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The Current Status and Planned Developments for Deep Underground Astro-particle Physics Science Facilities

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Abstract. The rigorous radiation background constraints imposed by several studies in particle and astro-particle physics, such as Galactic dark matter searches, man-made, terrestrial, solar and supernova neutrino studies and $0\nu\beta\beta$-decay studies, require deep underground science facilities to afford shielding from penetrating cosmic rays and their secondary by-products. New threads of research focused on deep sub-surface biology, chemistry, geology and engineering have also been developing rapidly at several sites, benefitting from the significant investment in underground access and infrastructure developed. In addition to planned, or completed, expansion at several of these deep underground facilities, additional new facilities are in early stages of construction or well advanced planning. These developments provide significant additional capability to these fields of study. This paper summarises the developments at these facilities, focused on those extremely deep uderground laboratories where expansion is underway or planned.

1. Introduction

Searches for rare decay channels or weak interactions in particle or astro-particle physics studies require the observation of rare events in dedicated detector systems. These rare events need to be observed against the significant backgrounds created by cosmic-ray and radioactive-contaminant generated signals. To enable the observation of these exquisite signal events, experiments must therefore be operated in the quiet environment afforded by shielded facilities in deep underground laboratories. These facilities remove cosmic ray induced backgrounds through a significant overburden of rock, reducing radioactive contaminant backgrounds from the surrounding environment by radioactively-pure shielding materials. Such facilities exist in many regions of the world, as dedicated underground facilities, or extensions to initial infrastructures constructed for single experiments. The field of underground science is burgeoning, with the development of these underlying infrastructures essential to provide the required capabilities to move these fields of study forwards.

Improved sensitivity of these experiments allows searches to extend deeper into the parameter spaces of these various physics decays and interactions, with the goal of unambiguous signal detection. As the scale of the projects increases, to provide these increases in sensitivity, the underground facilities need to maintain the required infrastructures and ensure the availability of the space required by the science communities. In addition to the traditional physics fields which have driven the underground space requirements, there are also new fields of study opening

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Site	Additional Space	Status	Year Available
Kamioka	$+5.5\times10^3$m^3	Complete	2008
SNOLAB	3×10^4m^3	Complete	2009
LSC	8×10^3m^3	Complete	2010
CJPL	1.7×10^3m^3	Complete	2014
SUSEL	$>3\times10^4$m^3	Complete	2011
Yangyang	1.6×10^4m^3	In Construction	2012
LSM	4×10^4m^3	Planned	2013
SURF	$>10^5$m^3	Planned	2015
INO	$>10^5$m^3	Planned	2017
ANDES	7.5×10^4m^3	Planned	2017
Baksan	4×10^4m^3	In Construction	Under Discussion

Table 1. Table showing volume expansion at various underground laboratories, status and planned availability date

up, within the gravitational wave, geology, mining, engineering and sub-surface biology, which require additional space and rather different constraints. There have thus been several initiatives around the world to develop greater capability and space for deep sub-surface studies. This paper reviews the status of the deep underground facilities around the world, focussed on those where additional capability has been, or is being, developed. A summary of expansions to these facilities, either underway or planned, is provided in Table 1. A brief review will be given of the techniques adopted for background reduction is also given.

2. Reduction of radiation backgrounds

The primary objective in many of the research fields serviced by deep underground laboratories is to detect extremely rare and exquisite signals from rare decay channels or weak interaction physics. These rare events need to be observed against the significant backgrounds created by cosmic-ray muon and radioactive-contaminant generated signals. To enable the observation of these rare events, experiments must therefore be operated in the quiet environment afforded by shielded facilities in deep underground laboratories, which remove the cosmic ray induced backgrounds by a significant overburden of rock, and the radioactive contaminant backgrounds from the surrounding environment by radioactively-quiet shielding materials.

The cosmic ray flux may be attenuated simply by placing these detector systems at great depth below the surface of the Earth. The soft component of the cosmic rays and subsequent air-showers is attenuated rapidly, with the penetrating muon flux reducing by an order of magnitude every $\sim$1.5 km.w.e. of overburden [4]. The reduction of the high energy γ-ray flux, above 3.5MeV, by rock overburden provides direct benefit especially to the field of nuclear astrophysics where accelerator based studies of low cross-section stellar nuclear processes are then made possible. The reduction of the cosmic ray muon flux not only reduces the large signals initiated by direct interaction of the muons within the detector systems, but also reduced the secondary by-products of these particles. In many cases, these by-products are even more troublesome, such as the small flux of high energy neutrons generated by muon spallation which can mimic the interaction of a dark matter particle in the detector system (and penetrate metres of shielding). The attenuation of the muon flux may have azimuthal and zenith angle dependencies depending on the nature of the over-burden: for facilities within mountains the angular dependence of the muon flux depends on the angular dependence of the mountain overburden; for flat-overburden sites the variation is a simple zenith dependence. In all cases the muon flux has a seasonal variation of several percent.

