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Underground laboratories

A. Bettini [a,b,*]

[a] Padua University and INFN Section, Dipartimento di Fisca G. Galilei, Via Marzolo 8, 35131 Padova, Italy
[b] Laboratorio Subterráneo de Canfranc, Plaza Ayuntamiento n1 2piso, Canfranc (Huesca), Spain

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ABSTRACT

Underground laboratories provide the low radioactive background environment necessary to frontier experiments in particle and nuclear astrophysics and other disciplines, geology and biology, that can profit of their unique characteristics. The cosmic silence allows to explore the highest energy scales that cannot be reached with accelerators by searching for extremely rare phenomena. I will briefly review the facilities that are operational or in an advanced status of approval around the world.

1. Introduction. Characteristics of the underground laboratories

The only known phenomena beyond the Standard Model, in neutrino physics, have been discovered in underground laboratories with natural sources (Sun and cosmic rays). In general, underground experiments provide an indirect reach to the highest energy scales. For example, a 50 meV neutrino mass corresponds, via seesaw mechanism, to a 10^{16} GeV energy scale. The higher is the energy the rarer are the corresponding phenomena. Consequently, pushing forward the high-energy frontier requires reducing as much as possible any source of background.

There are important physical and practical differences between the existing facilities, which range from fully developed laboratories to simple underground sites.

The muon flux decreases with the thickness of the rock overburden, roughly, but not exactly, exponentially. Under a flat surface the flux is $10^{-3}\,m^{-2}\,s^{-1}$ at a depth of 2.3 km w.e. (1 km water equivalent is about 300 m of rock), $10^{-4}\,m^{-2}\,s^{-1}$ at 3.7 km w.e. and $10^{-5}\,m^{-2}\,s^{-1}$ at 5.3 km w.e. Under a mountain, like at Kamioka or Gran Sasso, the angular dependence of the muon flux is complicated, due to the shape of the surface. It must be measured to provide the input to the background simulations needed by the most delicate experiments. The flux is time dependent with seasonal variations of several percent.

Neutrons originate mainly from (α,n) and fission processes (U and Th) in the rocks. The energies range from thermal to several MeV, and consequently they are not difficult to shield. The neutron flux is substantially independent of the depth (if larger than 100–200 m). It depends on the local geology. However, in practice the n flux is around a few $10^{-2}\,m^{-2}\,s^{-1}$ in several laboratories.

Muons interactions in the rocks produce dangerous neutrons at a depth-dependent rate. The fluxes are typically 3–4 orders of magnitude smaller than the main n flux. The energies are large, up to several GeV, demanding thicker shields. Even more dangerous are the neutrons produced in the shields, in the detector and in the materials around it. In the case of fast reactions, namely if a neutron immediately follows the muon, the background can be reduced by anticoincidence. Neutrons from metastable nuclides, which cannot be anti-coincided can be eliminated by working at a larger depth. Their effect depends on the details of the experiment, and is generally more severe for high-Z materials.

Radon (^{222}Rn) is a radioactive, volatile gas that is always present in the atmosphere, being continuously produced by the decay of ^{226}Ra present in the rocks. An important source of Rn is ground water. The Rn activity, which is typically 10–20 Bq m^{-3} in the open air, is larger by two orders of magnitude or more in closed underground cavities. It is reduced by ventilation. The equilibrium activity depends on the emanation rate and on the ventilation speed. The input air duct, which may be a few km long, should be made of SS or similar materials to avoid Rn collection input.

In general experiments need to be shielded. Indeed, the shield thickness determines the physical size of the most sensitive experiments. For example, the frontier double beta decay experiments presently under construction, CUORE and GERDA, have diameters of about 15 m, due to the shields. The next generation may need halls 20–30 m in diameter and height. On purpose one should remember that, depending on the rock nature, the maximum safe diameter of a cavity decreases while the costs increase with depth.

Laboratories differ in many other important aspects: distance from accelerators and nuclear power plants, horizontal or vertical access, interference with nearby activities (mine work, road

* Correspondence address: Padua University and INFN Section, Dipartimento di Fisca G. Galilei, Via Marzolo 8, 35131 Padova, Italy.
E-mail address: Bettini@pd.infn.it

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traffic, etc.), quality of the support infrastructures (laboratories, office space, assembly halls, etc.) and personnel on the surface, degree of internationality of the user community and programme, presence or not of an international advisory committee, policy of space and time allocation.

