction strength of the cold dark matter is the weak scale. Consequently, the WIMP, or weakly-interacting massive particle is being sought. Direct search experiments look for WIMP particles to scatter off nuclei in large target volumes. Observing nuclear recoils and discriminating those from background processes is the nature of dark matter experiments.

When a massive star exhausts its nuclear fuel it undergoes gravitational collapse. The hot, dense proto-neutron star that's formed is initially opaque to neutrinos. Neutrinos that manage to escape from the proto-neutron star cool it until scattering lengths become long enough that the bulk of the neutrinos trapped in the proto-neutron star can escape. When they do – and it's a total of 99% of the gravitational energy of the massive star that's released in the form of neutrinos – the neutrinos may re-heat the stalled shock created by in-falling material encountering material that previously fell in and bounced off the core. This mechanism may produce the final explosion that ultimately ejects the remaining envelope of material around the collapsed star producing a supernova. Supernova neutrinos were detected from SN1987A which was in the Large Magellanic Cloud. Building operating detectors that are larger, with greater sensitivity, with different targets and reactions, will enable physicists to "keep watch" for neutrinos from a gravitational collapse in our galaxy (expected once every 10 to 50 years) that could provide a wealth of astrophysical and particle physics knowledge that would be otherwise inaccessible.

There are close relationships between astroparticle physics in underground labs such as SNOLAB and other pursuits in the field. Typically "above ground" astroparticle physics experiments focus on the detection and study of very high energy particles, be they gamma rays, cosmic rays or neutrinos. That physics and that community have ties with the underground physics community, despite the fact that our aim is to shun cosmic rays. For example, the clumping of dark matter particles in large gravitational bodies may allow sufficient concentrations to accumulate that the self-annihilation of these particles might produce a detectable flux of high energy gamma rays or neutrinos. Thus, direct detection of dark matter by underground experiments and indirect dark matter searches in the cosmos by high energy gamma ray observatories (for example) are very complementary pursuits.

Astroparticle physics, of the SNOLAB variety, also has connections to high energy particle physics. The leading candidate for the dark matter relic particle is the neutralino from supersymmetry The lightest supersymmetric particle is predicted to be stable and it would have the properties of a WIMP (weakly-interacting massive particle). High energy experiments are looking for supersymmetry (SUSY) at the energy frontier; observation of supersymmetry and the determination of a few of the properties of the SUSY model would enable the cosmological significance of the neutralino to be estimated, placing cross hairs on the parameter space plot for direct dark matter searches. Conversely, constraints or observation by dark matter experiments might aid in constraining supersymmetric models and SUSY parameter space along with collider experiments.

The connections of SNOLAB astroparticle physics to nuclear physics are also evident. In double beta decay, for example, the theoretical calculation of the transition nuclear matrix elements is an important factor. Observation of neutrinoless double beta decay would imply that neutrinos have a Majorana mass; however, the neutrino mass scale (and its contribution to the neutrinoless double beta decay process) can only be determined as well as the determination of the nuclear matrix element. In this endeavour, there is a significant contribution that is needed from nuclear theory. There are also close connections in the testing of solar and supernova models and the determination of low energy nuclear cross sections, and with the understanding of the nuclear physics in standard solar (stellar) models.

As outlined above, the experimental research at SNOLAB address a diverse array of fundamental and exciting physics questions. Nevertheless, they all share several common features. All of them are low count rate or rare event search experiments that require very careful control of background radiation in the necessarily large target masses employed. Purity of materials, both active in the detector and passive as shielding, is a prime concern. The ability to distinguish interactions by different particles is a feature to be developed in many of the experiments. All of the experiments focus on control of radon, as it is a major background concern. In formulating a research strategy for astroparticle physics, it is clear that recognizing and exploiting these synergies will be effective. All of the experimental pursuits, addressing different areas, will see their development thrive in a common, shared research environment, such as SNOLAB.

Compared to the largest accelerator-based experiments, SNOLAB experiments are smaller and relatively inexpensive. Nevertheless, they are directed at some of the most fundamental physics questions of our time and positive measurements would have an impact similar to or greater than that of SNO.

Our vision is that we would like to see Canada as the world leader in astroparticle and underground physics. We would like SNOLAB to be the premiere clean and deep facility in the world, and provide infrastructure that allows these challenging experiments to be achieved. We would like to see significant Canadian experimental contributions and leadership in each of the major areas. We would like SNOLAB to be the major centre for the development of supporting technologies for this endeavour.

2. The SNOLAB Facility

2.1. Overview of the scientific programme of SNOLAB

The SNOLAB scientific programme focuses on the areas of astroparticle physics which build on the scientific and technological successes of SNO and which require the great depth and cleanroom environment which is unique to SNOLAB. There are a number of critically important topics that require these conditions.

- The study of the intense flux of low energy neutrinos from the Sun will extend the tests of solar models to the region where the theoretical calculations are even more precise. Such studies will allow demonstration of the MSW matter effects in neutrino oscillations and will also allow tests of non-standard models for neutrino oscillation. Extension of the existing measurements to lower energies will require even tighter controls on the radioactive environment than was developed for SNO.

- The SNO results, together with the Kamiokande and KamLAND data, have demonstrated that neutrinos have mass but these oscillation measurements provide only mass differences between pairs of neutrino states. The observation of neutrino-less double-beta decay would establish the absolute mass scale and, perhaps even more importantly, show that neutrinos are Majorana particles as predicted by many of the models that attempt to explain the neutrino masses. This process is only allowed energetically for a handful of nuclei and the event rates are expected to be at the level of a few events per year per tonne of material. Detection of this process will require extremes in background control.
- It is clear from measurements to date of neutrino properties that neutrinos cannot make up the bulk of the Dark Matter which is widely believed to consist of Weakly Interacting Massive Particles (WIMPs). A favoured candidate for Dark Matter WIMPs is the lightest supersymmetric particle (LSP) and a number of projects are being developed to search for interactions of WIMPs with normal matter. The resulting recoil energies are tiny and the event rates are very low. Thus this process requires the ultimate in low background. Particularly troublesome are fast neutrons from cosmic ray interactions. It is very difficult to shield or veto these particles and depth is the only real defence.
- Just as solar neutrinos are our window into the sun supernova neutrinos are the best window into the incompletely understood supernova mechanism. The average energy of supernova neutrinos, as observed in SN1987A, is sufficiently high that cleanroom conditions are generally not required but most supernova detector designs still benefit from significant depth. As a major Underground Science facility it is hoped that SNOLAB will contribute to the Supernova Early Warning System (SNEWS) in future either through a detector with supernova sensitivity but a broader physics scope, or with a dedicated detector.

There are a number of areas outside of astroparticle physics which may benefit from the deep underground laboratory. There is interest from Canadian seismologists to establish a 3 dimensional seismic telescope to extend our knowledge of global seismic effects as well as investigating local geology. Also, some biologists are starting to investigate the life forms that exist at great depth. While relatively low in density at depth, the total biomass in these new forms is comparable to the biomass at the surface. One of the critical questions is to study the populations as a function of depth and hence temperature. The limits on conditions for life are not well established. A detailed description of these possibilities is beyond the scope of this document.

There are some fascinating and important aspects of underground science for which SNOLAB is not well suited or for which its unique characteristics are not required. For example, the cavity volume required for a mega-tonne detector for proton decay searches or long baseline neutrino studies is not compatible with rock mechanics at SNOLAB depths or rock removal timescales. Such long baseline accelerator neutrino studies do not require great depth or extreme care in the elimination of low energy backgrounds.

2.2. Scientific Programme Development

The SNOLAB scientific programme has been developed in a series of workshops each of which attracted 80 – 100 participants from Canada, the US and Europe. The initial task was to look at the infrastructure needs of the different types of experiment. This led to a significant modification of the underground layout to provide separate spaces for each of the experiments, rather than having all experiments share a single hall. This change was largely motivated by the need to engineer safeguards against some of the hazards presented by some of the experiments. Invitations were extended for projects to submit Letters of Interest in which the scientific case for the particular measurement was outlined, the state of readiness was presented and the needs of the project were identified.

An international Experiments Advisory Committee was established to review the Letters of Interest and to come up with a roadmap for the science of the facility. To date, 20 projects have been presented to the EAC for consideration by scientists from 11 countries. Following receipt of the Letters of Interest each of the projects was presented at a workshop and each was reviewed both by the EAC for the scientific merit and by a team of SNOLAB scientists and engineers for technical compatibility with the facility. This resulted in a number of questions being sent back to the projects and these have subsequently been addressed. Following the most recent workshop in August of this year, the EAC came up with a selection of 9 projects which it recommended be a part of our initial scientific programme. Several of these projects are still at the R&D stage but will shortly require small underground spaces for prototyping. A few of the projects are at the stage where major initiatives can be mounted. In these cases, the project teams have been asked for a commitment that it is their intent to proceed at SNOLAB, subject to obtaining funding. Once this commitment is received, space will be reserved for the projects for a period to allow funding to be obtained, and the SNOLAB team will work with the project to ensure that the laboratory development is consistent with the needs of these projects.

It is no surprise that most of the groups submitting LOI's are pursuing projects in low energy solar neutrino physics, double beta decay or dark matter searches. There are several competing technologies being developed for these areas and it is not clear which will prove the most capable. The aim of the smaller R&D projects is to provide the basis for an informed choice between the concepts. As the projects currently in the R&D stage progress, it is expected that the effort will coalesce around a small number of larger initiatives. The EAC will continue to review the projects and be proactive in encouraging the focus on a few viable experiments. The EAC will also review progress on the larger projects and advise the laboratory on their status towards completion.

2.3. Operation of the Facility

SNOLAB has been funded as an International Facility for Underground Science and it is expected that it will operate as such. Experimental teams coming to SNOLAB should find the same type of infrastructure support as they would at a laboratory such as TRIUMF. Thus the facility expects to provide the basic infrastructure including power, cooling, water, materials handling, base level clean room conditions, and networking both underground and on surface. In addition there will be a small engineering and scientific staff who are charged both with reviewing all designs and procedures to ensure that the experiments can be safely and effectively carried out, and to assist the projects in meeting these criteria.

The costs of operating the SNOLAB facility can be estimated based on the experience at SNO. The largest cost is for staff. We anticipate a small but critical increase in the site staff to include 4 permanent site scientists and an additional engineer. In a few cases the skill level of the personnel will have to be increased. For example, our new chiller is in a class where we are required by regulation to have two licensed stationary engineers to look after it. There are higher materials, maintenance and utility costs reflecting the much larger surface facilities and doubling of the underground space. The total cost is estimated to be about $5M per year. This compares with the current cost of operating SNO and SNOLAB of $6M including approximately $1M of heavy-water insurance.

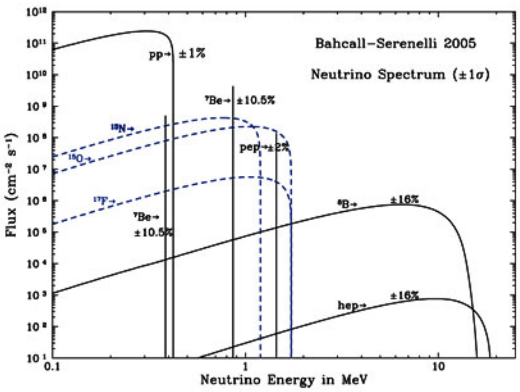
The source of operating support for SNOLAB has not yet been established. Currently funds are provided to SNO through the GSC envelope, from the US and UK and as part of the CFI award. SNOLAB has argued that the operating costs for the facility should be provided outside of the envelope as part of the Big Science programme. We feel the Long range Plan should make the case that operating this facility within the current envelope would lead to serious damage to SAP experimental programme. The mechanism for support must allow for community input and participation in a peer review process.

3. SNOLAB Type Projects with Canadian Participation

3.1. Solar Neutrino Program

3.1.1. Introduction

Exciting physics discoveries have come from detecting solar neutrinos with SNO. Solar neutrinos produced as electron neutrinos transform flavour in propagating from the core of the Sun to the Earth such that about 2/3 of them as detectable as the other active flavours (μ and τ). SNO demonstrated this as a neutral-current appearance experiment. Additionally, SNO confirmed that the total flux of ^{8}B solar neutrinos agrees with model predictions, validating our understanding of energy generation in stars and of the processes that go into solar models. These have been spectacular results. This discovery has generated a great deal of interest in the physics which underlies neutrino oscillations. Future solar neutrino experiments follow up on the discovery, and will explore the enormous amount of physics that lies beneath, and has not been previously probed by experiment. At low energies, solar neutrinos are abundant but are not as well studied. These neutrinos provide an opportunity to make precision measurements in neutrino physics that have sensitivity to new physics. The third recommendation of the APS Neutrino Study is for the “development of an experiment to make precise measurements of the low-energy neutrinos from the Sun.”



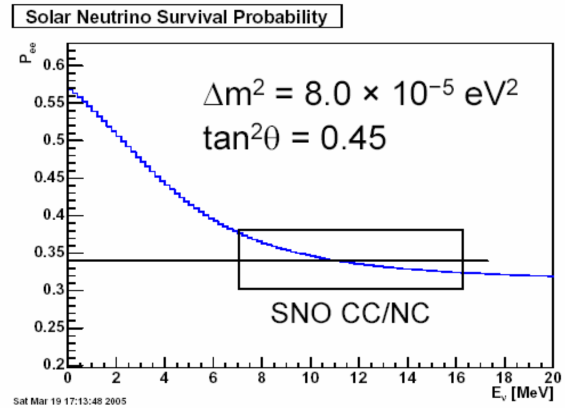


Figure 1: Left, solar neutrino energy spectrum from BS05 [1]. Right, the survival probability for solar neutrinos as a function of neutrino energy. The best-fit LMA oscillation parameters were used for this plot ($\Delta m^2 = 8.0 \times 10^{-5}$ eV^2 and $\tan^2\theta = 0.45$). The box illustrates SNO's constraint coming from the CC/NC ratio.

The following discussion focuses on the detection of the *pep* solar neutrinos. There is interest in studying *pp* and ^{7}Be solar neutrinos; however, for the purposes of SNOLAB, a *pep* solar neutrino experiment is of great interest – a *pep* experiment could be that experiment recommended by the APS Neutrino Study.

The flux of monoenergetic *pep* solar neutrinos is calculated to ±1.5% in the SSM. One could detect them by looking for the "Compton edge" in the recoil spectrum from neutrino-electron scattering. With a known source and negligible uncertainty in the reaction cross section, a measurement of the rate of *pep* solar neutrinos has the potential to be an order percent precision measurement. This would allow a *pep* measurement to further and tightly constrain the mixing angle θ_{12}, similar to what's being proposed by future *pp* experiments. In [2] it is stated "that a measurement of the ν-e scattering rate by *pep* solar neutrinos would yield essentially equivalent information about neutrino oscillation parameters and solar neutrino fluxes as a measurement of the ν-e scattering rate by *pp* solar neutrinos." The physics motivation and potential impact of a future *pep* solar experiment is the same as for future *pp* experiments. Precision determination of θ_{12} would be the goal, as well as illustration of the LMA solution's increased survival probability at low energies. This latter aspect has been a subject of considerable interest in the neutrino physics community recently.

Figure 1 illustrates the survival probability for solar neutrinos as a function of energy. At higher energies, neutrino propagation in the Sun is dominated by matter effects (adiabatic evolution of electron neutrinos produced in the Sun to emerge as the ν_2 mass eigenstate). The ^{8}B solar neutrinos that SNO has studied have energies above 7 MeV and the oscillation survival probability for these solar neutrinos is almost independent of energy and given approximately by $\sin^2\theta_{12}$. At lower energies the vacuum oscillation terms in the

Hamiltonian dominate the propagation and the survival probability approaches the vacuum oscillation average probability. In between, there is a transition region – this produces the rise in the survival probability at energies that are lower than what SNO can currently measure. Observing this rise in the survival probability would be solid evidence for the MSW effect and would confirm that solar neutrino physics is well understood. If there is new physics that affects the neutrino-matter interaction, it would manifest itself most strongly in the transition region. New physics includes possibilities such as non-standard interactions, sterile neutrino admixtures, a large value for θ_{13}, and CPT violation.