Neutron backgrounds originate from U and Th fission, and (α, n) reactions in the surrounding rocks, the detector shield and the detector components themselves. For detectors where γ-ray activity is important, or discrimination between incident species required, the γ-ray flux from radio-isotopes may also be a limiting factor. For this reason, radio-pure shielding environments are required to shield the detector systems from rock-induced events, and great care taken in the selection and screening of materials used in the construction of the detector. Many underground facilities provide screening capability for material selection, through the use of HPGe detector arrays, and other technologies such as α-β counters. Finally, radon, as a pervasive gas, can diffuse into the detector components and plate out radioactive daughter elements on surfaces, which may then lead to additional backgrounds. Sensitive detector systems are therefore constructed in radon-suppressed atmospheres, using aged air or clean gas, or detector components are lapped and protected from further deposition by radon exclusion. Many detection systems therefore have the requirement of construction and operation within a radon-controlled clean-room environment to suppress contamination, using radio-pure construction materials.

To accurately predict the backgrounds present in detectors, knowledge is required of the various components of the detector systems and environment, including intrinsic material contamination levels, activity of shielding systems, shielding and veto efficiencies, the facility background environment and local rock characteristics. For the latter, small changes in the composition of the rock can have significant consequences in the fluxes observed at the detectors, especially for materials with high neutron cross-sections. In first generation detector systems it was often the case that one source of background dominated, such as U, Th and K contamination in photomultipliers, as the detector systems become more sophisticated and sensitive it is clear that attention needs to be paid to suppression of backgrounds from all sources. Detailed background simulations are performed by many of the experimental collaborations using various frameworks, with the use of GEANT4 [5] becoming ubiquitous.

As the sensitivity of the detector systems used in underground science improves, the ultimate limiting factor becomes the depth of the underground facilities. This is not a limiting factor at pesent with all experimental systems utilising depth, shielding and veto systems to limit and identify backgrounds, however a further three orders of magnitude in reduction of muon flux is possible before upward-coming muons from neutrino interactions dominate. This ultimate limitation requires a depth of $\sim$11 km.w.e. [6] To achieve greater depth will be a significant challenge for underground facilities, though not unsurmountable as the required mining technologies are developed to reach deeper ore bodies.

3. The Underground Facilities

Underground facilities generally take two forms - cavities excavated within mines, either operational or not, and cavities excavated within mountains as part of tunnel complexes for transport or power generation. Commonly those facilities within mines require vertical access through the mining shafts, thosse within mountains may usually be reached by horizontal access by vehicle (although there are sites which break this generality). Facilities may also need to contend with differing constraints based on interference from nearby activities, such as mining activity, road and rail traffic, legislative issues, impact on the local environment and communities, etc. All facilities require significant attention to health and safety protocols and regulative issues. Access to facilities may vary depending on the national or international nature of the laboratory, the access protocols and experiment peer-review processes and funding and cost of operations. All of these factors come into play when determining the most appropriate location of an experiment, in addition to the physical characteristics and backgrounds discussed above.

Those facilities with new, or planned, expansion space are detailed in the following sections.

Much of the following information on the capabilities and specifications of the underground facilities is drawn from the excellent reviews undertaken by Bettini [1] and Coccia [2] for previous TAUP conference papers, the ILIAS reports on "Deep Underground Science Laboratories" [3], with additional input directly from the Laboratory Directors and facility websites.

3.1. ANDES - Agua Negra (Argentina)
The ANDES laboratory [7] is a new initiative to develop a Southern hemisphere deep underground laboratory. The facility would be cited in a planned road tunnel between Argentina and Chile between San Juan and Coquimbo through the Agua Negra. This road tunnel has been ratified through a bi-national agreement, with completion of the $850 M tender action expected at the end of 2011. The proposed road tunnel route would be at an altitude of 3700 m, with a maximum vertical depth of 1750 m. This would provide the proposed facility, expected completion date 2017, with an overburden of between 4500 m.w.e. and 4800 m.w.e., in andesite rock, expected to provide low radio-active backgrounds. The planned facility would comprise three large hallways, two with dimensions 20 m by 25 m by 50 m, the third as a pit of 20 m diameter and 20 m depth. Such a facility provides a low reactor neutrino background, an anti-phased seasonal modulation to Northern hemisphere facilities and significant baselines from potential neutrino beam sources.