Scientific sectors different from astro-particle physics, such as biology, geology and engineering can profit of the very special underground environment provided by the laboratories and their facilities. Space does not allow these important issues to be discussed here. This review is limited, for reasons of space, to the larger facilities ($>1000\,m^2$) at not too shallow depth (>800 m), which host a number of experiments and provide a range of services to an international community of users. I will proceed in geographical order, from W to E. A number of smaller facilities exist, which are often managed and used by a single Institution, mainly for R&D activities and for small-scale experiments. I will limit to mention them together with the URL of their web-site: CUPP Centre for Underground Physics in Pyhäsalmi (Finland) http://cupp.oulu.fi/; SUL Solotvina Underground Laboratory (Ukraine) http://lpd.kinr.kiev.ua/LPD_SUL.htm; Y2L YangYang Laboratory (Korea) http://dmrc.snu.ac.kr; Oto Cosmo Observatory (Japan) http://wwwkm.phys.sci.osaka-u.ac.jp/info/syoukai/oto-e.html. Some underground science is also present in the WIPP Waste Isolation Pilot Plant, (USA) http://www.wipp.energy.gov/science/index.htm. For details see Refs. [1–3].

2. BUL. Boulby Palmer Laboratory (UK)

2.1. http://www.hep.shef.ac.uk/research/dm/boulby/boulby.php

The site was developed starting in 1988 by N. Spooner and collaborators initially from RAL. An active potash mine at 1100 m depth under a flat surface hosts it. The access is through a shaft. The salt environment limits the cavities width to about 5 m. A clean area of approximately $1500\,m^2$ is available to experiments. The neutron flux with $E>0.5$ MeV is $1.7\times10^{-2}\,m^{-2}\,s^{-1}$ and the muon flux is $4.5\times10^{-4}\,m^{-2}\,s^{-1}$. A building on the surface ($200\,m^2$) hosts laboratories for computing, electronics and chemistry, offices, a conference room, changing rooms, mess rooms, a mechanical workshop, storage and construction rooms. The scientific programme is focused on dark matter search with ZEPLIN II, based on two-phase Xe (30 kg), ZEPLIN III, also with Xe 2-phases and DRIFT II, in the R&D phase. There are low radioactivity measurements and geophysics research. About 30 scientists work at the laboratory.

3. LSC. Laboratorio Subterrneo de Canfranc (Spain)

3.1. http://www.lsc-canfranc.es/

The first underground facility located under the Pyrenees, close to a dismissed railway tunnel, was created in the 1980s by A. Morales and the Nuclear and High-Energy Physics Department of the Saragossa University. Taking advantage of the excavation of a parallel road tunnel, the new laboratory was built later. The underground structures have been completed in 2005. However, design and construction defects have emerged and necessary reparation work is under way, to be completed by mid 2010. LSC is managed by a Consortium between the Spanish Ministry for Education and Science, the Government of Aragon and the University of Saragossa. A surface building containing headquarters, administration, a library, a meeting room, offices, laboratories, storage areas and a mechanical workshop, safety structures and management, for a total of approximately $1500\,m^2$ is under construction, to be completed by end 2010. A dozen of employees are being hired.

The access is horizontal, via both tunnels. The entrance must be communicated to the freeway tunnel control. The spaces available underground are: Hall A, measuring $40\times15\times12(h)\,m^3$, Hall B of $15\times10\times8(h)\,m^3$, Clean room of $45\,m^2$ and Services for $215\,m^2$. The old lab area is $100\,m^2$. The maximum rock coverage is 850 m. The muon flux is between $2-4\times10^{-3}\,m^{-2}\,s^{-1}$, depending on the location; the n flux is $2\times10^{-2}\,m^{-2}\,s^{-1}$. The Rn activity in the air is 50–80 $Bq\,m^{-3}$ with a ventilation of $11\,000\,m^3\,h^{-1}$, i.e. one lab volume in 40 minutes.

An International Scientific Committee helps the management in the processing of the proposals and in the monitoring of the development of the experiments. The following experiments have been approved to date: on dark matter search, ANAIS searching for annual modulation with NaI and ROSEBUD developing scintillating bolometers in the frame of EUREKA; on double beta decay, NEXT with 100 kg of enriched ^{136}Xe high pressure TPC; on condensed matter at extreme low temperature, ULTIMA on liquid He. Two other projects are ancillary to experiments in other laboratories: BiPo for the SuperNEMO proposal and SUPERKGD for material screening in view of a possible addition of Gd into the SK water. GEODYN will be an underground geodynamic observatory integrated in the TOPO-IBEIRIA and TOPO-EUROPE networks. A new hall to host an underground accelerator facility dedicated to nuclear astrophysics is under design. A special facility is dedicated to low-radioactivity measurements.