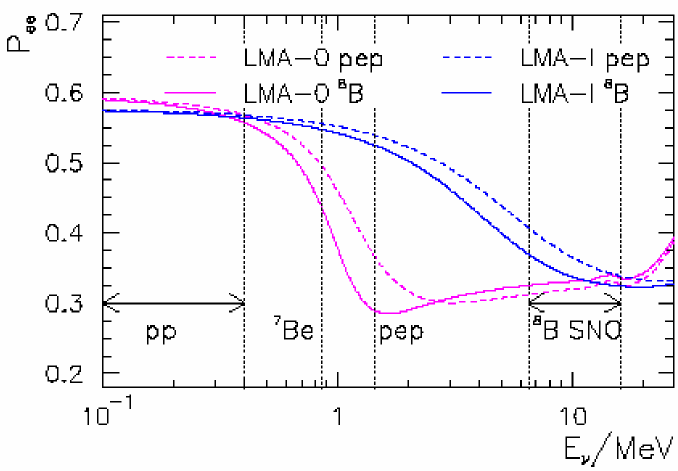


Figure 2. Survival probability [3] for solar neutrinos when non-standard interactions for neutrinos are included (lower magenta curves) compared with normal neutrino interactions (blue curves).

As an example of sensitivity to new physics, the possibility of non-standard neutrino interactions (flavour changing as well as flavour conserving) was examined in [3]. Figure 2 illustrates the effect of including non-standard interactions on the resultant survival probability curve. Solutions (LMA-0) exist that are compatible with all existing solar neutrino experiment data and with KamLAND data. These solutions also include non-standard interactions with strengths that are within the existing bounds for non-standard neutral-current couplings for neutrinos. Current bounds on non-standard interactions are derived from neutrino scattering experiments and are not very restrictive. In fact, the NuTeV neutrino scattering experiment already shows a possible small deviation from the Standard Model [4]. It is interesting to note that the MSW effect is linear in G_F whereas a scattering experiment depends upon the coupling strength squared; thus, probing the neutrino-matter interaction has greater sensitivity to possible new couplings.

This situation is a parallel to measurements of the weak mixing angle at different values of Q^2. Though well-measured at the Z-pole, precision measurements of the weak mixing angle at other Q^2 values offer sensitivity to effects beyond the Standard Model. For solar neutrinos, measurements by SNO established solar neutrino flavour conversion (likely to be due to matter-enhanced neutrino oscillations). This is already physics beyond the "massless neutrino" Standard Model. Other new effects involving neutrinos are effectively probed by looking at the energy dependence. SNO+ measurements at the *pep* energy (1.44 MeV) probe the physics connected to neutrinos and their propagation in the Sun.

One sees from Figure 2 that the *pep* solar neutrinos have the greatest potential for discriminating solutions with non-standard interactions. This can be seen from equations as well as from plots. By equating the MSW potential with the vacuum oscillation term in the Hamiltonian, and noting that where they appear they do so with a relative minus sign, the energy range of maximum sensitivity can be found. To search for a small effect from new physics, one looks for the large terms to cancel each other out leaving the new physics small term to exert its influence in the Hamiltonian for propagation. Given the best-fit oscillation parameters for Δm^2 and $\tan^2\theta$, and the electron number density in the centre of the Sun, one finds the energy region of maximum sensitivity to new physics lies between 1 and 2 MeV. The *pep* solar neutrinos at 1.44 MeV are the best probe. Recall also that the pep solar neutrinos have a SSM predicted flux uncertainty of ±1.5%. One thus finds the ideal blend of precision with sensitivity in the measurement of the survival probability of *pep* solar neutrinos in SNO+.

3.1.2. SNO

The SNO papers published to date have involved a number of physics discoveries and have been very well received by the scientific community. Results from SNO alone or in combination with other measurements have included:

- The first definitive neutrino oscillation "appearance" measurement by SNO, showing clearly that about 2/3 of the electron neutrinos from the Sun change to other active neutrino types before reaching the Earth. The hypothesis of no flavour change for neutrinos has been ruled out at the 5.3 standard deviation level by the data from the pure D2O phase and at greater than 7 standard deviation in the SNO salt phase.

- The SNO measurement of the total active flux of ^8B neutrinos from the Sun, via the NC reaction in the salt phase, is in excellent agreement with solar model calculations. The experimental uncertainty is about 9%, roughly one-half the theoretical uncertainty of the standard solar model calculations for the ^8B flux. These results have provided a clear resolution of what had been referred to as "The Solar Neutrino Problem".

- The SNO salt measurements of the NC and CC reactions on deuterium combined with other solar and KamLAND measurements, rule out Maximal Mixing at greater than 5 standard deviations for the mixing angle Θ_{12}. The Large Mixing Angle (LMA) MSW solution centered on $\Delta m_{12}^2 = 8 \times 10^{-5}$ eV^2 is now favoured over all other regions at the 99% confidence level.

- The MSW flavour-change mechanism associated with the LMA region involves matter interactions in the Sun. It therefore defines part of the neutrino mass hierarchy for three active neutrinos with masses 1,2,3 and determines that mass 2 is larger than mass 1.

- The agreement between the recent KamLAND measurements with reactor neutrinos and the solar neutrino measurements, including the latest SNO results, strongly supports oscillation arising from finite neutrino mass as the clear mechanism for flavour change. Other proposed mechanisms such as Resonant Spin Flavor Change and neutrino decay can only contribute to the observed flavour change as subdominant effects.

- The combination of SNO and KamLAND data provide a stringent, solar-model-independent upper limit on the contribution of sterile neutrinos to the oscillations.

In addition, the specification of parameters for mass 1 and 2 mixing, (Δm_{12}^2, Θ_{12}) from the solar neutrino measurements, and similar parameters for mass 2 and 3 mixing from atmospheric neutrino disappearance measurements by SuperKamiokande, have provided the principal information on 3-active-neutrino mixing for the design of future long baseline measurements. These experiments at accelerators and reactors are aimed at determination of the other neutrino mixing parameters, including CP violation. The neutrino mixing parameters also provide a basis for predictions of lifetimes for double beta decay, with the potential to determine if neutrinos are Majorana particles and provide an accurate determination of neutrino mass.

The SNO experiment is in a "precision" measurement phase. During 2005, a detailed paper on the full data set from the salt phase was published with improved accuracy for neutrino fluxes, with a detailed study of the spectral shape for electron neutrinos detected by the Charged Current reaction and improved sensitivity for studies of day-night flux differences sensitive to flavor regeneration in the Earth. The array of ^{3}He-filled proportional counters (Neutral Current Detectors or NCD's) that were installed in 2004 will detect neutrons from the NC reaction independently from the CC and ES reactions observed through light detected by the photomultiplier (PMT) array in SNO. This removes or strongly reduces the correlations between the signals from the three reactions and enables more accurate measurements of fluxes and CC spectral shape to be performed. As the systematic uncertainties are very different from the previous phases, this will provide a new measurement of the solar neutrino quantities with considerable independence from the previous measurements. The overall accuracy obtained for neutrino oscillations will be improved by analyzing the full set of data from all three phases of SNO, providing the most accurate measurements to date of the mass 1 to 2 mixing and adding restrictions for mass 1 to 3 mixing. The ongoing analysis program also includes measurements of the hep reaction in the Sun and observations of atmospheric neutrino fluxes with a valuable capability to observe above the horizon. SNO also maintains its supernova detection capability.

By the end of 2006, the accuracy of the SNO measurements in phase 3 will be limited by irreducible systematic uncertainties rather than by statistics. Therefore, the SNO Collaboration has decided that they will cease data taking at the end of December, 2006 and remove the NCD's and heavy water during the calendar year 2007. Analysis of SNO data and publication of final physics papers is projected to continue until April 2009.

3.1.3. SNO+

The concept of SNO+ is to fill the SNO detector with an organic liquid scintillator after the heavy water is removed. This would increase the light yield in the detector by a factor of 100, allowing access to low energy neutrinos. SNO+ will be able to explore several different areas of neutrino physics, including low energy solar neutrinos, geo-neutrinos, reactor neutrino oscillations and supernova neutrino detection. Low energy solar neutrinos are the primary focus, as described above. A few additional words on solar neutrinos follow below, and geo-neutrino and supernova neutrino capabilities are outlined below as well.

By making a precision measurement of the survival probability for *pep* solar neutrinos, SNO+ probes the details of the neutrino-matter interaction. In order to make a clean detection of the *pep* solar neutrinos with a liquid scintillator, it is necessary for the detector to be located very deep underground. The cosmogenic production of ^{11}C in a liquid scintillator by muons can be a sizeable background to the *pep* solar neutrinos. This isotope has a 20 minute half-life; consequently, a large detector at a shallower depth, such as KamLAND, sees a large background from ^{11}C that is virtually impossible to veto or tag since approximately 26,000 muons traverse the KamLAND detector each day. In contrast, at SNOLAB depths, the SNO experiment sees only 70 muons per day. The background from ^{11}C is thus negligible (and a 20 minute half-life isotope could be tagged when the muon rate is so low). SNO+ is not only an ideal solar neutrino experiment at low energies, combining precision with sensitivity to new physics, SNO+ is also unique in being able to target this physics measurement with negligible background.

Geo-neutrinos – the electron antineutrinos emitted by natural radioactivity in the Earth – have become exciting of late since KamLAND published the first detection of geo-neutrinos in July 2005 in Nature [5]. The interest in geo-neutrinos lies in their potential for surveying the whole Earth at once thus making a direct measurement of the total amount of U and Th in Earth’s crust and mantle. This would provide breakthrough data for geophysical and geochemical models of Earth and Earth’s thermal history. Uranium and thorium radioactivity is thought to account for anywhere from 40% to 100% of Earth’s total heat flux (present-day); direct information coming from detecting the antineutrinos from natural radioactivity in the Earth would be extremely valuable in clarifying this situation.

KamLAND’s first measurement was interesting but contributed little geological science due to the limited statistical significance and due to KamLAND’s much higher reactor neutrino background (KamLAND is primarily a reactor neutrino experiment). In contrast, nuclear power reactors in Ontario have larger distances to Sudbury than the typical reactor distances in the KamLAND experiment (and there is less total reactor power in Ontario than Japan). The signal-to-background in SNO+ for geo-neutrinos compared to the reactor background will be 5-10 times better. SNO+ would be an excellent follow-up to KamLAND's first detection of geo-neutrinos. SNO+ has the opportunity to significantly improve upon the KamLAND geo-neutrino measurements since reactor backgrounds are lower and because the geological configuration around Sudbury is simpler (resulting in smaller uncertainties in the model interpretation).

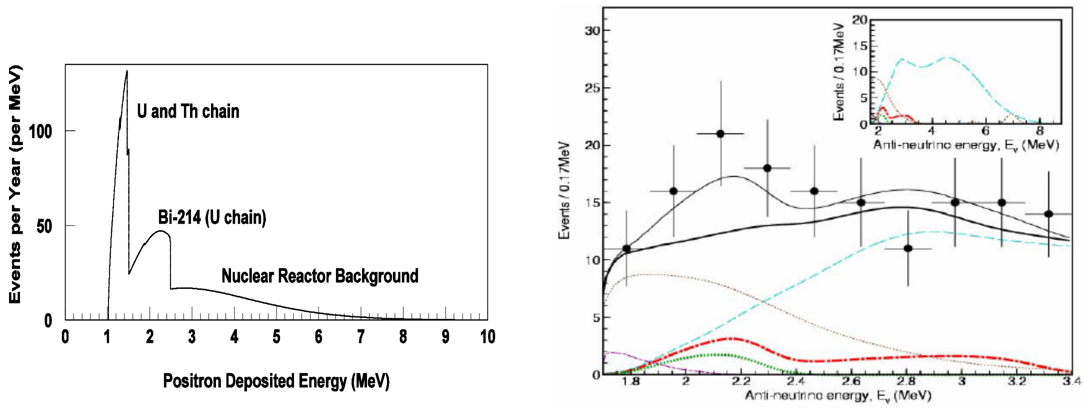


Fig. 4. Left, based upon calculations in [6], calculated geo- and reactor neutrino signals in SNO+. Energy resolution was not included in this plot. Right, from [5], geo- and reactor neutrino data in KamLAND, for which the geo/reactor ratio (red and green versus light blue) is much less favourable.

A large (1 kton) quantity of scintillator serves as an excellent supernova neutrino monitor with physics similar capabilities to the present SNO experiment. In a liquid scintillator, the dominant reaction for detecting supernova neutrinos is the inverse beta decay reaction “nuebar-proton,” a charged-current reaction. Almost equally numerous are the events that would occur due to neutral-current neutrino-proton scattering. Neutral-current reactions provide sensitivity to the heavier neutrino flavours which are produced at higher energies in the core collapse supernova. Operation of the SNO+ experiment, after conversion into a liquid scintillator detector, maintains supernova neutrino physics capabilities and SNO+ would also continue as an element of SNEWS, the supernova early warning system intended to alert astronomers of the opportunity to observe a new supernova’s early light.

The SNO+ project made significant R&D progress during the past year. This includes, most importantly, the development of a new organic solvent as an excellent liquid scintillator for neutrino physics experiments. The solvent, linear alkylbenzene (LAB), has the chemical mildness of mineral oil, with the fluorescence yield of 100% aromatic. It is a safe liquid with a high flash point 130 ºC, and low toxicity. It is also a low cost liquid that is produced with high purity by Petresa Canada's plant in Quebec, an important practical and logistical consideration.

The Canadian-led SNO+ project currently has the involvement of six Canadian faculty and is recruiting collaborators in the US and Europe. Proof-of-principle has been achieved with preliminary engineering considerations of the revised mechanical support of the SNO acrylic vessel completed and with the identification of a high light output liquid scintillator that's compatible with acrylic, safe, and low cost. Purification R&D (to remove trace levels or radioactive contaminants from the scintillator) will continue through 2006 and proposals for capital funding will be submitted at the end of 2006. The target is a funding profile to begin in 2007, enabling a seamless transition from SNO to SNO+ as the heavy water is removed in 2007.

The conversion of SNO into a multipurpose liquid scintillator detector offers many exciting scientific prospects and would enable SNOLAB to have relatively early and steady science output in a variety of areas in astroparticle physics (and some outside the field). The Experiment Advisory Committee for SNOLAB drew the same conclusion. SNO+ was endorsed by the SNOLAB EAC in August 2005 who stated “we endorse development toward SNO+ for *pep* solar neutrinos and geo-neutrinos. We applaud the technical progress in developing the liquid scintillator and encourage continued R&D, development of the necessary collaboration and proposal to secure funding. We look forward to a receiving a full technical proposal.” There is a real opportunity for the SNO+ experiment to explore interesting, new science on a relatively short time scale.

3.2. Dark Matter Physics Program

3.2.1. Introduction

The search for cosmological dark matter in the form of weakly interacting massive particles (WIMPs) is currently an area of intense activity worldwide. Detection of dark matter particles would make those the largest known component of our universe, and would require the most extensive revision to the standard model of particle physics since its inception.

The recent WMAP satellite observations of the Cosmic Microwave Background (CMB) anisotropies give evidence for a cosmological matter density of Ω_m =0.27±0.04 [7]. This value may be compared with the value of the baryon density of Ω_b = 0.044±0.004 as indicated by nucleosynthesis and the height of the first acoustic peaks in the CMB data. Cosmological observations also indicate that we live in a flat Universe with Ω_{tot}=1.02±0.02 and it was found from determinations of the relation between the distances of type Ia supernovae inferred from luminosity and their red-shift, that a new form of “dark energy” provides a contribution of Ω=0.73±0.02. These findings imply that 86% of the gravitationally traceable matter of the universe is non-baryonic and surveys of the large scale structure formation from galaxy and cluster, give independent confirmation of the fact that a significant fraction of the matter of the universe is dark and non-baryonic!

Guided by supersymmetry models, which independently predict the existence of a new stable WIMP, there are theoretically well-motivated reasons to expect WIMP-nucleon coupling cross-sections of 10^{-45} to 10^{-46} cm^2. These cross-sections could be probed by experimental searches with sensitive target masses on the order of 100 to 1000 kg. The most promising non-baryonic candidate for dark matter from the particle physics point of view is the neutralino. These particles are assumed to be concentrated in a halo around our galaxy with a Maxwellian velocity distribution in the galactic frame with a mean velocity of ≈230 km/sec and a local density at the solar position of ≈ 0.3 GeV/c^3. To detect neutralinos, one measures the energy of nuclear recoils arising from neutralino elastic scattering off nuclei in the detector. For all detector materials, this recoil energy is expected to be less than 100 keV.