3.2. Baksan Neutrino Observatory (Russia)
. The Baksan Laboratory [8] is sited under Mount Andyrchi in the Caucasus and is the oldest facility built specifically for scientific research, as opposed to operating an experiment in existing infrastructure, having been initiated in 1966 with experimental work commencing in the early 1970's. Surface operations were conducted in a village built specifically for the purpose, providing all required services to the facility, with ∼50 staff involved in the underground operations.

The underground facilities are developed along two dedicated 4 km long and parallel horizontal tunnels, with several experimental halls at various distances along the tunnels. Access is horizontal through these tunnels, with train transportation for personnel and materials. The experimental halls have varying overburden, dependent on their distance within the mountain. BUST, a scintillator based telescope for supernova neutrino detection, operational from 1978, is housed in a hallway 24 m by 24 m by 16 m, which, at 300 m depth, has the least overburden of 850 m.w.e. The second main hallway, 60 m by 10 m by 12 m, houses the SAGE gallium/germanium neutrino telescope, and has a much greater overburden of 4800 m.w.e. In the SAGE cavity, which is lined with 60 cm of low-background concrete, the muon flux is attenuated to $3.0{\times}10^{-5}/\mathrm{m}^2/\mathrm{s}$ [9], with a neutron flux above 1 MeV of $1.4{\times}10^{-3}/\mathrm{m}^2/\mathrm{s}$. The radon contamination levels in the air, which is exchanged 7 times per hour, is 40 $\mathrm{Bq/m}^3$. A few smaller halls with intermediate rock overburden are used for smaller scale developmental work and experiments on Galactic dark matter and $0\nu\beta\beta$-decay studies, and host a low-background screening facility using HPGe detectors.

In terms of potential expansion, excavation of a larger and deeper hall, providing ∼40,000 m^3 of additional volume, started in 1990 but was suspended at the time of the collapse of the Soviet Union. The status and completion of this additional expansion is under discussion.

3.3. BUL - Boulby Underground Laboratory (UK)
The Palmer Laboratory [10] at the Boulby Potash mine on the North Yorkshire coast, U.K., was developed from the early 1990's to host the U.K. Dark Matter Collaboration projects. The Boulby mine is a working rock-salt and potash mine, operated by Cleveland Potash Ltd., with the laboratory within the rock-salt strata to reduce γ-ray backgrounds and provide greater rock stability. Access is through the vertical shaft maintained by the mining company, 1100 m to

the laboratory level. The facility is operated by the STFC Rutherford Appleton Laboratory, on behalf of the University of Sheffield.

A new underground facility was constructed at the turn of the millennium, operated as a monolithic clean room through several tunnels of width ∼5 m, totalling an area of ∼1500 m^2. With a flat overburden the minimum coverage is 2850 m.w.e., attenuating the muon flux to a measured level of $4.1\times10^{-4}/m^2/s$ [11]. The fast neutron flux, above 0.5 MeV, has been measured to be $1.72\times10^{-2}/m^2/s$ [12], with a radon concentration throughout the laboratory less than $3Bq/m^3$. This low level is due to the nature of the surrounding rock, a sedimentary salt deposit, which also provides the intrinsically low γ-ray background. Surface facilities, totalling 200 m^2, provide offices, changing rooms, a galley, computing services, warehousing, chemical and electronic laboratories and a mechanical workshop.

The science programme at the facility has so far focussed on Galactic dark matter searches with the completion of the NaIAD and ZEPLIN programmes, and continuation of DRIFT directional dark matter target. New research threads in atmospheric (SKY), environmental and inter-disciplinary science are being developed with funding secured for operations to 2014 to develop these new research programmes. Due to the easy nature of excavation in halite deposits, the Boulby facility is also investigating the viability of excavating long-term large cavities for the LAGUNA project.

3.4. CJPL - Chinese JingPing Deep Underground Laboratory (China)

The Chinese JingPing Deep Underground Laboratory (CJPL) [13] is a new facility that has been constructed in a hydro-electric power development on the Yalong river in the Sichuan Province of China. The Yalong river makes a 150 km long turn around the JingPing mountain (4193 m height), providing the opportunity to utilise the height differential for power generation. Two transport tunnels have been excavated through the JingPing mountain, completed in August 2008, each 17.5 km long, with 6 m by 6 m cross-sections, to facilitate the construction of the four headrace tunnels and an additional drainage tunnel.

The underground facility is located in the centre of one of the tunnels, providing a minimum rock overburden of greater than 2500 m, making the CJPL laboratory the deepest current facility. Access to the facility is by vehicle through the horizontal tunnel, with accommodation, restaurants, and sport facilities available at the tunnel entrance. Phase-I of the construction is completed with the development of a 6 m by 6 m by 40 m hallway to accommodate dark matter searches, with an anticipated muon flux of $2\times10^1/m^2/yr$ [14]. Further development of the facility with a similar scale second hallway, Hall B, and a large-scale 20 m by 20 m by 100 m hallway constructed between them awaits future approval which is being sought in 2014.

The Science programme for the initial stage of the CJPL facility concentrates on Galactic dark matter searches using an array of HPGe detectors (CDEX) [13], joining with the TEXONO and KIMS collaborations. This will take a phased approach to the construction of large scale detector systems, starting with kg-scale detectors in the now available Hall A.

3.5. CUPP - Center for underground physics in Pyhäsalmi (Finland)

The CUPP facility [15] is hosted in a working mine near Pyhäsalmi, Finland, and has been developing underground space since 2001. Several cavities have been made available by the mining company, totalling ∼1000 m^2, at a depth ranging from 75 m to 980 m. The capability to provide additional cavities up to a depth of 1400 m exists, providing ∼4 km flat overburden. Access to the facility is either through vertical shaft or a spiral ramp which provides vehicular access. In addition, small surface facilities are available, including offices and a guesthouse.

The science programme is currently targeted at small and medium scale projects that may make use of the existing cavities, with the EMMA experiment on cosmic ray muons is currently hosted underground at the 75 m level. The potential for the large scale detector systems is also being assessed by CUPP, as a potential site for the LAGUNA long-baseline neutrino far detector.

3.6. INO - India Neutrino Observatory, Tamil Nadu (India)
The India Neutrino Observatory [20] is a proposed iron-calorimeter to study solar and atmospheric neutrinos, led by the Tata Institute of Fundamental Research. Being based in India, this observatory would be located near the Earth's equator, offering interesting consequences for solar neutrinos which would then pass through the core of the Earth in their passage to the detector from the Sun at night. Following some initial environmental concerns with the proposed location of the INO, approval has now been granted clearances by the Ministry of Environment and Forests for the Department of Atomic Energy to perform a feasibility study based around a site in the Bodi West Hills Reserved Forest in Theni district of Tamil Nadu, with land transfer arrangements underway.

The proposed facility would consist of four hallways, the largest being 132 m by 26 m by 32.5 m in size to house the 50 kilotonne magnetised iron tracking calorimeter. The anticipated overburden would be greater than 3000 m.w.e. [21]. This site is also at a distance of 7000 km from CERN and JPARC, providing interesting baselines for potential future long-baseline neutrino beam experiments.

3.7. Kamioka Observatory, Gifu Prefecture (Japan)
The Kamioka Observatory [22] is operated by the Institute for Cosmic Ray Research, University of Tokyo, and was established in 1983 as the Kamioka Underground Observatory, to host the KamiokaNDE nucleon decay experiment. This was a 3 ktonne water Cherenkov detector, subsequently upgraded to Kamiokande-II and used for solar and atmospheric neutrino studies. Additional expansion of this cavity led to a 40 m diameter by 41 m height cavity, housing 50 ktonnes of water for the Super-Kamiokande experiment, the largest underground experiment yet realised. Super-K now acts as the far detector for the T2K $\theta_{1,3}$ neutrino oscillation studies using a neutrino beam from J-PARC, 295 km away. In addition to the water Cherenkov detectors, the KamLAND experiment is operated within the Kamioka observatory by the University of Tohoku.

The overburden is 1000 m of rock, reducing the muon flux to $3{\times}10^{-3}/\mathrm{m}^2/\mathrm{s}$. The thermal neutron flux is $8{\times}10^{-2}/\mathrm{m}^2/\mathrm{s}$, with a fast neutron flux of $11{\times}10^{-2}/\mathrm{m}^2/\mathrm{s}$. The ventilation flow is 3000 m^3/hr. Vehicle access is possible to the facilities through horizontal tunnels, separated from the mining activity elsewhere within the mine. Surface facilities provide offices, computing facilities and administration, with 15 on-site support staff.