Experiments in this field are thus currently aiming to develop technologies to build tonne-scale WIMP-sensitive detectors, and it is envisioned that should cosmological WIMP particles be detected, we would in the next decade begin to set our sights on kilotonne-scale experiments for precision measurements and WIMP astronomy. We emphasize that the lack of experimental constraints on WIMP structure results in a bifurcation of the field into two broad classes of experiments: those primarily sensitive to spin-dependent and those to spin-independent coupling. Until more is known about WIMP structure and coupling, these are complimentary endeavours.

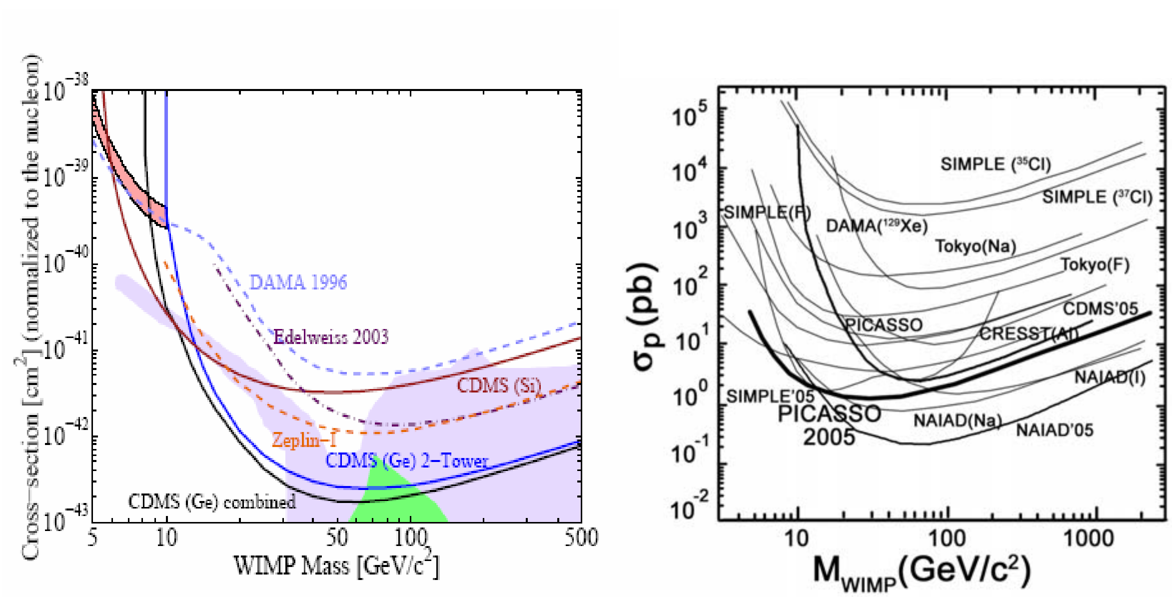


Figure 3: Summary of spin-independent WIMP-nucleon cross section limits (left) and spin dependent WIMP- proton cross sections (right) at 90% C.L. as a function of the WIMP mass. The published PICASSO limits [8] coincide with the recent SIMPLE limits; new spin dependent results from CDMS'05, ZEPLIN '04 and NAIAD '05 are also shown.

3.2.2. PICASSO

The Detector:

PICASSO (Project In Canada to Search for SuperSymmetric Objects) is an experiment searching for cold dark matter through the direct detection of weakly interacting massive particles (WIMPs) via their spin-dependent interactions with nuclei. It uses a liquid fluorocarbon, C_4F_{10}, as the active material and searches for WIMP interactions on ^{19}F. This choice is motivated by the fact that ^{19}F is one of the most favorable nuclei for direct detection of spin-dependent interactions [9]. In fact the nuclear form factor of ^{19}F enhances the signal by nearly an order of magnitude compared to other frequently used materials (Na, Si, Al, Cl).

To detect dark matter, PICASSO exploits the well-established and extremely successful bubble chamber technique [10], [11], [12]. In this technique, the detector medium is a metastable superheated liquid and a phase transition is initiated by a heat spike due to the energy deposited by a charged particle traversing it. At a given temperature a certain critical amount of energy W_c has to be deposited within a critical length L_c to cause a phase transition. The quantities W_c and L_c are functions of the surface tension and superheat of the liquid, where superheat is defined as the difference between the vapor pressure of the liquid and the externally applied pressure. By dispersing the superheated liquid in the form of droplets (with diameters between 10 to 100 μm) in polymerized water based gels or viscous liquids, the detectors have essentially a 100% duty cycle. Moreover a phase transition, or droplet burst, is accompanied by an acoustic signal, which is recorded by piezoelectric transducers mounted on the container's exterior wall. Detectors of this type are known as bubble detectors or superheated droplet detectors and have matured into standard devices in neutron dosimetry.

Droplet detectors are threshold counters where each individual superheated droplet acts as an independent bubble chamber detector. PICASSO detectors are operated in the temperature range from 20^o to 47^o with a sensitivity to ^{19}F recoils from 500 to 6 keV (ε = 50%). WIMP induced recoil energies are expected to be smaller than 100 keV and therefore become detectable above 30^oC.

First Physics Results:

A test facility for PICASSO detectors was installed in July 2002 at a depth of 2070 m in the Sudbury Neutrino Observatory in order to study all performance aspects in view of a larger PICASSO experiment. The detectors were fabricated at UdeM in a clean environment and special efforts were made to purify the detector components to reduce alpha particle emitters from the U and Th decay chains. Two piezoelectric transducers read out each detector. A batch of three detectors each was installed in a thermally and acoustically insulated box and two of these units were run in parallel. Water cubes, providing a 33 cm thick shielding against neutrons coming from the rock walls surrounded the entire set up.

Physics data were recorded between April 2004 and October 2004. The effective exposure for the detector ensemble was 1.98 ± 0.19 kg-days of ^{19}F after time cuts. The observed data are well described by the known temperature profile of the alpha response of the detectors. Since the expected WIMP response curves *differs significantly* from that of the alpha background, the two contributions can be fit simultaneously to the data and an upper bound can be obtained for WIMP induced recoils as a function of the WIMP interaction cross section on ^{19}F (σ_F) and the WIMP mass (M_{WIMP}). We obtain a maximum sensitivity for a WIMP mass of M_{WIMP} = 29 GeV/c^2 and a cross section of $\sigma_p = 0.20 \pm 0.80$ pb (1σ), which is compatible with no effect. We translate this result into an upper bound on the spin dependent cross section on protons of σ_p = 1.31 pb at 90% C.L for M_{WIMP} = 29 GeV/c^2[8]. These results ruled out some parameter space in the region of small WIMP masses below 20 GeV/c^2 which had not yet been excluded by other experiments.

Schedule:

With first physics results obtained and published and with more experience gained with the new superheated droplet detection technique, the PICASSO collaboration proposed a scenario and timeline for the future development of the project in three phases, with successively increasing active mass (2 kg, 25 kg and 100 kg), with reduced background and increasing sensitivity.

Phase Ib: The aim of this phase, with data taking starting December '05 until July '06, is to operate larger detector modules, with increased loading and with a new readout system, which is scalable to the larger size of the next project phases. This phase is presently ongoing and a total of 32 detectors of 4.5 litres (Figure 4) are to be installed at the location of the old PICASSO experiment. The total active mass will be 2 kg. With a potential sensitivity of 0.04pb, the physics goal of this stage is to check the DAMA result, which is still not ruled out in the spin dependent sector.

Figure 4: A module of the new 4.5 litre detectors with an active mass of 60g. The container is entirely fabricated from acrylic. Each module is equipped with 9 piezo-electric sensors for event localization.

Phase II: During Phase II we envisage to introduce the first set of 30-litre detector modules with an active mass of 0.4 kg. Detector readout and DAQ are scaled up from Phase Ib. A critical task in view of the successful completion of Phase II will be the demonstration of background reduction by purification of the detector ingredients. In a first step we anticipate a factor 10 reduction in alpha contamination by improved purification techniques for a 3kg array, consisting of 8 modules. We anticipate data taking will begin in August '06 and will make optimum use of the present PICASSO site

and installations and lead to limits at the level of $1.2x10^{-2}$ pb after only 6 months of data taking.
During data taking in this interim Phase IIa, we will work to achieve another factor of ten in purity to be able to start series production for 64 modules of the 25 kg experiment of Phase IIb. Beginning of data taking with the 25 kg set up depends on the availability of underground space; at the moment we assume a start early in 2008. With a six month measurement period we anticipate cross section limits at the level of 10^{-3} pb.

Phase III: The aim of the 100kg phase is to reach sensitivity between $1x10^{-4}$ to $1x10^{-5}$ pb by the end of August 2009. This sensitivity can only be reached with a decrease by an additional factor of 10 to 100 of the internal background by purification, and this will be the major effort of this phase. To accomplish this, substantial changes to the detector matrix are anticipated. Otherwise, the experiment will be a scaled up version of the 25kg stage, with a total of 256 modules of 30 litres, and increased shielding for neutrons and gamma rays.

Collaboration:

Starting at Université de Montréal, PICASSO has evolved into a well-established collaboration with members from Queen's University, University of Indiana (Southbend), BTI Industries, Chalk River, the Czech Technical University of Prague and Yale University; recently a MOU was signed with members of the SIMPLE collaboration from the Universities of Lisbon and Paris 6/7.

3.2.3. DEAP

It is clear that new and innovative technologies will be required to reach the tonne scale for dark matter detectors. One possibility that is "strongly encouraged" by the SNOLAB EAC is the DEAP project which intends to utilize liquid argon as a dark matter target.

DEAP aims to detect nuclear recoils in an underground liquid argon target induced by spin-independent WIMP-nucleon coupling. DEAP is Canadian-led project based on a new idea to use pulse-shape discrimination available in argon to deal with the low-level background radiation that ultimately limits all experiments searching for WIMPs. The underlying technique has recently been demonstrated at Los Alamos with a 1 kg experiment, and a new joint Canadian-US group is currently building a CFI-funded 10 kg detector, DEAP-1, with a view of seeking early SNOLAB space and mounting a sensitive search experiment in late 2006. Success of the 10 kg experiment would both demonstrate the technology and improve current sensitivity to WIMP particles. We plan to scale up the detector to a 1000 kg mass, at a capital cost of approximately $2M, for data taking beginning in 2010. The key to the DEAP experiment is its potential scalability, which may allow us to search for WIMPs with a targeted one-tonne mass, and beyond. This innovative approach is expected to provide the one-tonne sensitivity for a capital cost of a few K$ per kg. The technological difficulty in scaling up current approaches is manifested by the CDMS collaboration, the current leader in the field, which plans to scale up their technology to 25 kg in 2010, with an estimated cost of $600K per kg.

Scaling up significantly more than this will rapidly become cost prohibitive and new technologies will be need.

3.3. Neutrinoless Double Beta Decay Program

3.3.1. Introduction

The search for neutrino-less double beta decay has been identified in a recent NUSAG review as the highest priority topic in neutrino physics with very good reason. Neutrinoless double beta decay will occur if neutrinos are Majorana particles, that is, if the antineutrino and the neutrino are identical particles. The decay rate depends upon the absolute mass of the neutrinos. Measurements of neutrino oscillations have established that neutrinos have non-zero mass, and have determined the square of the mass differences between neutrinos. We know further that the individual lepton flavour numbers are not conserved. A measurement of a non-zero rate of double beta decay will prove that neutrinos are Majorana particles, as expected in models such as the SeeSaw model, which is invoked to explain the very small scale of neutrino masses. Combined with oscillation experiments, this will determine the absolute mass of all three known neutrino mass states. It has been suggested that the Majorana nature of the neutrino is a central element of the mechanism which results in the universe being dominated by matter rather than anti-matter.

It is not known whether neutrinos are Majorana or Dirac particles. The interpretation of the Dirac equation led to the concept of particles and antiparticles. Historically, Weyl applied the Dirac equation to massless fermions in 1927, three years before Pauli postulated neutrinos. In 1937 Majorana proposed that for neutral particles, antiparticles and particles could be identical. If neutrinos are massless the distinction between Majorana and Dirac neutrinos would vanish [13]. However, since we have established that neutrino oscillations occur [14],[15],[16],[17], neutrinos are massive. No experimental measurements to date can distinguish between the two possibilities. It appears that the first experimental evidence must come from the observation of neutrinoless double beta decay.

Following a more complete treatment that appears in the Majorana “White Paper” [18], the neutrinoless double beta decay rate, $T_{1/2}^{0\nu}$, can be expressed in terms of the two-body phase-space factor including the coupling constant, $G_{0\nu}$, the Fermi and Gamow-Teller nuclear matrix elements, $M_F^{0\nu}$ and $M_{GT}^{0\nu}$, the axial vector and vector weak coupling constants, g_A and g_V, and the effective Majorana electron neutrino mass m_ν:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0, Z)\left|\langle m_\nu \rangle\right|^2 \left|M_f{}^{0\nu} - (g_A / g_V)^2 M_{GT}{}^{0\nu}\right|^2$$

The effective neutrino mass is related to the neutrino masses, mixing angles, CP phases, and Majorana phases. The current knowledge of allowed neutrino parameters defines Figure 5, which shows the allowed regions of effective neutrino mass in terms of the smallest neutrino mass.

A determination of neutrino mass from a measurement of neutrino-less double beta decay lifetimes is limited by the ability to calculate nuclear matrix elements. Typical uncertainties in the calculated matrix elements would result in neutrino masses accurate to within a factor of 3 [19],[20],[21]. There is considerable theoretical activity in this field, and it is expected that new developments may reduce the uncertainty significantly.

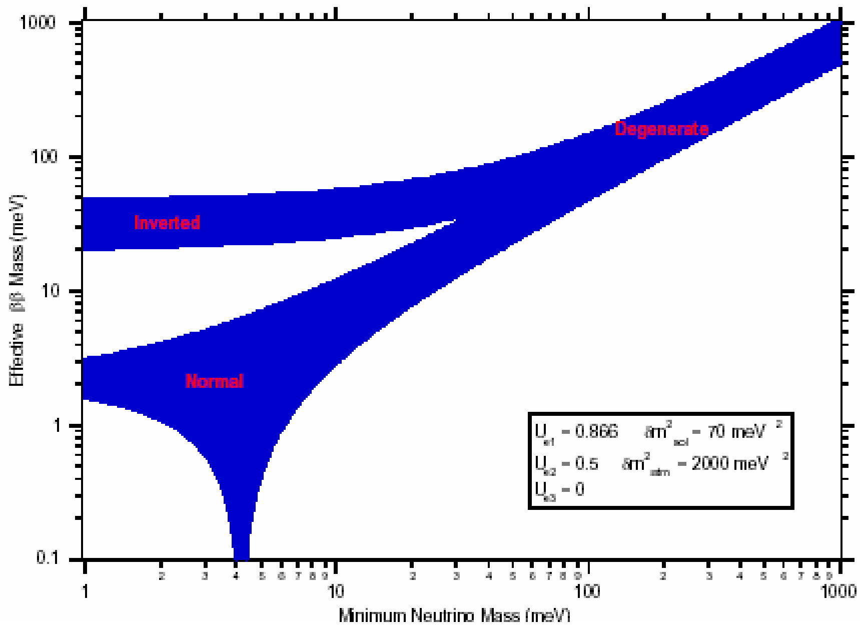


Figure 5. The allowed regions for the effective double beta decay neutrino mass as a function of the smallest neutrino mass. The regions appropriate to the normal, inverted and degenerate hierarchies are indicated.