Additional cavities have recently been completed for a variety of science threads. The new Hall A is 15 m by 21 m by 15 m and houses the XMASS 800kg liquid xenon Galactic dark matter target. The new Hall B is 11 m by 6 m by 11 m and houses the $0\nu\beta\beta$-decay CANDLES CaF detector array. Hall 40 (40 m by 4 m) hosts the Newage directional dark matter detector and a superconducting gravity probe, Hall 100 comprises two 50 m by 4 m arms for a gravitational wave interferometer (CLIO). Future projects that have been proposed for the Kamioka facility include a Megatonne Hyper-Kamiokande detector and LCGT a cryogenic gravitational wave antenna.

3.8. LNGS - Laboratori Nazionali del Gran Sasso (Italy)
The LNGS facility [23] under the Gran Sasso mountain in the Abruzzo region of Italy is currently the largest of the underground facilities around the World. Following the proposal in 1979 by A. Zichichi, the incumbent President of the INFN, construction was completed in 1987, contemporaneously with two road tunnels through the mountain. These road tunnels provide the horizontal access by road vehicle to the facility, allowing transport container delivery.

The underground facility comprises three main hallways, with several other experimental tunnels available, including two 90 m hallways used for a Michelson interferometer for geological studies. The main hallways (Hall A, B, C) are $\sim$ 100 m by 20 m by 18 m, providing a total area of 17,300 m^2, with a total volume of $\sim$ 180,000 m^3. A surface campus provides offices and administration facilities, computing and conferencing capabilities, laboratories, electrical and mechanical workshops, warehousing facilities, library, restaurant and sleeping accommodation.There is a permanent staff of 76 physicists, engineers and technicians, with $\sim$20 non-permanent staff, servicing a user community of $\sim$800 users from across 26 countries.

The rock overburden is 1400 m, with an azimuthal and zenith distribution due to the topology of the mountain range which varies between 3100 m.w.e. and 3800 m.w.e. This reduces the muon flux to a measured value of $2.87\times10^{-4}/m^2/s$ [24, 25]. Measured neutron fluxes are $2.93\times10^2/m^2/s$ and $0.86\times10^2/m^2/s$ for thermal and fast neutrons (with a breakpoint defined at 1 keV) respectively [26]. Radon levels in the air range between 50 and 120 Bq/m^3 with the ventilation system providing one exchange of air in 3.5 hr.

The science programme at LNGS is very broad, with neutrino beam studies (OPERA and ICARUS), galactic dark matter searches (DAMA/LIBRA, WArP, XENON, CRESST), $0\nu\beta\beta$-decay studies (CUORE, GERDA and COBRA), solar and geo-neutrinos (Borexino), supernova neutrinos (LVD) and nuclear astrophysics through a low energy ion accelerator (LUNA). In addition, low background counting facilities exist with the STELLA HPGe detector array and the Borexino test facility.

In terms of expansion of the facility, there are no current plans to extend the available underground space, with new areas becoming available as the current experimental programme evolves and projects are completed.

3.9. LSC - Laboratorio Subterraneo de Canfranc (Spain)

The Canfranc underground facility [27] has developed from an earlier laboratory developed under Mount Tobazo in the Spanish Pyrenees by the Nuclear and High Energy Physics Groups of the University of Saragossa. These first facilities consisted of three separated hallways, one large, two small, near a disused railway tunnel, with $\sim$156 m^2 of floor space. The rock overburden ranged from 780 m.w.e. to 2400 m.w.e. across the various hallways. These original areas were used for $0\nu\beta\beta$-decay (IGEX) and Galactic dark matter searches (ROSEBUD and ANAIS).

Exploiting the subsequent construction of a road tunnel between Spain and France parallel to the railway tunnel, a new and expanded facility has been constructed at a depth of 850 m. Construction of this facility was completed in 2006, but due to some geological instabilities that were subsequently identified, rectified through additional civil engineering, the facility was inaugurated in 2010. The facility is operated as a consortium between the Spanish Ministry for Education and Science, the Government of Aragon and the University of Saragossa.

This new underground facility has two main halls (A and B) with dimensions 40 m by 15 m by 12 m and 15 m by 10 m by 7 m respectively. In addition to these two large halls there are ancillary tunnels providing services and additional experimental facilities such as a clean room and low background counting capability. In total this provides an underground area of $\sim$1250 m^2, or a volume of $\sim$10,000 m^3. Access is through one of the new roadways constructed through the mountain.

The maximum overburden in the new laboratory is $\sim$ 2400 m.w.e. attenuating the muon flux to between between 2×10^{-3} and $4\times10^{-3}/m^2/s$ depending of the location. Characterisation of the facility in terms of neutron flux, γ-activity and radon is underway. These characteristics for the old facility were a neutron flux of $2\times10^{-2}/m^2/s$ and a radon level of 50-80 Bq/m^3 with a ventilation of 11 000 m^3hr^{-1}, an air-change through the facility every 40 minutes.

A surface facility is now completed, which provides administrative services, offices, accommodation, library and meeting rooms, laboratories, warehousing and workshops, with a floor area of $\sim$ 1500 m^2. A dozen staff are being recruited to maintain and operate the facility. The science programme at LSC is being developed, with experiments in dark matter (ANAIS, ROSEBUD), $0\nu\beta\beta$-decay (BiPo, NEXT), geology (GEODYN) and low background counting (SuperK-Gd) already approved. The LSC therefore provides an excellent opportunity for additional space within the European network of underground laboratories.

3.10. LSM - Laboratoire Subterrain de Modane (France)

The LSM Modane underground laboratory [28] is located in a road tunnel under the Frejus mountain, near the French-Italian border and is the deepest underground facility available in Western Europe with an average rock overburden of 4800 m.w.e. The infrastructure is run jointly by CNRS/IN2P3 and by CEA/DSM. The excavation of the laboratory was completed in 1982 to host the "Frejus" iron tracking colorimeter proton decay experiment, completed in 1988. Access to the facility is through the single road tunnel between France and Italy, and currently necessitates stopping the trans-border traffic. The 300 m^2 surface facilities, opened in June 2009 in Modane, provide offices, warehousing, a workshop and accommodation and a permanent visitors centre, supported by a staff of 10.

The main hall of the facility is 30 m by 10 m by 11 m, a 70 m^2 Gamma Spectroscopy Hall containing 13 HPGe detectors, and two secondary halls of 18 and 21 m^2. The attenuated muon flux at the depth of 1700 m has been measured to be 5.76×10^{-5}/m^2/s [29]. The fast neutron flux above 1 MeV has been measured as 1.1×10^{-2}/m^2/s, with a thermal neutron flux of 1.9×10^{-2}/m^2/s [30, 31]. The average radon levels in the facility is $\sim$ 15 Bq/m^3 with ventilation providing an air-change in the laboratory every 40 minutes. Radon reduction plant has been installed underground which is capable providing radon-free air (15 mBq/m^3) at a rate of 150 m^{3}hr^{-1}.

Two experiments currently fill the available space at LSM, the edelweiss Galactic dark matter search and the NEMO-III $0\nu\beta\beta$-decay detector. In addition, the Gamma Hall has 13 HPGe detectors used for background screening and environmental measurements. An extension of the laboratory of 45,000 m^3 is planned to take advantage of the excavation of a new safety tunnel parallel to the existing single road-way, which started in September 2009. This expansion, the ULISSE project, will create two new large Halls, Hall A (24 m by 100 m by 15 m), and Hall B (18 m by 50 m by 15 m) being currently envisaged. Completion of this expanded facility is anticipated by 2013, following a year of outfitting once the excavation of the tunnel reaches the current LSM facility. This new facility would host the EURECA Galactic dark matter search and SuperNEMO $0\nu\beta\beta$-decay detector.

3.11. The SNOLAB Underground Facility, Sudbury (Canada)

The SNOLAB underground facility [32] exploits the success of the Sudbury Neutrino Observatory which contained a kilotonne of heavy water as a target material for solar neutrinos. Through differing reactions in the heavy water, all flavours of neutrinos, as well as the electron neutrino directly, could be measured allowing for the first time the direct observation of solar neutrino oscillations.

The SNOLAB facility is at a depth of 2070 m, in the working Creighton nickel mine operated by Vale Ltd., near Sudbury, Ontario. Significant in-kind operational support from Vale in terms of mining operations ensures the SNOLAB operational costs are minimised, with vertical access provided through the Vale maintained shaft and conveyances (3.7 m by 1.5 m by 2.6 m, with slinging for larger components). A unique feature of SNOLAB is that all the experimental areas are operated as Class 2000 clean rooms, with additional cleanliness available as appropriate. This minimises the potential for cross-contamination between experiments and ensures the facility staff can manage material transport efficiently. A surface facility of 3100 m^2 has been operational since 2005 and provides offices, conference rooms, changing facilities, warehousing and storage, IT systems, 440 m^2 of clean room laboratories for detector construction and chemical assay and measurement. SNOLAB staff total 55 across both campuses.