The best current experimental limits for the ^{76}Ge half-life are 90% upper confidence limits of 1.9 x 10^{25} y [22] and 1.6 x 10^{25} y [23]. A recent measurement by Klapdor-Kleingrothaus [24], claims to observe neutrinoless double beta decay in 11 kg of enriched ^{76}Ge with a 1.19 x 10^{25} y half life. Based on this measurement, one would conclude that the neutrino mass is 0.2-0.6 eV. This claim has generated considerable controversy, based on concerns about how well backgrounds are understood. Currently, several groups are investigating techniques to improve double beta decay sensitivity using a variety of isotopes. A recent review is found in Elliott and Engel [25]. Promising isotopes include ^{76}Ge, ^{128}Te, ^{130}Te, ^{136}Xe and ^{150}Nd. Techniques that are being used to measure double beta decay include solid state detectors, drift chambers, scintillators, and low temperature bolometry.

In considering strategies to measure neutrinoless double beta decay, the community has concluded that a phased approach is the logical way to approach the problem. As is clear from Figure 5, for the normal mass hierarchy we would need to approach a mass limit of 1 meV. This would require that the product of the active mass and running time that is about 40000 times larger than the current limits, and that backgrounds be reduced by a similar factor. The first generation of experiments will address the degenerate hierarchy and confirm or reject the Klapdor-Kleingrothous claim. If neutrinoless double beta decay is not discovered, future experiments will need to scale to larger masses and lower backgrounds.

3.3.2. EXO

The EXO project aims to seek neutrino-less double beta decay in xenon. The advantages of xenon for this search are the ease of purifying a noble gas, the ability to re-purify or to develop improved purification techniques without the need to re-grow crystals, the lack of any long lived radioactive isotopes, the ability to transfer the expensive material from one detector to another and the prospect that the daughter barium could be tagged on an event by event basis. The collaboration has considered two forms for the detector, one liquid and one gas. There are obvious advantages for a liquid detector in that the size remains modest for a detector of several tones and this in turn means that the shielding can be much more compact. The main work of the EXO collaboration is focused on this approach. There are, however, advantages of the gas option. These include the ability to get tracking information on the decay electrons, improved gamma rejection, and better prospects for in-situ barium daughter tagging.

The Canadian group on EXO is contributing to the liquid detector and are leading the investigation of the gas option. The group consists of 8 senior researchers (4 at Carleton, 3 at Laurentian and 1 at NRC) 3 engineers, 3 RA's and currently 1 graduate student. The total FTE effort is about 9 PYs.

The Canadian team is providing the lead engineering for a 200 kg separated isotope, liquid Xenon detector. This prototype will be assembled at Stanford and then tested at WIPP. It should provide the first measure of the 2 neutrino decay rate for xenon but it will not include a barium tag so it will not have the ultimate sensitivity for the neutrino-less decay mode. The Canadian group have also played a major role in the establishing a low radioactive background for the prototype. The work has covered a number of systems. Radon emanation is always a concern in low background detectors. Work is in progress to measure the radon production in various parts of the system and to design filters that would eliminate it. Studies of radioactivity in the LAAPD photon detectors showed a significant surface contamination by radon daughters. This is now being investigated with the manufacturers. The qualification of materials for detector construction is being carried out at the NRC laboratories.

Much of the work in Canada is directed towards the demonstration of the feasibility of a gas phase detector. There is an obvious disadvantage to the use of the gas phase which is that the detector is much larger than if a liquid form can be used. This leads to the need for much more shielding material but with the same total radioactivity budget. We propose to use water as the main shield. There is an obvious incentive to operate the detector at high pressure and this would normally require a massive pressure vessel. We propose to explore a solution in which the gas pressure is matched by pressure in the water and this load is ultimately carried by the rock of the cavern. The gas containment vessel then need only deal with the difference in hydrostatic head between the top and bottom of the vessel (~0.5 bar for a 10 tonne detector at 10 bar).

The basic concept is to have a TPC filled with xenon. If a decay occurs in the xenon, the electrons will drift to the anode where the tracks will be recorded. The daughter will drift slowly towards the cathode. If the tracking information suggests a double beta decay then a laser beam tuned to the S -> P transition in the barium ion will be introduced just above the cathode to cause the barium to fluoresce. Because the P state decays about to a D state with a 20% branching ratio, it is necessary to also introduce laser light to pump this state back to the P state. Detection of the fluorescence is the key tag that promises to eliminate almost all backgrounds to the double beta decay process. (At shallow depths there are a number of cosmogenic processes that can produce radioactive Cs which can decay to Ba giving backgrounds but these are negligible at the depth of SNOLAB)

There are several issues that need to be addressed before a large scale double beta detector can be designed. First, the performance of a tracking chamber in high pressure Xe needs to be explored. Some of the issues include gas purity to control electron loss, gas additives to enhance the electron drift velocity, shift the wavelength of the light produced, change the Ba charge state form ++ to +, gain mechanisms to allow high energy resolution and tracking ability. Test rigs to allow investigation of these effects are under construction at Carleton. One of the most critical parameters to determine is the energy resolution that can be achieved as this is the only way to separate the 2 neutrino decay mode from the neutrino-less decay mode. The fano factor implies that resolutions close to that of Ge should be possible but this has never been achieved. A resolution of 1% would be adequate to give complete separation of the two decay modes and previous studies have come close to this performance.

The tagging of the barium presents new challenges. Single atom detection of barium has been reported but only in localized traps and at low pressure. At elevated pressure the transitions are broadened requiring more laser power to achieve a given fluorescence rate and neither the laser nor the detection optics can be tightly focused. All of these issues will lead to much higher sensitivity to backgrounds, particularly from scattered laser light. A system to investigate these issues is being developed at SNOLAB. Barium ions will be produced by pulsed, localized heating of thin foils of platinum onto which a thin barium layer has been evaporated. These will drift towards tuned red and blue laser beams and the fluorescence detected in a phototube. A number of techniques for controlling the backgrounds will be explored including the use of atomic filtering and a number of pulsing strategies.

After completion of the above programmes, the detection techniques will be merged in a single small prototype detector. This is envisioned as a 30 cm chamber with a tracking readout at the anode and a steer able laser close to the cathode. It will be filled with Xe and a weak source of radioactive ^{134}Cs will be added. The Cs decays to Ba will be detected in a way analogous to the proposed double beta decay of Xe. This will allow almost all aspects of the detection scheme to be demonstrated. There is one additional test which is to demonstrate detection of the Ba when it is created as a doubly charged ion.

This can be done by using ^{137}Cs as the source. The beta decay of ^{137}Cs leads to an isomeric state in ^{137}Ba which has a 10% internal conversion branch. This decay mode can be identified by the presence of two sequential beta decays having the same x,y coordinates. The decay leads to a doubly charged ion of Ba. One has to correct for the hypefine effects in this system but this can be calibrated. This prototype would allowing a full simulation of the double beta decay process and allow the necessary efficiencies and backgrounds to be determined.

If the above testing proves successful, the next step would probably be a 200 kg detector using the separated Xe from the liquid prototype. The design appears to scale in a straight forward way so it may prove attractive to have a modular design that could be expanded to the several tonne scale. If the backgrounds are really well controlled then it may prove economical to make a larger detector of natural xenon. However, at present the data are not available to substantiate such a choice. Even a 200 kg a detector would have a sensitive mass comparable with the largest anticipated by that date anywhere in the world and the Ba tagging promises to give the lowest backgrounds. This would be a real world leading development. The detector might take the form of a cube 1.5 m on each side with a central cathode plane filled with xenon at 10 bar. It would require of order 200,000 channels of electronics.

The costs for this programme are estimated to be as follows:

At present the groups receive 170K/a for operations. This is not adequate for a programme with several students and this research presents many exciting thesis topics. We suggest 300K is more reasonable as we proceed, especially if the manpower increases with the completion of SNO.

Funds are available for the first round of prototyping. For the 30 cm detector we would require about 200K to cover the chamber, electronics, vacuum systems and underground installation. This would be requested in next year's application.

By the third year of the forward look it is expected that the project will be in a position to request major capital funding for the large detector. This would be an international project with the isotopic xenon coming from off shore and presumably many of the detector components. An estimate of the Canadian component would be $5M over 2 years.

3.3.3. Majorana

The Majorana collaboration is writing a proposal to build a large segmented ^{76}Ge detector in an ultrapure copper cryostat. ^{76}Ge is an ideal material because it can be both the source and the detector. There are a variety of new techniques to reduce and measure backgrounds that will be incorporated into the detector design. These include segmentation, pulse shape discrimination, time correlations, SNOLAB depth, Compton reconstruction, cryostat and shielding construction and purity, and underground material processing and fabrication.

Several of these enable us to reject gamma induced backgrounds by ensuring that the energy is deposited in a single site. There is also a European ^{76}Ge experiment, called Gerda, underway that will be sited at Gran Sasso. This experiment uses complimentary background reduction techniques, involving submerging the detectors into a liquid nitrogen cryostat. Gerda and Majorana are cooperating, and we expect that the two experiments will merge around the year 2012, and make a single international collaboration that will decide on the best technology and propose a future tonne scale experiment. This should happen during the time scale of this LRP.

In terms of a funding scenario, there should be a significant Canadian contribution to Majorana. We have stated that our responsibilities would include the on-site infrastructure. This is approximately $2M, primarily in 2008 and 2009. A significant fraction of this would be to implement clean underground manufacturing for electroformed copper, and the required assay techniques. Money early in the funding cycle from Canada would be particularly useful, since it could accelerate the schedule for the entire experiment. In particular, it would be possible to purchase several natural germanium crystals, which would enable the crystal suppliers to tool up their facilities to produce Majorana crystals, generate the masks, and set up the entire manufacturing process. At a later stage when Majorana and Gerda merge there will be an increased level of capital funding required from Canada, provided that the ultimate experiment is sited at SNO.

3.4. Other Initiatives

In this section we comment on a few other possibilities that are not currently official projects with Canadian participation, but for which the potential exists.

HALO Supernova Detector.

When the Cosmic Ray observatory in Chalk River closed, it was realized that the surplus lead could be useful in the construction of a supernova search detector. Approximately 100 tonnes of lead was acquired, and is now in storage in Sudbury. The first proposal, LAND, was developed by C. Hargrove at Carleton. However, this proposal did not proceed due to a lack of available personnel at the time SNO was at its busiest. In the LAND proposal, the lead was to surround some BF_3 detectors, also acquired from the Chalk River facility. It has since been recognized that the NCD detectors in SNO combined with the lead in storage would make an excellent supernovae detector.

This detector, dubbed HALO, is not yet at the level of an official proposal, but there are small groups in Canada and the US who are developing this idea. It would be a rather inexpensive experiment, as much of the material, detectors, and electronics are already in hand. Ideally, the first phase of this experiment would begin with the spare NCD detectors at SNO and be online before the end of SNO data taking in order to have continuity of supernova monitoring. Should the feasibility studies show promise, and a group rally behind this effort, we expect that proposals to SNOLAB and the funding agencies will be forthcoming.

Cryogenic Dark Matter Detector (CDMS).

The CDMS project is currently operating a cryogenic dark matter search experiment (CDMS-II) in the Soudan Mine in Northern Minnesota. They are presently the world leaders in the spin independent searches for dark matter WIMPS. In the near future, until the next generation of dark matter detectors currently being developed come on line, they will continue to make significant progress on the cross section limits.

The detectors are state-of-the-art thin film superconducting germanium or silicon crystals (250g and 100g respectively). Each crystal can simultaneously measure the energy deposited in phonons and ionization. This helps enormously with the suppression of gamma and beta particle backgrounds. Neutrons cannot be distinguished from WIMPS on an individual basis, and so must be reduced to as low a level as possible.

A disadvantage of Soudan is the relatively shallow depth compared to SNOLAB, and after a few years of running at full capacity, they expect to be background limited by neutrons. Hence, the CDMS collaboration is designing a large scale version of their detector (SuperCDMS) which they plan to install at SNOLAB. They have received very strong endorsement from the Experimental Advisory Committee:

"We strongly endorse the SuperCDMS project as a natural extension of the CDMS program and encourage a detailed assessment of the experimental layout and infrastructure needs."

While there is no official Canadian collaboration within CDMS at the moment, CDMS is actively looking for collaborators within the Canadian community. This is a very mature group, with a proven technology, and plans for a major upgrade of their detector. This will surely draw some interest from within Canada. Based on the excellence of the physics, the strength of the collaboration, their location in SNOLAB, and their ability to continue physics data collection while new technologies are being developed, we can anticipate eventual participation by Canadian scientists on CDMS.

4. Physics Reach Under Various Funding Scenarios

4.1. Overview of Goals, Program Costs and Resource Requirements

The long range planning exercise has asked the community to consider how various funding scenarios would affect their ability to accomplish their physics ambitions. To discuss this in a meaningful way, we first comment on the vision of the community for this field and establish the baseline for funding at the "status quo".

Vision:

The vision of the Canadian underground astroparticle physics community is clear:

- **Excellence in Physics:** The physics being addressed by this community is recognized worldwide as being of the utmost importance. We have come to realize that probing the universe at the largest scales is intimately related to our understanding of particle physics at its smallest scales. Fundamental amongst the questions are the nature of dark matter and dark energy and the masses of the neutrinos and how have they shaped the evolution of the Universe. The physics required to explain the recent observation of neutrino oscillations is intimately related to the issue of CP violation and the apparent matter-antimatter asymmetry in the early Universe. The recent awarding of the Nobel prize to Masatoshi Koshiba and Ray Davis for their pioneering work in neutrino astrophysics underlines the importance the community puts in this physics.

- **Major Impact:** In particle physics today, the nature of the research generally requires large international collaborations to build, operate, and analyse data from extremely large and complex detectors. The Canadian underground astroparticle physics community wants to make a major contribution to these efforts through participation, scientific leadership and innovation. The contribution by Canada will depend on the resources available, in terms of funding and the number of participating researchers.

- **Best Facility:** For the foreseeable future, SNOLAB will be the largest, deepest, and cleanest facility available for underground astroparticle physics. While the building of a facility in the US is recognized as being of the highest importance, the process there will take many more years, and one cannot envision a full scale national underground laboratory being ready for occupation before 2012. SNOLAB is far deeper than other present laboratories, which is of critical importance in terms of background reduction. Numerous experiments proposed for SNOLAB have reached the level of sensitivity attainable in their current locations, and now propose to come to SNOLAB for their next phases. Space is also a major consideration, with little or no available space in the currently operating facilities. In fact the pressures on SNOLAB already in terms of space are such that we are considering proceeding immediately with phase II if the funding can be established. SNOLAB will be built to the same cleanliness criteria that were essential for the successful operation of SNO. This is essential for the next generation of experiments in order that background radiation be reduced to a minimum.

In short, the community wishes to seize this unique opportunity to play a leading scientific role in addressing some of the most fundamental questions of physics today in the new state-of-the-art SNOLAB facility.

The vision of the Canadian astroparticle physics community is to continue as world leaders in this field by exploiting the unique aspects of SNOLab, the deepest and cleanest facility of its kind, and the expertise developed by the SNO experiment. We wish to seize this opportunity to do the best science in the best facility and to do this in Canada.

Establishing the Status Quo:

In order to consider the impact of the various proposed funding scenarios, we must first establish what the "status quo" and other funding scenarios mean in terms of an emerging field. We must then derive a baseline for the costs to develop, construct and operate the scientific program, and see how that fits within the proposed budgets.

As a matter of definition, we will take the status quo to be the amount of GSC-19 funding currently being directed towards underground astroparticle physics. The current annual NSERC support for the SNO experiment is about 4.4 M$. This includes support for SNO at the University of British Columbia, Carleton, Guelph, Laurentian, and Queen's, as well as the Canadian contribution for the on-site experimental expenses. The support from NSERC to support the development of the 4 SNOLAB projects PICASSO, EXO, Majorana and SNO+ amounts to about 600 k$. Hence, the status quo being spent on R&D is observed to be 5.0 M$. This would be used to support both operational and capital costs in the new program. We also note that NSERC reserves about 4 M$ per year for capital expenditures. As a subfield of sub-atomic physics in a growth period, we anticipate that roughly 25% of this reserve would naturally be directed at capital costs for SNOLAB projects. Hence we establish the baseline status quo funding to be 5 M$ annually with an assumed supplementary contribution of 1 M$ annually from the capital fund.