SNOLAB is now fully completed as a monolithic clean room throughout the facility. The original SNO cavity was 24 m diameter, 30 m high (250 m^2, 9400 m^3), with the new excavations for SNOLAB comprising the Ladder Labs: 32 m by 6 m by 5.5 m (190 m^2, 960 m^3) and 23 m by 7.5 m by 7.6 m (170 m^2, 1100 m^3), the Cube Hall: 18 m by 15 m by 20 m (280 m^2, 5600 m^3) and the Cryopit: 15 m diameter, 20 m high (180 m^2, 3900 m^3). In total SNOLAB now has an excavated area of 7200 m^2, volume 47000 m^3, which provides a clean room area of of 5000 m^2, volume 37000 m^3 and experimental laboratory space of 3060 m^2, volume 29600 m^3.

The flat overburden is 2070 m of rock, with an attenuated muon flux of $3\times10^{-6}/m^2/s$, a thermal neutron flux of $4.7\times10^{-2}/m^2/s$ and a fast neutron flux of $4.6\times10^{-2}/m^2/s$. The radon levels in the air are 130 Bq/m^3, with the 100,000 cfm ventilation provided to the facility allowing 10 air changes per hour in the smaller laboratory areas and 5 air changes per hour in the three main detector cavities. To maintain cleanliness and minimise heat load, only 10% of the air within the laboratory is brought in as make-up air, with the rest scrubbed and recirculated. This also balances and minimises the radon emanation. The HVAC system provides 1 MW of cooling capacity, with ∼100 kW due to the steady-state heat load of the rock at 40°C. SNOLAB provides ultra-pure water as a shielding material to the experimental systems, 150 l.min^{-1} at 183 kΩm. Water disposal is through the mine facilities, except for sewage which is handled with a bespoke bacteriological sewage treatment plant.

SNOLAB has a broad science programme, with the SNO+ detector reusing much of the SNO infrastructure, replacing the heavy water in the target with Nd-loaded LAB-based scintillator. The science programme for SNO+ includes solar and geo-neutrinos, supernova neutrinos and $0\nu\beta\beta$-decay. A dedicated supernova neutrino detector, HALO, re-uses some of the infrastructure from the SNO experiment, namely the helium-3 neutron counting tubes, embedded in a lead target. Several dark matter experiments are underway or in construction, including liquid argon targets in DEAP (3.6 tonnes) and miniCLEAN (800 kg), superheated droplet detectors in PICASSO (3 kg) and bubble chambers in COUPP (4 kg). Additional low background counting and screening facilities exist using the SNO infrastructure for F40, α-β counters and X-ray fluorescence counters.

At present, the Cryopit is unallocated to any experimental programme. The International Experiment Advisory Committee will be assessing statements of interest for next generation detectors that may wish to utilise the Cryopit within the next few years.

3.12. Soudan Underground Laboratory (U.S.A.)

The Soudan underground laboratory [33] is located in the Soudan Underground Mine State Park in Northern Minnesota, U.S.A. The mine was originally the richest and oldest iron ore mine in Minnesota, although mining operations ceased in 1962 and the mine was converted to a tourist attraction and for educational purposes.

The Soudan facility provides two large project halls, one at 70 m by 15 m by 13 m hosting CDMS-II, a Galactic dark matter search, the other at 82 m by 15 m by 13 m hosting the MINOS far detector for the NuMI beam studies of neutrino oscillation parameters. In addition a smaller cavity houses low background screening facilities. A 650 m^2 surface facility provides offices, a galley and changing facilities. Access is through an inclined shaft, providing the ability to hoist materials 1.3 m by 2 m by 10 m long. The overburden is ∼700 m, providing a muon flux within the facility of $2\times10^{-3}/m^2/s$. The thermal neutron interaction rates are ∼ 10/kg/day with fast neutron interaction rates of 0.01/kg/day from muon spallation in the rock.

Radon activity is seasonal, varying between 300 and 700 Bq/m^3, winter to summer respectively. The facility has natural ventilation of ∼500 m^3hr^{-1}, with an exchange of air within the laboratories every two hours.

Additional expansion would be possible to enhance the low background counting facility, creating a cavity of 25 m by 14 m by 14 m. In addition, as the MINOS experiment completes its operational cycle, now anticipated to include an extended science run, the existing space may be available for future systems or upgrades.

3.13. SURF and SUSEL - Sanford Underground Research Facility, Homestake (U.S.A.)

The Homestake gold mine in South dakota hosted the initial studies that elucidated the solar neutrino problem by Ray Davis and John Bahcall. This experiment was conducted at the 4850' level of the, then-operating, mine.