The Status Quo funding for underground astroparticle physics is 5 M$ annually, plus an assumed supplementary 1 M$ average annual capital contribution

The operation of the SNOLAB facility itself is expected to cost of order 5-6 M$ annually. Clearly, this cannot be supported by the existing envelope of GSC-19, and SNOLAB is working with various agencies to find a means of supporting the operation of the facility with new money. In this way, any GSC-19 support for underground astroparticle physics will be directed towards supporting Canadian scientists as leaders of experiments at the forefront of this field. Any other assumption would relegate Canadian participation in the field to being the humble host and financial supporter of international experiments sited in our facility. Hence we assume that the operation of the facility will be funded from peer reviewed support outside the nominal GSC-19 envelope.

It is essential that the Operational costs of the SNOLab facility are funded separately from the experimental program, with new money, and an established peer review process.

Most of the SNOLAB projects currently under consideration are in the process of developing detectors and conducting engineering studies. Hence it is difficult at this stage to speak definitively about overall project costs. It is also difficult to speak definitively about the eventual suite of experiments that will run at SNOLAB. However, one can estimate the total cost for those experiments currently being developed to determine a baseline cost for the field. Exactly how many and which experiments will be determined as the experimental programs evolve. It will also depend on the resources available in terms of personnel and funding. This will be discussed in more detail in the sections under the various funding scenarios. It is the clear desire of the community to have the greatest impact by consolidating its efforts on a few experiments.

One cost that is somewhat independent of the decisions on which experiments are built is the total cost for research personnel in astroparticle physics. Consider, for example, a proposed experiment that does not proceed to deployment. Faculty, postdocs and graduate students who have been involved in the R&D will almost certainly join other related SNOLAB experiments that are going forward. The total number of supported FTEs in the field is therefore considered to be a conserved quantity and can provide an estimate for the ongoing annual operational costs. We refer to this as the "conserved total personnel cost" estimate. With the vision that this is a growth field a long range plan should accommodate an expansion of personnel, with new faculty hires (discussed in the following section), research support for SNOLAB research scientists, and the possibility that researchers established in other related areas in subatomic physics may be attracted to join SNOLAB experiments. Thus, the following exercise in estimating project costs allows for some growth in personnel in this field.

Estimated Project Costs.

The projects currently under development in Canada including DEAP, EXO, Majorana, PICASSO and SNO+ have all considered their costs to develop a full-scale detector under the assumptions of the current technology and according to their current research plans. This will undoubtedly evolve as various obstacles emerge and first physics results are obtained. Nonetheless, it is a useful exercise in order to establish the baseline costs of the entire program. It is not realistic to assume that this is then the program and profile for the next 10 years. This is an evolving field and it is certain that new ideas will come to the fore and some projects may be completed. Allowing for new initiatives in the latter years of the 10 year plan is absolutely essential. We expect that new initiatives and upgrades to existing experiments will require more capital funding in the second half of the 10 year plan. However, for planning purposes, we will use the reasonably well understood first 5 years as a starting point and ask what could be done within the various scenarios.

The following table lists the estimated operating and capital costs for various projects over the next 5 years. Note that SNO has a well defined plan to cease data taking at the end of 2006. This will be followed by a year of effort to return the heavy water and recover the NCDs. It also plans to continue analysis on the existing data for another 2 years. Most of the cost for the project in the years pertinent to the LRP is related to the removal and return of the heavy water, and it would be difficult to significantly reduce the costs for this. The costs are mainly associated with staff salaries and insurance on the heavy water. Reduced support will only reduce the number of active staff, delay the return of the heavy water, and extend the period for which insurance must be paid. We also note that in terms of cost estimations, SNO+, with much of the detector already existing, is perhaps in the best position to make realistic cost estimates. SNO+ capital costs are considered below to be entirely funded by Canada although it is the aim that foreign collaborators will be able to make significant contributions. SNO+ operating expenses, on the other hand, assume the cost is only for the present Canadian contingent. The required operating cost for the whole experiment and the required number of collaborators for SNO+ is significantly larger than what is considered below, and it is expected that additional foreign collaborators will make up their portion. The reason for costing in this manner is to be able to extract the “conserved total personnel costs” for SNO+, as discussed above.

Project Cost	2006	2007	2008	2009	2010	Σ 5-Year
DEAP Operations	172	189	300	300	500	1461
DEAP Capital			1000	1000		2000
DEAP Total	**172**	**189**	**1300**	**1300**	**500**	**3461**
EXO Operations	170	300	300	660	660	2090
EXO Capital		200	0	2500	2500	5200
EXO Total	**170**	**500**	**300**	**3160**	**3160**	**7290**
Majorana Operations	100	300	300	300	300	1300
Majorana Capital			667	667	667	2000
Majorana Total	**100**	**300**	**967**	**967**	**967**	**3300**
Picasso Operations	561	552	450	450	500	2513
Picasso Capital			300	700		1000
PICASSO Total	**561**	**552**	**750**	**1150**	**500**	**3513**
SNO+ Operations	374	450	450	550	560	2384

SNO+ Site Operations				550	560	1110
SNO+ Capital		5000	5000			10000
SNO+ Total	**374**	**5450**	**5450**	**1100**	**1120**	**13494**
SNO Site Operations	3167	2372	245			5784
SNO Institutions	1484	1061	696			3241
SNO Capital	0	0	0		0	0
SNO Total	**4651**	**3433**	**941**	**0**	**0**	**9025**
Total Capital	0	5200	6967	4867	3167	20200
Total Operations	6028	5224	2741	2810	3080	19883
TOTAL COSTS	**6028**	**10424**	**9708**	**7677**	**6247**	**40083**

Table 1. Estimated Project funding for SNOLAB projects over the next 5 years. All values are in 1000's of dollars. The last column gives the sum over the first 5 year period.

The total cost of the above program for the next 5 years is 40.1 M$. Of this, the capital costs for the 5 new projects totals 20.2 M$, and the operational cost to complete SNO is 9 M$. The remaining 11 M$, spread over 5 years, is the total conserved personnel and operating costs for underground astroparticle physics. The 11 M$ does not include an allowance for growth in personnel in the field. However, we do expect growth, and have conservatively estimated it to be 2 new persons per year. Prorating their research costs, we estimate the total personnel and operating costs for the field will be 13 M$ over 5 years. Including the costs to operate SNO until completion, the total operational costs for the field over 5 years are expected to be 22 M$.

This can be compared to the anticipated status quo amount of 30 M$ (6 M$ for 5 years). If all operational costs are realized, approximately 8 M$ would remain for capital expenditures during this 5 year period.

4.2. Status Quo Scenario

In the status quo, we expect a flat funding level of 6 M$ per year (based on current funding levels of 5 M$ per year, to be used for operations and capital costs, and an assumed 1 M$ per year in additional capital support during this period of development). This amounts to 30 M$ over 5 years. Given the relatively fixed costs to complete SNO of 9 M$, and the conserved personnel and operational costs of 13 M$, the remaining funds for capital projects amounts to about 8 M$. The capital costs of DEAP, EXO, Majorana, PICASSO and SNO+ are about 2, 5, 2, 1, and 10 M$ respectively. Clearly, in the status quo scenario, there are insufficient funds to support all projects at the levels suggested.

Even under these conditions, the objective of the group is to contribute significantly to a number of experiments within an overall program that covers all the main elements of the basic science proposed for SNOLAB. In order to maintain the healthiest program possible under these conditions, major concessions would be required. SNO+ would need to find significant capital support from international collaborators, and the capital contributions to foreign led projects, like Majorana, would likely be substantially reduced. Other projects would likely ramp up more slowly as the available capital gets distributed over more years. Alternatively, one could consider reducing the fractional funding directed towards operational costs. This would mean less support for postdoctoral fellows and students, and would lead to suffocation in the field. This should be avoided at a time when we expect a new international facility in Canada will be attracting great interest in a growth area.

The slow ramp up of projects is a serious concern. The experiments being considered are a major step towards eventual detectors of large mass and high sensitivity. We expect that in 5 years time, and with sufficient funding, the Canadian SNOLAB program would be on the brink of the next exciting stage, competing at an international level, not struggling to mount experiments due to financial constraints.

There is no money in the status quo scenario for new initiatives and the amount of support for new researchers in the field (faculty and HQP) would be very limited. This would stifle the research potential of the many new CRC and faculty appointees in this developing field. We would not achieve the vision of leadership in all areas of the SNOLAB astroparticle physics programme.

Hence one finds that in the status quo, financial constraints impose limitations on the physics program long before human resources would become an issue. While it is clear that some of the exciting physics would still be attainable, the status quo would certainly not lead to the optimal, broad-based physics program we are striving for, and there would be no money available for new initiatives.

4.3. Falling Funding Scenario

In the -20% scenario, we assume this implies a gradual reduction of the base rate of 6 M$ to 4.8 M$ after 10 years. This suggests a decrease each year to ~97.8% of the previous year, and has the net affect that in the first 5 years of the LRP, only 28 M$ would have been made available.

Under the assumption that we should try to keep the community as healthy as possible, the impact would mainly be in the loss of capital funding support. In this scenario, only about 6 M$ would be available over 5 years for capital spending. In the falling funding scenario Canadian scientists might have limited participation in the SNOLAB physics program. Their role on some experiments of interest to this community would be largely relegated to host, rather than leader. On other Canadian-led experiments the impact would be increased reliance on foreign contributions to capital and operating costs perhaps to the point the Canadian-led nature of these projects is jeopardized. The consequences would be the erosion of support by Canada to international projects at SNOLAB and a severe need to find significant funds offshore for Canadian-led projects. Leadership on these projects would gradually become the responsibility of the larger international collaborating groups.

Unless adjustments were made elsewhere within the SAP GSC-19, this option would stifle activity at SNOLAB, and compromise Canadian participation in the SNOLAB facility. This would have a devastating impact on personnel, reversing the trend of growth in the field, contrary to the requirements for establishing a new facility.

4.4. Significantly Increased Funding Scenario

In this scenario, we assume a gradual doubling of the GSC-19 envelope, and assume that the fraction available to astroparticle physics remains the same. A doubling over 10 years suggests an annual increase of about 7%, which is well within the realm of possibilities. In this case, one would expect a net contribution to astroparticle physics of about 37.1 M$ in the first 5 year period. The main cumulative effects would only be felt later.[1]

With this amount of funding there would be about 17 M$ available for capital expenses. This would allow a significant scientific programme to be pursued.

- It would allow Canadians to become leaders in the worldwide astroparticle physics program, driving the research and using SNOLAB as the host.
- It would ensure that Canadian physicists participate in SNOLAB at a level consistent with the personnel resources available.
- It would make it possible for 3 or 4 experiments to be conducted, and would not limit the range of physics topics.
- The physics could be addressed in the quickest possible time. There would be no need to prolong or defer some research programs due to financial delays.
- It would allow some money for new initiatives in the field, an essential element of any healthy research program.

This scenario is the one which allows for substantial participation in the SNOLAB facility by Canadian scientists, and which also supports a healthy growth in the field through new initiatives. In this model, Canadians will fully reap their investment made in the SNOLAB facility, and will be well placed to become world leaders in addressing many of the most fundamental questions of physics today.

This is also the only scenario consistent with the expected growth in the field. With SNOLAB operations beginning in 2007, a major new international facility will be available for Canadian researchers. Based on the development of other national laboratories, we expect sizeable growth in the interest in this field. An increase in GSC-19 funding at the level suggested is absolutely necessary to support Canadian involvement in the Laboratory at a level which will ensure that Canadian scientists are at the forefront of astroparticle physics for the next decade.

[1] The IPP brief assumes that each year the amount of funding increases by 10% of the base level. In this case 39 M$ would be available during the first 5 years of the plan. The different treatments have little impact on the conclusions.

4.5. Planning Beyond 2010

In all the funding scenarios considered above, we only examined the upcoming five years and the current suite of proposed projects. The NSERC LRP exercise wishes to take a longer term view of 10 years. In an emerging field like astroparticle physics, planning beyond five years takes on a different nature. Despite the fact that subatomic physics experiments traditionally have long lead times, our current situation is very dynamic, with a new lab and new experiments being developed.

Consider the last NSERC long range planning exercise in 2000. At that time, SNOLAB didn't even exist as a concept. If the previous plan had charted the research directions for subatomic physics until 2010, any detailed budgetary considerations would now be obsolete in light of the new reality of SNOLAB. We find the value of longer range planning for underground astroparticle physics to be in outlining the longer-term physics directions. There may be new discoveries in the upcoming five years that change the course of astroparticle physics. There could be experiments within the current suite proposed that do not successfully reach full scale. In pondering the longer range plan, beyond 2010, our considerations are thus not solely budgetary. However, we can say that given the long-term nature of the experiments proposed, the strong international interest in this field and the likelihood of new ideas being proposed by 2010, the total cost per year is unlikely to be lower than that which is required for the years from 2005-2010.

Neutrinoless double-beta decay in the next generation of experiments reaches down in neutrino mass an order of magnitude with sensitivity to the degenerate mass hierarchy. If there is no evidence for neutrinoless double-beta decay in the next five years, the field will continue its strong activity as it pushes down another order of magnitude to the inverted hierarchy – a tantalizing prospect set by the mass splitting of atmospheric neutrino oscillations. This neutrino mass range is within reach of scaled-up experiments. Beyond that, pushing down another order of magnitude to the normal hierarchy will require that new technology be developed. We consider the research prospects beyond the fifth year to be exciting and believe it will have the same funding demands as the upcoming five years.

If neutrinoless double-beta decay is observed, the physics program will evolve into a new generation of experiments capable of sorting out the mechanisms that contribute to the process. These will require new detector technologies that track the energy and angular correlation of the emitted beta particles, for example, and detectors composed of other candidate double-beta decay nuclei.

In the quest for dark matter detection, a positive signal will lead to the next challenge of measuring the WIMP directionality. Seeking orbital or diurnal modulations in the dark matter signal rate is the first step toward a grander vision of WIMP astronomy. Technologies and detectors that explore this possibility are currently being developed. This research will continue beyond 2010.

The physics program of a large detector such as SNO+ is varied. Precision measurements of low energy solar neutrinos will certainly extend beyond 2010. Geo-neutrino studies represent pioneering steps in a new field. SNO+ would be the 2^{nd} experiment after KamLAND to study geo-neutrinos. A result with deep geological significance from SNO+ will surpass the scientific impact of KamLAND's first observation, and will set the course for future studies. Possibilities for later developments in the SNO+ detector, such as double beta decay searches with neodymium dissolved in the liquid scintillator (or dispersed in the form of nanoparticles) are interesting technologies being developed now which may drive the physics program beyond the fifth year being considered here.

Our conclusion is that the physics program is just getting underway at SNOLAB. Beyond 2010, regardless of which specific experiments develop to full scale, there is tremendous scientific potential in continuing to fund activities at expanded levels beyond 2010. This growing field is already attracting an increased numbers of researchers, as described in the next section. Physical space in SNOLAB for all of the proposed experiments will not be limited in 2010.

5. Demographics and Training of Highly Qualified Personnel

In the following sections we present the current and anticipated numbers of researchers (faculty, research scientists, postdoctoral fellows, graduate students and other highly trained personnel) and try to measure the impact that SNO and SNOLAB experiments have had on the training of highly qualified personnel. We also comment on the link to industry and other disciplines.

5.1. Demographics: Faculty and Research Scientists.

The astroparticle physics community in Canada is one of the largest sub-disciplines of Subatomic Physics. The number of faculty and research scientists currently active on either SNO or one of the developing SNOLAB projects includes 33 faculty and research scientists. Of these, nine are active emeritus professors. The current FTE from these faculty and research scientists on SNOLAB activities amounts to 22 PY.

The past few years have been very difficult, financially, for Universities and most departments have downsized through attrition. It is worth noting that while overall department sizes have dropped, support for astroparticle physics has been very strong. This has been made possible in part by the Canada Research Chair (CRC) program. In the past few years there have been 5 new CRC positions created within the Universities to support astroparticle physics[2]. These have come with generous CFI support to provide the infrastructure required to establish new research groups in their respective departments. There has also been a regular faculty appointment at Laurentian. During this period five new Research Scientist positions have been created at SNOLAB. These positions were

[2] This includes a new CRC at Queen's University which is currently in the final stages of the hiring process. The other CRC positions are at UBC(1), Carleton(1), and Queen's(2).

created with the initial operations support from CFI, and are equivalent in nature to TRIUMF or IPP Research Scientist positions. Three of these Research Scientist positions have already been filled. Hence in the last few years alone, 11 new positions were created, 9 of which have already been filled.

It is difficult to predict the continued growth in SNOLAB activities. However, just as TRIUMF began operations with a small contingent of personnel in the early 1970's, and has since grown to become a major research facility with hundreds of employees, it is reasonable to expect that SNOLAB, having already attracted so much international interest, will have substantial growth. This anticipated growth has to be recognized in the long range plan.

In terms of new faculty positions, we are aware of at least 3 that are likely to be filled in the next year or two. One faculty appointment has been approved for Carleton and the University of Montreal plans on hiring an astroparticle physicist in 2007. The planning exercise conducted at Queen's anticipates at least one further appointment in this field. Current plans call for two new research scientists to be appointed at SNOLAB in addition to the three presently in place. When SNOLAB becomes operational we expect to see an increased interest in the facility from established researchers in similar fields, and the creation of new research groups in Universities not currently active in astroparticle physics. At Trent University, one established researcher has recently joined SNO and has interest in future participation in SNO+, and we have had expressions of interest from some faculty members on the East coast. This increase in support is welcome and necessary as we go forward with a number of new projects, and as we anticipate a gradually diminishing contribution from two colleagues at UBC and TRIUMF who are ramping up their participation in the closely related T2K neutrino oscillation experiment.

5.2. Training of Postdoctoral Fellows, RA's, and Graduate Students:

SNO, and now SNOLAB, have benefited greatly from participation by postdoctoral fellows and RA's, and students, both graduate and undergraduate. As can be seen in Table 2, SNO is on the verge of reaching a major milestone, with almost 100 PhD and Masters degrees granted collaboration wide. This is a strong testament to the student participation in SNO.

Institution	Training Completed		
	M.Sc.	Ph.D.	Postdoc/RA
SNO Group (Canada)	**47**	**14**	**28**
British Columbia	3	2	4
Carleton	9	2	9
Guelph	7	3	3
Laurentian	6	-	5
Queen's	22	7	7
PICASSO	**5**	**1**	
Montreal	5	1	

TOTAL Canadian	**52**	**15**	**28**
SNO: Non-Canadian	3	31	20

Table 2. Graduate degrees and postdoctoral training on the SNO and PICASSO projects.

On SNO, there have been a total of 50 M.Sc. theses (47 of these in Canada, and 3 in the US and UK, where the awarding of an M.Sc. is not the norm). There have been 45 Ph.D. theses completed, for a grand total of 95 theses completed on SNO. There have been 5 M.Sc. and 1 Ph.D. thesis completed on PICASSO. Hence, these two projects have combined to yield 101 degrees to date!

SNO has been equally fertile in providing training for postdoctoral fellows. As shown in Table 2, there has been 28 postdocs and RA's distributed amongst the Canadian universities and a further 20 from our colleagues in the US and UK, for a total of 48 postdoctoral (or RA) positions on SNO.

Finally, we note, in Table 3, that SNO, PICASSO, and the new SNOLAB projects continue to attract a healthy number of graduate students and postdoctoral fellows. There are currently 29 graduate students active on SNOLAB projects, and 19 postdoctoral fellows and RA's.

Institution	Active Participation		
	M.Sc.	Ph.D.	Postdoc/RA
British Columbia	0	1	2
Carleton	0	4	3
Guelph	0	1	1
Laurentian	4	-	3
Montreal	3	4	1
NRC	-	-	1
Queen's	6	6	8
TOTAL Canadian	**13**	**16**	**19**
SNO: Non-Canadian	-	11	7

Table 3. The number of Postdocs, and graduate students currently active on SNOLAB projects. This includes DEAP, EXO, Majorana, PICASSO, SNO and SNO+. As some students are yet to decide on their thesis topic, and many postdocs have participation in more than one project, we have not itemized the numbers for each project. For reference, we indicate the numbers appropriate for SNO for our US and UK collaborators.

It is useful to try to understand how this training has helped in the formation of these students. We have compiled a list of subsequent training of our students. Although incomplete, there is enough data to make some observations, albeit encumbered by the small statistics, particularly in light of the large number of alternate career paths. Table 4 presents our findings. Of the 26 students known, 5 went directly into industry, usually high tech or computing. A further 21 went on to the Ph.D. degree. Of these, 8 are still in progress, and 13 have been completed. Of the 13 completed Ph.D's, 9 are still in an academic stream, 4 have eventually found positions in industry or in research. Hence, it appears that roughly 75% of our M.Sc. students continue to pursue jobs in academia, whereas about 25% have landed in positions in industry and the high-tech sector. We note that these results may be misleading, in that the students we are more likely to have followed, are precisely those students who have continued their affiliation with academia.

Total Canadian M.Sc. Students on SNO	47
Of these:	
M.Sc. Students whose career path is known	26
Of these:	
Number who went into industry or computing	5
Number of these who have gone on to a Ph.D. in Physics	21
Of these:	
Ph.D. in progress	8
Number who have completed a Ph.D.	13
Of these:	
Currently a post doc	5
Postdoc, then faculty	1
Postdoc, then Research Scientist	3
industry or technical research staff	4

Table 4 Career paths of students who began in Canada with an M.Sc. on SNO.

We have tracked the career paths of our 15 Ph.D. students on SNO and Picasso. Table 5 below indicates where they are now. Once again, one sees a similar breakdown, with about 75% of the students continuing with an academic stream, and 25% moving into high-tech positions in industry.

Total Canadian Ph.D. Students on SNO and PICASSO	15
Of these:	
Ph.D. Students whose career path is known	14
Of these:	
Number who went into high-tech industry or computing	3
Number of these who are presently a postdoc or RA	7
Number who have a faculty or Research Scientist position	4

Table 5 Career paths of students who began a Canadian Ph.D. on SNO or PICASSO.

A similar trend is seen in the career progression of post doctoral fellows and research assistants who were originally based in Canada, and who have now completed their original appointment. This is shown in Table 6, below. For the postdoctoral fellows and RAs we were able to track, we note that about 25% of our trained personnel have positions in the high-tech industrial sector, whereas the remainder have continued in the academic stream.

Canadian based postdoctoral fellows on SNO	28
Of these:	
Number whose career path is known	24
Of these:	
Number of these who are presently in a new postdoc or RA	7
Number who went into high-tech industry or computing	6
Number who have a faculty or research position in academia	10
Number who went for a new degree.	1

Table 6. Career progression of SNO Postdoctoral fellows and RA's originally located in Canada.

Roughly 25% of all graduate students and postdoctoral fellows have found careers in the high-tech industrial sector. The other 75% are predominantly in academic research institutions as faculty, research scientists, or senior research assistants.

5.3. Other Highly Trained Personnel:

In this section, we comment on the training provided to other personnel. In particular, we have benefited greatly from undergraduate students in coop programs or summer research positions. We also have highly trained technical and engineering staff at SNO and SNOLAB, and in many cases these staff members have been able to advance their careers through on the job development.

All institutions have been active at employing undergraduate students on SNO and other SNOLAB projects, as can be seen in Table 7 below. We have also had a number of students hired by SNO directly, and supervised by on-site research scientists or our engineering staff. While the bulk of the students had a physics background, the interdisciplinary nature of SNO has enabled us to accept students from a variety of backgrounds such as chemistry, computing, engineering, environmental studies, mathematics and biology. Roughly 135 students have profited from participation on SNO in the past 6 years. This is a slight underestimate, as the statistics were not available for all faculty members, particularly those that retired in this 6 year window. None-the-less, SNO has made a tremendous contribution. Undergraduate summer students have also contributed greatly to the PICASSO program, with over 20 students having been employed over the past 6 years.

Institution	Supervised	Co-Supervised
British Columbia	16	1
Carleton	10	2
Guelph	3	0
Laurentian	31	7
Queen's	54	3
On-Site	12	
TOTAL	**126**	**13**

Table 7. Undergraduate coop and summer student training at SNO in the past 6 years. Data taken from NSERC forms of active faculty only and records of activity on-site.

‖ SNO has employed about 135 coop and summer research students in the past 6 years. ‖

SNO currently employs about 30 staff members. They have the responsibility to maintain and operate the complex ultra-pure water systems, operate the SNO detector, and design and commission new installations. There are currently 4 licensed engineers on staff. Of these, three obtained their P.Eng. while making their apprenticeship on SNO. Several of the technical staff have received technical training that has allowed them to receive provincial certification as water treatment operators, and one employee became registered with OACETT as an engineering technologist using his work at SNO as the basis for his application.

There are also a number of senior engineers at the universities who are contributing in a significant way to the design and operation of the SNO and SNOLAB facility, and should really be counted in the FTE of the project based on their substantial contributions over many years.

‖ SNO has about 30 staff, including many highly trained technicians and engineers. ‖

5.4. Interdisciplinary Relationships

One of the strengths of the astroparticle field is the inter-disciplinary nature of much of the work. Indeed the very title speaks to the blending of two major fields of physics. SNO was a good example of an experiment that not only discovered fundamental new information about the nature of neutrinos but also provided a unique and sensitive test of conditions at the centre of the Sun. SNO also required developments in chemistry such as the need to detect contaminants at unprecedented levels. These types of interplay continue as we seek ever more sensitive ways to probe rare processes. The search for neutrino-less double beta decay has spurred the study of how to suspend nanoparticles in liquids and has also led to the search of techniques using special laser spectroscopy to identify single atoms which might be produced once per year by neutrinoless double decay processes in a multi-tonne detector. The search for dark matter brings together particle physics, astronomy and cosmology in one of the most pressing challenges in physics today. This challenge has also led to strong synergies between experimental groups and the bubble technology industry. The proposed SNO+ detector would allow a measurement of neutrinos from the earth which would probe the inner workings of the earth's mantle. There are other links that grow out of the unique opportunity that a deep underground laboratory presents. The POLARIS seismology group is investigating with SNOLAB the prospects for a three dimensional seismic detector. This too could reveal details of the inner structure of the earth as well more local geology of importance to the mining industry. Finally, the field of astroparticle physics shares the links that all of sub-atomic physics areas have with applications such as medical imaging.

6. Conclusions and Recommendations.

In the following, we present the main conclusions and recommendations coming out of this planning exercise.

Conclusions:

- We conclude that the science being addressed by Canadian scientists at the SNOLAB facility addresses some of the most exciting and fundamental questions of science today. Astroparticle physics has become one of the main thrusts in particle physics world-wide.

- With the advent of the SNOLAB facility, Canadian scientists have a unique opportunity to become world leaders in one of the most relevant and rapidly growing fields of physics.

- As SNOLAB becomes operational we anticipate a strong growth in participation and scope, nationally and internationally, as has been observed at other national facilities.

- The funding for astroparticle physics experiments is currently 5 M$. In all scenarios considered, this, plus a share of the capital equipment fund to supplement the capital costs, is the base support for ongoing funding of experiments, not the operation of the facility. We assume that the money for operation of the SNOLAB facility must come from additional, peer-reviewed funding, probably also with overview from the Major Science Initiative Panel and herein we discuss GSC 19 funding status to be related to funding of experiments only.

- In the Status quo scenario for GSC 19, Canadian scientists would be able to participate significantly in some projects at SNOLAB. With the personnel resources available, they could reach a higher potential, but funding constraints will limit the scope of the physics attainable and lengthen the time to achieve it.

- In the -20% scenario , Canadian scientists will play an ever diminishing role in their own laboratory. They would be able to lead only one or more smaller projects, but would be relegated to hosts on a number of critical experiments where we have the potential to be leaders.

- There is enough scientific merit and human resources available to warrant pushing hard for the +100% increased funding scenario. Canadians would have full participation in their laboratory and would be well poised to become world leaders in the field. There would be sufficient money in the GSC 19 envelope to support a healthy program and allow for new initiatives.

- The astroparticle physics community consists of about 33 faculty and research scientists, has extensive support of specialized engineers and technical support staff, and has developed a strong base of young researchers through the training of 100's of undergraduate and graduate students, and postdoctoral fellows. The community is large, capable and vibrant.

- The growth in the field has been healthy, as is demonstrated by the number of recent new appointments, including several Canada Research Chairs, and the number of new positions being generated.

Recommendations:

- We strongly recommend that the funding for the operation of the SNOLAB facility be new money, outside the current NSERC GSC-19 envelope. The Major Science Initiative should address the question of which agency would be best suited to receive and administer the funds for the operation of SNOLAB. The allocation of these funds must be subject to an ongoing peer review process.

- We strongly recommend that the LRP committee seizes the opportunity to make the best case possible for a significant injection of new money into the GSC-19 envelope. The timing is perfect with a new facility being launched, strong growth in all of SAP, and optimistic financial conditions in government.

- We recommend that the SAP community take advantage of the favourable press associated with SNO, the development of a major new international facility in Canada, the general appeal of astroparticle physics and major accomplishments in other areas of Subatomic Physics to promote our field to a more general audience. This includes lobbying of governments, universities, funding agencies and our own community.

- We recommend that the LRP recognize the need to reserve funding for new initiatives and new investigators. This is particularly important for the last 5 years of the planning period, where new initiatives are very likely, built upon the most successful R&D in all areas during the first 5 years.

- We recommend that the Canadian led projects DEAP, PICASSO and SNO+, continue their efforts to strengthen their collaborations internationally. We recommend that offshore participation should include some capital contributions to defray the strain on the GSC-19 envelope.

- We recommend strong support from GSC-19 for Research and Development of SNOLAB projects to determine the optimal set of experiments in neutrinoless double beta decay, dark matter searches, and solar, supernova and geo- neutrino physics.

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Appendix A: The LRP Process and the Astroparticle Physics Brief.

The NSERC GSC-19 has struck a committee to form a plan for the next 10 years of Subatomic Physics (SAP) in Canada. The committee has solicited comments in the form of briefs from the community. The mandate of the exercise is to layout the scientific priorities of the next decade, and to do so while considering a variety of funding scenarios. The committee has also been asked to address a number of issues, including the relationship between NSERC and other funding agencies, and the balance between operating and capital expenditures. The latter are particularly relevant in a discussion of SNOLAB, whose construction is being funded by large grants from CFI and several other agencies. Also, the Canadian government is currently debating the means to fund the operation of Major Science Initiatives.

During the past 5 years the SNO collaboration has received world wide acclaim for their research on the nature of solar neutrinos. The dramatic results from SNO and other astroparticle physics experiments have revolutionized our thinking about neutrinos, their role in the cosmos, and the standard model of particle physics. We have also entered an era of precision astronomy which has led to a convincing realization that some 95% of the mass and energy in the Universe is of a form completely unknown to us, a view we would not have dared to believe only a decade ago. The combination of these efforts has led to a much better understanding of particle physics and the structure of the Universe. It has also raised many extremely important fundamental questions: what are dark matter and dark energy, what has happened to the anti-matter in the universe, and what is the exact nature of these elusive neutrinos?

Worldwide, scientists have begun to address these questions with renewed vigour and innovation. The field of astroparticle physics has grown enormously, and there are many large international programs underway to address these questions. However, the number of facilities capable of housing such experiments is very few and there is a great pressure on those that do exist. A great number of the experiments currently being developed require an ultra-clean facility located deep underground to shield them from the constant stream of cosmic rays present on the surface of the earth. SNO demonstrated the unprecedented technical feasibility to operate such a clean facility at great depth. The new SNOLAB facility currently under construction will provide experimental space in the deepest, cleanest, underground laboratory in the world. SNOLAB will also provide the scientific and technical expertise appropriate for a major international laboratory. Canada as host is well poised to be centre stage for research in astroparticle physics in the decade to come. It is extremely important that this great opportunity is realized by the Canadian subatomic physics community, the universities, and the funding agencies so that Canada develops the resources to be able to lead the scientific effort on a number of experiments.

Following the 4th SNOLAB workshop in Sudbury in August, 2005, a meeting was held to discuss the LRP process, and how best the astroparticle physics community could contribute to it. Astroparticle physics is unique in subatomic physics now.