Following the termination of mining operations, and a detailed site assessment and review, the Homestake mine was selected as the site for the U.S. deep underground science facility in 2007, with a wide remit of the science to be undertaken there. As a pre-cursor to the DUSEL facility, the South Dakota Science and Technology Authority (SDSTA), coupled with private donations from T.D. Sanford, have developed the existing facilities at the 4850' level to create the Sanford Underground Science and Engineering Laboratory (SUSEL). Prior to this development, significant effort was required to pump the mine dry, following flooding after the mining operations ceased, and re-instate required infrastructure and services. The 10,000 m^2 surface facilities of the mine were also donated to the SDSTA, providing all required services for mine operations and maintenance, offices and workshops, and the ability to develop surface laboratories. In addition, commensurate with the requirements of the Sanford donation, a major science centre is planned for the Homestake site.

The SUSEL [16] science programme focuses on early deployment of the LUX liquid-xenon Galactic dark matter detector in the original Davis cavern at 4850', refurbished and expanded to take the new detector systems, and the Majorana germanium $0\nu\beta\beta$-decay detector in a new bespoke cavity excavated at the same depth for this purpose. Beneficial occupancy of both experimental halls is anticipated in Spring, 2012. In addition to these physics detectors, several geology and biochemistry experiments have already been conducted at SUSEL. The muon flux at this depth has been measured to be $4.4\times10^{-4}/\mathrm{m}^2/\mathrm{s}$ [18, 19].

Development of a full Preliminary Design Review of the anticipated space for a larger facility was completed, driven by the needs of the science community that had been co-ordinated by the design team. This focussed on two campuses, one at the existing 4850' level where large cavities may be excavated for a large scale long baseline neutrino experiment (LBNE) project, used as a target for a neutrino beam from Fermilab, the other at a deeper level of 7400'. The laboratory module for the non-LBNE detectors is 20 m by 20 m by 75 m at the 4850' level, with the construction of two such modules anticipated, and a module size of 15 m by 15 m by 75 m at the proposed campus at 7400'. The muon flux at the 7400' depth has been extrapolated to be $1.65\times10^{-4}/\mathrm{m}^2/\mathrm{s}$ [**?**, 19].

Following a refocussing of the funding model for the Homestake facility, the SURF [17] facility is now predicated on a broad science programme at the 4800' level, including a single laboratory module housing a third generation $0\nu\beta\beta$-decay target, a third generation Galactic dark matter detector and a larger cavity housing the LBNE detector. The LBNE detector will also be at a scale where proton decay studies are possible. When constructed SURF will clearly provide a significant increase in the space available for deep underground science.

3.14. Y2L - YangYang Laboratory (Korea)

The YangYang Laboratory [34] is located 700 m under Mt. JeomBong (∼1400 m high) in the Kangwondo-prefecture of Korea, where the YangYang Pumped Storage Power Plant is currently under construction. The facility is operated by the Dark Matter Research centre of Seoul National University. A surface facility, operational since 2003, provides 100 m^2 of space for offices, computing and detector test facilities.

The current underground laboratory provides 100 m^2 of experimental area, currently occupied by the KIMS Galactic dark matter search. Other activities include development of $0\nu\beta\beta$-decay detection systems and low background screening facilities with a HPGe detector. Access is 2 km through the horizontal tunnel of the Power Plant, and is by car. The muon flux within the facility is $2.7{\times}10^{-3}/m^2/s$. For neutrons between an energy of 1.5 MeV and 6.0 MeV, the flux is $8{\times}10^{-3}/m^2/s$. Radon activity is between 40 and 80 Bq/m^3

Partial funding has been secured for a new experimental hall to be constructed at the same location, within the Power Plant. This would provide a hallway 40 m by 20 m by 20 m, providing an additional 800 m^2, or 16,000 m^3 volume, of experimental area.

4. Conclusions

The field of deep underground science encompasses many of the highest priority questions in contemporary physics - what is the major constituent of the matter of the Universe? What is the mass and nature of the elusive neutrino? What led to the matter-antimatter asymmetry we observe in the Universe? How do stars burn and supernovae explode? How can life survive without sunlight? Why is the Earth hot?

These questions will provide a rich field of study over the next decades, which are complementary to other fields of study such as accelerator based particle physics. The breadth of scale in detectors and infrastructures provides a wide portfolio of projects for physics exploitation and training of highly qualified personnel.

To deliver these experimental systems requires the development of high quality infrastructure, and available space in underground facilities. Expansion of several of the deep underground facilities world-wide is completed, underway or well advanced in planning which will provide significant additional space and capability in the near term, with larger facilities planned for the next five to ten years. These facilities will allow the underground science community to maximise the likelihood of successfully deploying and exploiting the every-more complex detector systems required to probe the various physics parameter spaces.

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