- The community is in a period of development. SNO prospered through the combined effort and consolidation of resources of much of the Canadian astroparticle community. Only now, as SNO begins to ramp down, are resources and research time becoming available to tackle the tough questions ahead.
- The experiments under consideration have very different physics goals, and hence there will need to be several. The community is reorganizing itself based on the physics interests. Hence, at the moment the community is driven by a small number of more specific experiments and by a vision of how the field should develop over the next years.
- The new SNOLAB facility has benefited from about $38M funding support from agencies outside of NSERC, and will be ready for occupation in 2007. The role of this facility needs to be clearly described.
- With regards to funding, the environment in Canada is quite optimistic. New monies and positions are clearly being generated through the CFI and CRC programs. The government has launched a study on funding for Major Science Initiatives. More than ever before, one should take seriously the opportunity to "think big". In order for the entire subatomic physics community to benefit from these opportunities, we need to capture the sense of urgent excitement that we feel and convey that to the scientific community, the universities, the government and the funding agencies. The astroparticle physics program is well poised at the moment to capture this sense of urgency and excitement, and this should be combined with the major opportunities elsewhere in sub-atomic physics and conveyed outside our field.

The astroparticle physics community decided that considering the above and the somewhat unique nature of our field at the moment, a separate brief complementing the IPP and Nuclear Physics briefs would best aid the LRP process. Projects like SNO and PICASSO, already IPP projects, benefit greatly from the support received from IPP and the Nuclear Physics community. We feel that there is great potential for several new SNOLAB experiments to become IPP projects in the future and there is also a strong overlap with the objectives of the nuclear physics community in Canada, such as for double beta decay and solar neutrino experiments at SNOLAB, and the strong programs in fundamental interactions and nuclear astrophysics in the nuclear programs. Therefore, although we outline enthusiastically our future program for SNOLAB in this document, we wish to work closely with the broader particle physics and nuclear physics communities to develop an overall long range plan that emphasizes the common objectives for excellent science within all of sub-atomic physics.

Appendix B: Details on the SNOLAB Facility.

B-1 Description of the Facility

SNOLAB is a deep underground facility for experiments in astroparticle physics requiring ultra low backgrounds. Currently under construction, the laboratory is an expansion of the existing SNO facilities situated 2 km below the surface on the 6800 ft level of the INCO Ltd. Creighton nickel mine near Sudbury, Ontario. When complete, the facility will provide over 50,000 sq ft of clean room space for experiments and the supporting infrastructure underground. As well there is a 34,000 sq ft surface facility to provide support for the staging and operation of the underground experiments. The great depth of SNOLAB provides the equivalent of 6010 m water overburden making it the deepest laboratory in the world. The resulting cosmic ray muon flux is less than $0.27/m^2$/day. Following the highly successful model of the SNO experiment, the entire laboratory will be operated as a Class 2000 or better clean room to provide a low radiological background environment.

The construction of SNOLAB is to be done in two phases, Phase I, which is currently under way, will add a large rectangular cavern and a network of smaller drifts.[3] Phase II will add another large cylindrical cavern intended for cryogenic experiments. Phase II is under consideration but a decision has not yet been made whether Phase II will be contiguous with Phase I. If not constructed now, it will be possible to add Phase II at a later date. In addition to the experimental spaces, SNOLAB will provide the personnel and material handling facilities; electrical services; HVAC; and communications systems necessary to conduct experiments underground in a state of the art clean room facility. In it's full implementation, SNOLAB will be able to host three large experiments (hundred to kilo-tonne scale) in the rectangular hall, cryogenic cavern and existing SNO cavern (after the termination of the running SNO experiment). Two medium scale experiments will be housed in the drift network and various spaces will be available for smaller prototyping activities.

B-1.1 Underground Laboratory

SNOLAB will augment the existing SNO underground facility with an additional 68,000 sq ft of excavations of which 40,000 sq ft will be clean room space contiguous with the existing facility (Figure 6). The entrance to the laboratory will be relocated for the expanded facility and some already existing excavations will be converted to additional clean room space. The resulting SNOLAB underground laboratory (Phase I and II) will be a 53,600 sq ft clean room. Of this 34,000 sq ft will be experimental laboratory space with the remainder providing the laboratory infrastructure necessary to conduct the experiments. There will be an additional 28,000 sq ft of excavation outside the clean

[3] ``Drift'' is a mining term for tunnel

room used by SNOLAB for the service infrastructure and material transportation and storage.

Part of the increased clean space will include relocated and enlarged personnel facilities (change rooms, showers, lunch and meeting rooms, office space) and equipment facilities (carwash for cleaning equipment entering lab, clean storage). New lab space for experiments will include the excavation of a new experimental hall (60' x 50' x 50') for a large 100 tonne class experiment; a network of connected 20' x 19', 25'x25' and 15' x 15' drifts for smaller experiments and the reclaiming of the personnel drift from the existing SNO facility.

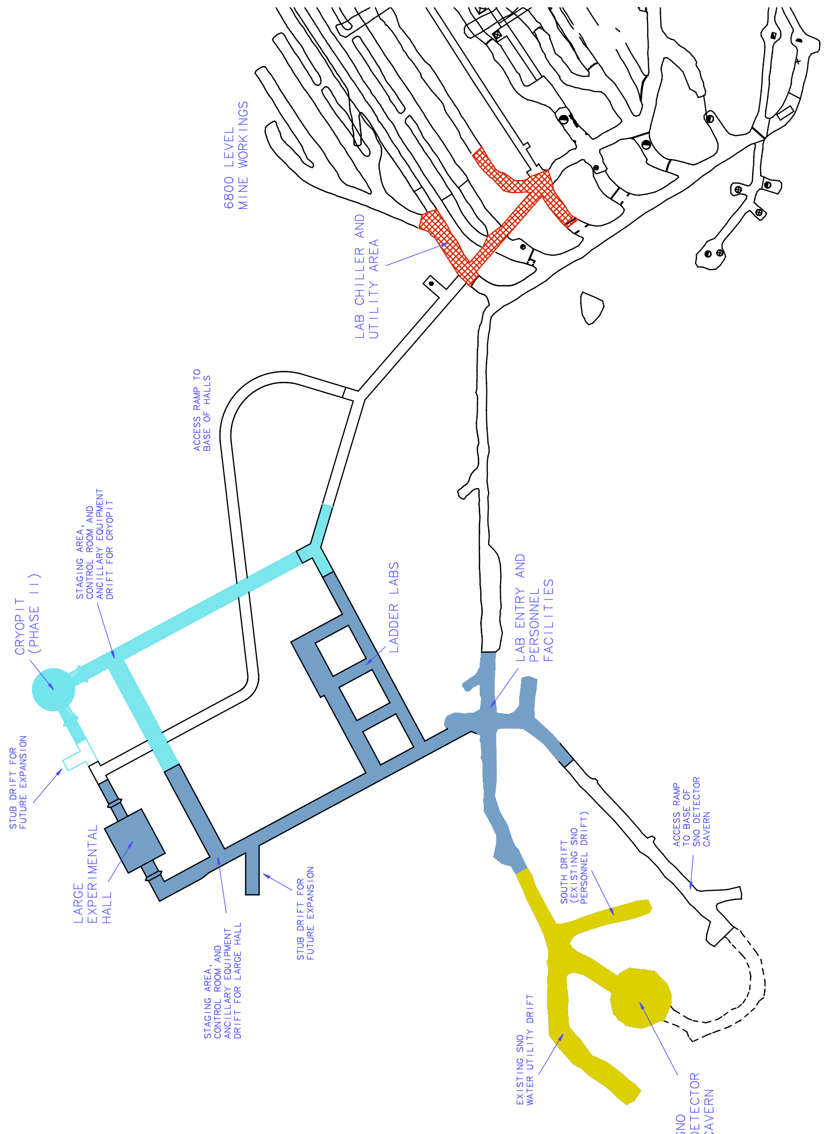

Figure 6 The SNOLAB layout showing the existing SNO facility (yellow), the new SNOLAB clean excavations Phase I (dark blue) and Phase II (light blue).

The major experimental space that will be constructed with SNOLAB is an approximately rectangle shaped hall located to the north of the existing SNO facility (Figure 7). The Rectangular Hall will be dimensioned to provide a clear space 60 ft long by 50 ft wide. The base of the hall will be situated 50 ft below the base level of the laboratory and the maximum height of the hall will be 65 ft. During the assembly of an experiment it will be possible to access the hall through an airlock located at the base of the hall. Access to the airlock is from a ramp used during the excavation of the hall. This ``construction access" to the hall allows large civil construction activities to occur in the hall without the risk of compromising the cleanliness in the remainder of SNOLAB. However, normal access to the hall from SNOLAB will be at the top of the hall through a staging area. Personnel will be able to access the floor of the hall by a stairway. Material will be moved from the staging area into the hall with a 5 tonne monorail crane. Apart from the crane and stairwell, the initial outfitting of the hall will be minimal but provision is made to allow future steel work (decks and platforms) to meet specific experimental needs. Adjacent to the Rectangular Hall is a staging area, control room and a large utility drift (tunnel). The utility drift is 20 ft wide by 110 ft long and is intended to house the support equipment required to operate experiments in the Rectangular Hall. Laboratory services to the Rectangular Hall (HVAC and electrical) are situated in the access drift adjacent to the utility drift.

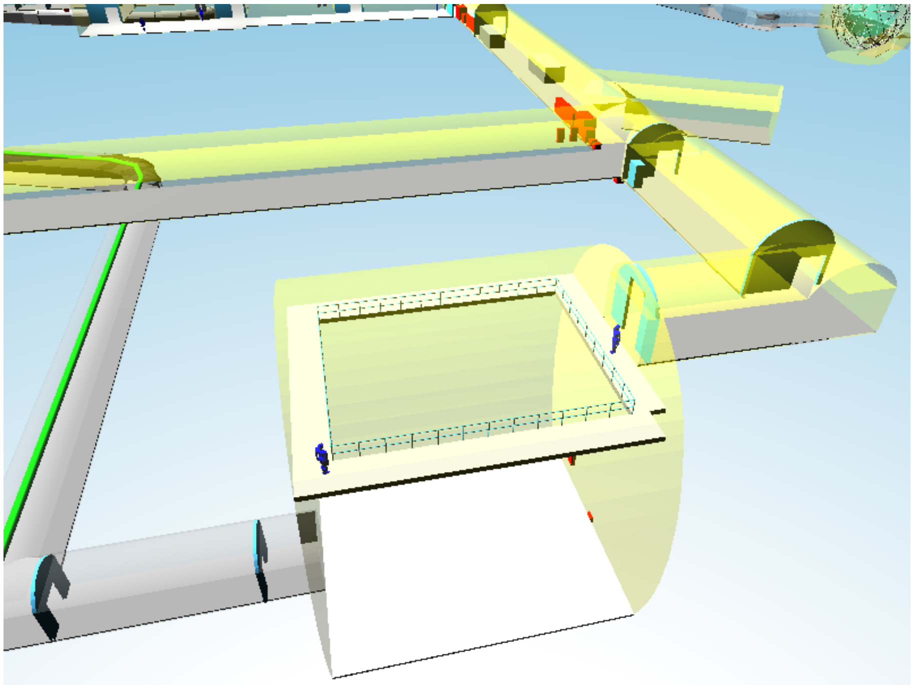

Figure 7 Rectangular Hall.

For smaller experiments, SNOLAB has a series of drifts oriented in a ladder arrangement (Figure 8). One ``rail'' of the ladder is a large drift in two segments. One segment is 20 ft wide, 19 ft high and 105 ft long. The second, larger, segment is 25 ft wide, 25 ft high and 75 ft long. The other rail and the ``rungs'' of the ladder are 15 ft wide by 15 ft high. The combined area of the ladder drifts is 9,375 sq ft. Services for the Ladder Labs (air handlers, electrical room, communications) are located in an access drift to the west. A chemistry lab will be located at the east end of the ladder labs where a fume hood will be ducted to the mine return air system. It is expected that the Ladder Labs will house two medium sized experiments (at the 1 Tonne scale) as well as providing some prototyping space.

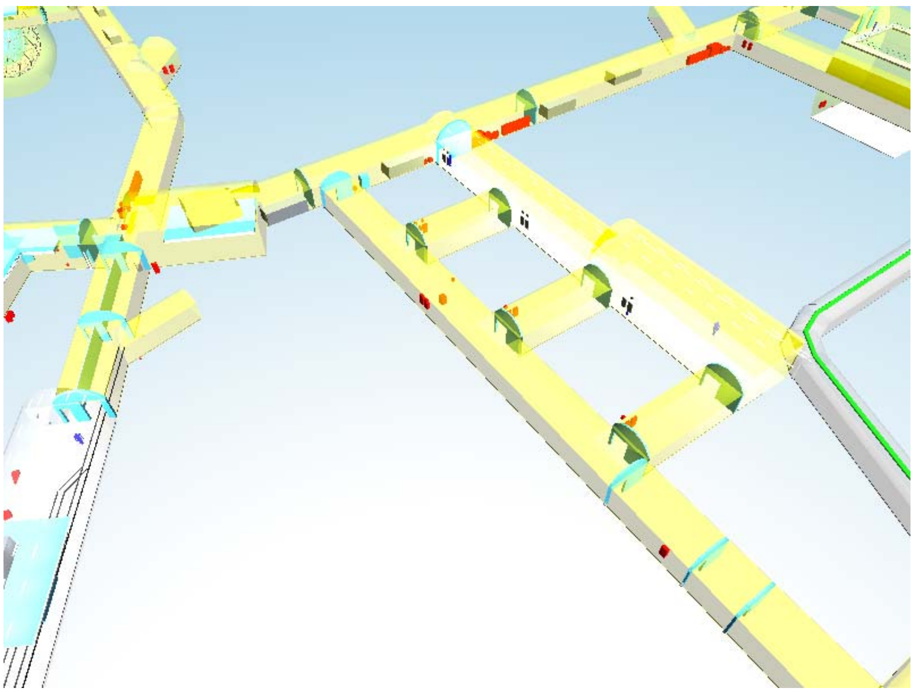

Figure 8 Ladder Labs.

In addition to the Rectangular Hall and Ladder Labs, SNOLAB will have available the existing SNO Cavern (Figure 9), a barrel shaped cavity 72 ft in diameter, 110 ft high, and its utility drift for new experiments once the running SNO experiment is decommissioned. With the relocation of the personnel facilities, the existing SNO personnel drift will be reclaimed for experimental space.

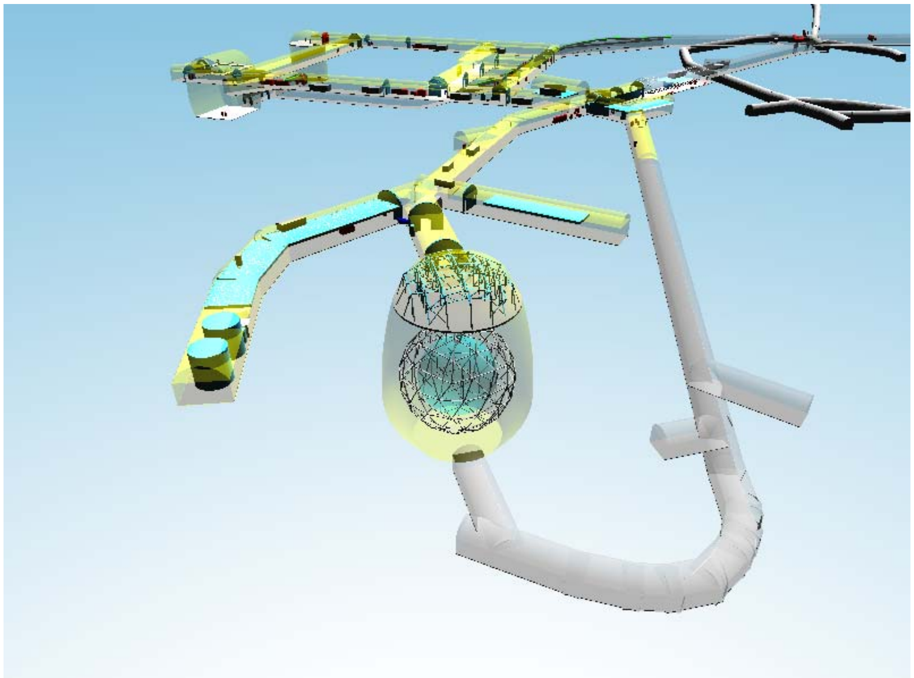

Figure 9 SNO Cavern.

Phase II of the SNOLAB project would add another large experimental cavern referred to as the ``Cryopit''. The Cryopit will be a cylindrical cavern 50 ft in diameter, 65 ft high along with a staging area, control room and utility drift (Figure 10). The Cryopit is envisioned as housing an experiment with a large volume of cryogenic liquid. In the event of a catastrophic boil off of the cryogen, high pressure bulkheads would isolate the Cryopit from the laboratory. A vent system would direct the boil off safely into the mine's return air system.

SNOLAB will provide the infrastructure for the assembly and operation of experiments. Since the core purpose of the facility is to provide a low background, dust free environment, SNOLAB will be built to the same standard as was used in the SNO experiment and will provide 53,600 sq ft of class 2000 clean room space. This will be achieved with an extensive HVAC system consisting of fourteen air handlers with HEPA filters providing ten air changes per hour in most of the clean room spaces. To bring equipment and personnel from the dirty mine environment into the clean room laboratory, the appropriate entry facilities are critical. SNOLAB will provide separate male and female change rooms and shower facilities able to accommodate up to 70 personnel. Equipment and material will be brought into the laboratory through a ``carwash'' facility where the clean room standards of SNOLAB will be enforced before anything is allowed to enter the laboratory. Keeping material clean will be accomplished by either having it cleaned on surface and brought underground in sealed shipping containers or by cleaning in the carwash prior to moving it into the laboratory. Equipment and material are brought underground on the narrow gauge railway used throughout the mine.

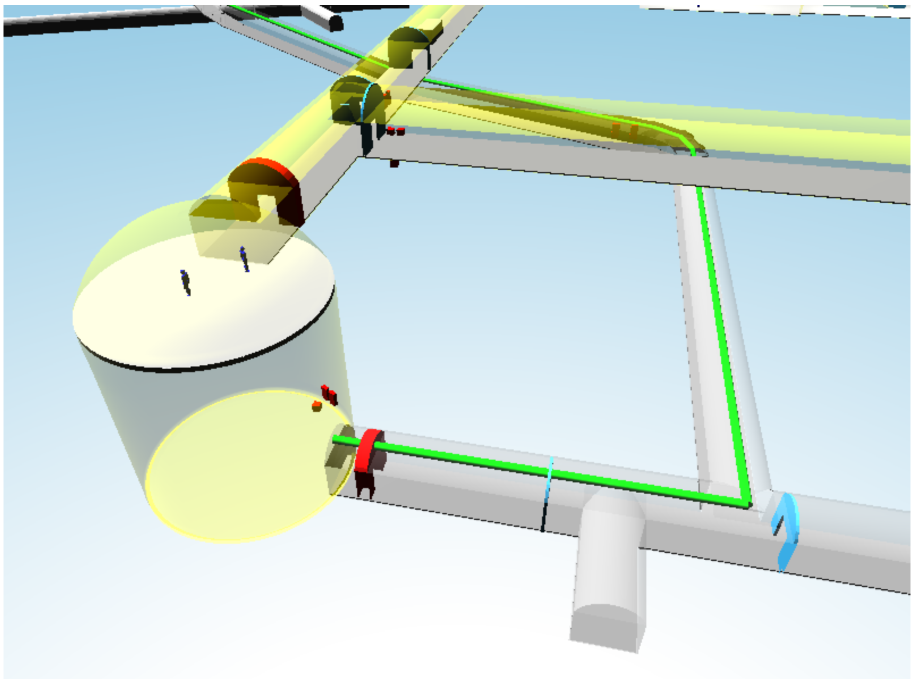

Figure 10 The Cryopit (Phase II)

Personnel are allowed to work underground in up to 12 hour shifts. SNOLAB will provide lunch, meeting and washrooms for personnel working within the clean laboratory. As well some office space and a refuge station (in the event of a fire within the mine) will be provided. Within the clean boundary will be a small machine shop and an electronics shop to allow some level of fabrication and repair of equipment while underground. A chemistry laboratory will provide facilities (including a fume hood) to allow the handling of chemical reagents underground). A low background counting facility will be available for screening materials incorporated into experiments. Liquid nitrogen will be provided but a decision has not yet been made on whether it will be shipped from surface or liquefied underground. Options for providing radon reduced air are being investigated.

Services in SNOLAB include 1300 kVA of available electrical power brought into the laboratory on a 600V distribution system supplied from the mine's 13kV power grid. 300 kVA will be available initially for experiments but the supply can be expanded in future. A standby diesel generator with a 48 hour run time provides 200kVA of emergency power intended to maintain communications and critical services for the experiments. Cooling of the laboratory is achieved with chilled water which is cooled by a 320 Ton (1.1 MW) air cooled chiller located outside the clean laboratory. The waste heat from the chiller is removed by 100,000 CFM of ventilation air provided by the mine. SNOLAB is constructing an intricate system of shafts and tunnels to vent the cooling air from the chiller into the mine return air system. The ventilation system is isolated from the inhabited spaces of the mine to allow the safe exhausting of cryogens from experiments in SNOLAB. Process and potable water is provided by the mine at a rate of 50 gpm. As well, the existing SNO experiment's water systems will provide Ultra Pure Water for future experiments. A sewage treatment plant located in the Utility Area near the Chiller and Standby Generator will service the showers and washrooms in the laboratory. Communications between the underground facility and surface is through a four kilometer fibre optic link with multi GB bandwidth. Telephony is Voice over IP. The laboratory slow controls system will permit monitoring and operation of key laboratory systems remotely from surface.

B-1.2 The SNOLAB Surface Facility

An important aspect of SNOLAB is to have adequate facilities on the surface to support the underground experiments. A three storey, 34,000 sq ft facility has been constructed for this purpose (Figure 11). It is located on the INCO Creighton Mine site approximately 100 m from the 9 Shaft head frame. The new surface building replaces the existing SNO trailer complex and provides clean laboratory and assembly space for staging experiments going underground. It provides office space for 65 inhabitants and several meeting rooms including a 100 seat auditorium. Locker and shower facilities are provided for personnel going underground. Three control rooms are provided for monitoring experiments from surface. There will be an electronics shop and a machine shop for fabrication and repair on site. A climate controlled IT server room with UPS will be available for computing on site. 4,200 sq ft of the third floor is unfinished and will be available for future expansion.

Figure 11 The new SNOLAB Surface Facility. The large structure to the right is the head frame over Creighton Mine 9 Shaft.

The central feature of the new surface facilities is a 4,700 sq ft block of clean room laboratories and the associated material handling facilities to transport materials and apparatus for experiments underground in a clean fashion (Figure 12). The laboratories will provide space for prototyping, staging the assembly of experiments underground and maintenance. There is a chemistry laboratory and a low background counting lab. The laboratories have 15 ft clear ceilings and there is a 2 tonne bridge crane for the assembly of large apparatus. There is a warehouse and a cleaning facility (Carwash) adjacent to the laboratories for material handling. A narrow gauge railway goes from the surface facility to the 9 Shaft head frame and materials sent underground are loaded onto rail cars. The design of the surface and underground material handling facilities will permit clean materials to be transported from the clean surface labs to the clean underground lab in sealed shipping containers without exposure to dirt in the mine environment.

The new surface building is connected to the existing SNO Operations Control Building which contains a small warehouse and rooms which were used for control and monitoring of the SNO experiment. These functions are being moved to the new facility and the spaces in the existing structure refitted for other uses including a small assembly space and a laundry facility. There is also the existing SNO ``Water Building" which was used for D_2O storage and water chemistry. The chemistry work is being moved to the new facility and the water building will be refitted as a machine shop.

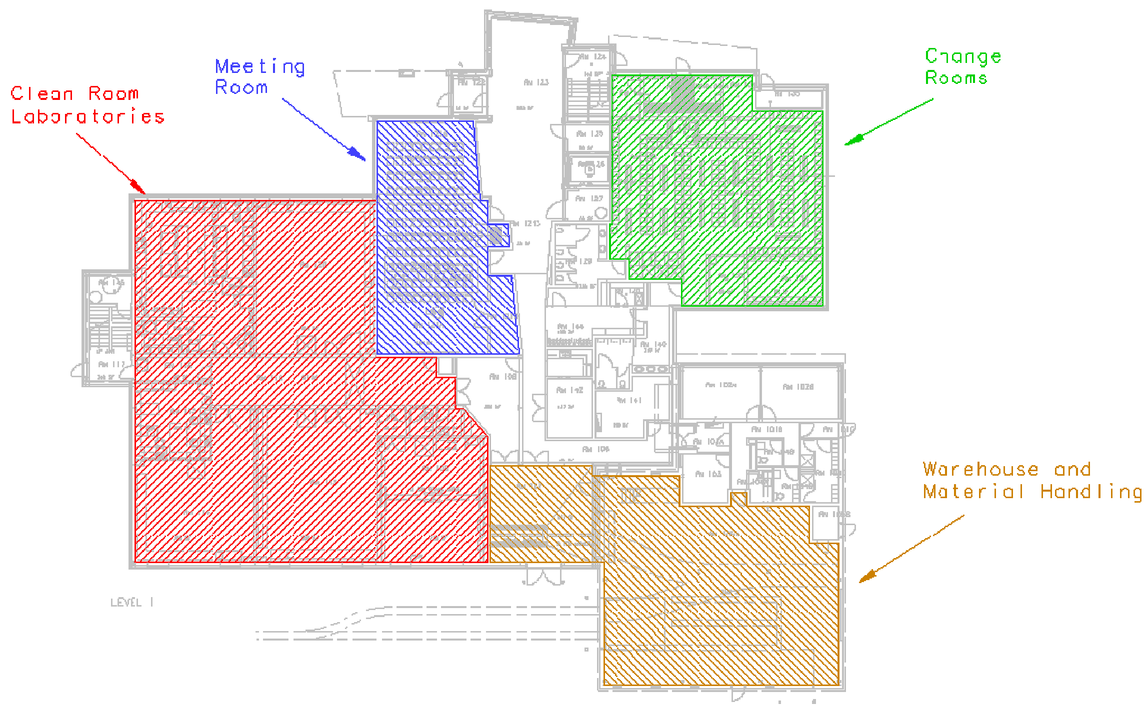

Figure 12 SNOLAB Surface Facility, Ground Floor showing the laboratories, meeting room, change rooms and material handling facilities.

Services for the surface facility include a 150 kW standby generator with a 48 hour run time which provides emergency power for communications and critical systems in the facility. Ultra pure water and compressed air is provided to each laboratory. Liquid nitrogen is available from a large storage dewar outside the warehouse. The boil off nitrogen from this dewar is piped into the laboratories and provides a high purity cover gas for radon mitigation. The laboratories are also equipped with an off-gas header system for the removal of waste gasses.

In addition to the surface facility at site, there will be a radio-tracer lab located on the Laurentian University campus. This facility is intended for wet-chemistry radioisotope analysis. Radioisotope spike work that would not be permitted on site could be conducted at this facility.

B-2 Construction Progress Report

The laboratory excavation status as of November 2005 is shown in Figure 13. The laboratory utility spaces which will house the chiller system, standby generator and sewage treatment plant are complete. Most of the excavation of the Ladder Labs is complete (Figure 14). The ramp to base of the Rectangular Hall and the upper level access drifts are half complete. The new excavation is within a few meters of the existing excavations. The breakthrough between the new and existing excavations is waiting for rehabilitation work on the existing spaces to be completed and is expected to occur in December 2005. In addition to the main excavations for the laboratory, excavations on higher levels of the mine used for the SNOLAB ventilation system have been completed (Figure 15).

Above ground, the new surface facility is now essentially complete (Figure 16). The offices are occupied and the fourth SNOLAB workshop was held in the facility in August (Figure 17). Although there are a number of small jobs still outstanding, the laboratories were commissioned in November and the SNO surface laboratories are being moved into the new facility in November and December 2005.

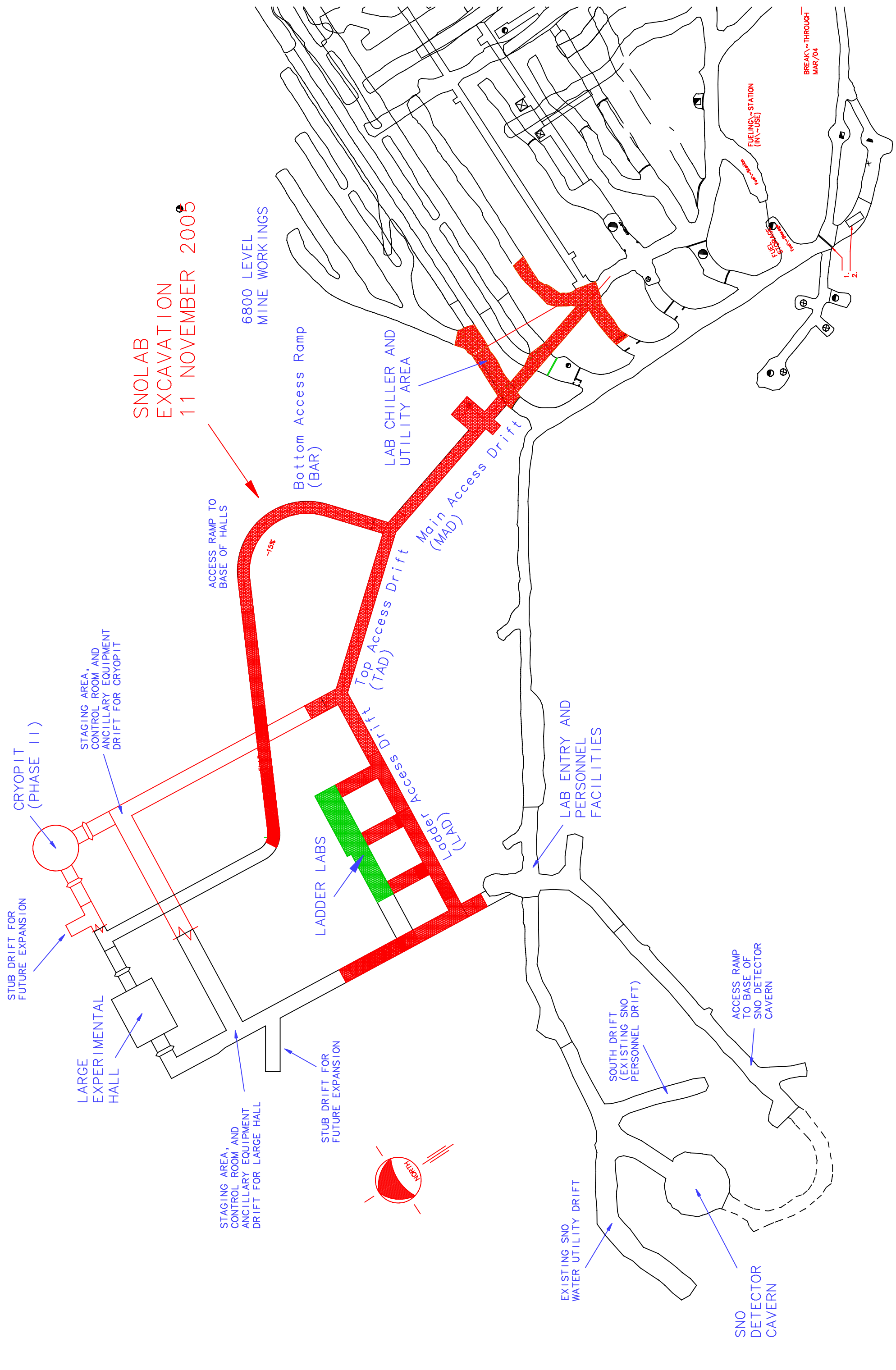

Figure 13 SNOLAB Excavation Status. Areas shown in red are fully excavated, areas in green are partially excavated.

Figure 14 Excavation in the Ladder Labs. Top: Ladder Lab Access Drift. Bottom: The Large drift of the Ladder Labs. This is the top bench and is 4m above the finished floor level.

Figure 15 Excavation of the ventilation raises. Top: The raise bore which drills the 3m diameter ventilation shaft. Bottom: The top of the ventilation shaft on the 6600 L of the mine.

Figure 16 Surface Facility.

Figure 17 Surface Facility spaces. Top: Clean room Laboratory. Bottom: Auditorium.