4. LSM Laboratoire Subterrain de Modane (France)

4.1. http://www-lsm.in2p3.fr/

The Laboratory is operated jointly by CNRS/IN2P3 and CEA/DSM. Excavation of the Laboratory started in 1979, and was completed by 1982, to host a 900 t iron tracking calorimeter to search for proton decay. The "Frejus" experiment was finished in 1988.

The access is horizontal through the Frejus roadway tunnel. Intervention of the tunnel control is needed to stop traffic at the entrance or exit of a vehicle from the lab. The Main Hall is $30\times10\times11(h)\,m^3$, the Gamma Hall has an area of $70\,m^2$, two smaller halls have $18\,m^2$ and $21\,m^2$ areas, for a total of $400\,m^2$. The surface building includes offices ($100\,m^2$), a warehouse and workshop ($150\,m^2$) and a flat. The personnel include eight technicians and engineers and one post doc.

The rock overburden is 1700 m. The μ flux is $4.7\times10^{-5}\,m^{-2}\,s^{-1}$. The n flux is $5.6\times10^{-2}\,m^{-2}\,s^{-1}$. A low Radon activity in the air, $15\,Bq\,m^{-3}$, is obtained by in taking fresh air at the rate of 1.5 lab vol h^{-1}. An "antiradon factory" produces $150\,m^3\,h^{-1}$ of air with $10\,mBq\,m^{-3}$. The laboratory is almost full with NEMO 3 (double beta decay), EDELWEISS (dark matter), which should run at least up to 2010, and a low-radioactivity counting facility. About 100 scientists work at the lab.

A surface building has been completed, hosting outreach facilities, offices, technical laboratories and sleeping rooms. The Ulisse project profits by a unique opportunity given by the construction of a new tunnel approved by the French and Italian Governments to increase the safety conditions of the traffic. Two large halls are foreseen: A of $100\times24\,m^2$ and B of $18\times50\,m^2$. An extremely low-background environment will be obtained in Hall B by surrounding its central volume with a water shield and by artificially producing a very low Rn content atmosphere ($0.1\,mBq\,m^{-3}$). The user community is about 200 strong of scientists of 31 Institutions from seven Countries.

5. LNGS. Laboratorio Nazionale del Gran Sasso (Italy)

5.1. http://www.lngs.infn.it/

LNGS is a national laboratory of the INFN. It is the largest in the world, serving the largest and most international scientific community. In 1979 the President of the INFN A. Zichichi proposed to the Parliament to build a large underground laboratory close to the Gran Sasso freeway tunnel then under construction (an opportunity that substantially reduced the cost). In 1982 the Parliament approved the construction, which was completed by 1987.

Access is horizontal, through the freeway. The underground laboratories consist of three main halls (called A, B and C), about $100 \times 20 \times 18(\mathrm{h})\,\mathrm{m}^3$ plus ancillary tunnels, providing space for services and small-scale experiments. Two 90 m long tunnels were built for two Michelson interferometers to be used for geology studies. The total area is 17 300 m^2, the total volume 180 000 m^3.

Services hosted on the surface campus include offices, a mechanical workshop, storage facilities, a chemical lab, an electronic workshop, an assembly hall, computers and networking, a library, a canteen, sleeping rooms, conference rooms, headquarters, administration. Special care has been given to the development of structures, procedures and training activities in matter of safety, of the users and of citizens, as well as environmental impact. Rigorous anti-seismic rules have been defined on the basis of a careful seismic characterization of the site. The experimental and technical infrastructures are requested to follow these rules. This procedure protected the structures from the consequences of the strong quake of 6 April 2009. A number of outreach activities and visits to the lab are systematically organised by a dedicated Service. A Training Service has been created to exploit the technological and scientific transfer of the lab expertise to young people of the Abruzzo region. Personnel (physicists, engineers, technicians, administration) include a permanent staff of 76 and 20 non-permanent positions.

The rock overburden is 1400 m. The μ flux is $3 \times 10^{-4}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$ and n flux is $3.78 \times 10^{-2}\,\mathrm{s}^{-1}\,\mathrm{m}^{-2}$. Radon in the air is 50–120 $\mathrm{Bq\,m}^{-3}$ with a ventilation system providing one lab volume of fresh air in 3.5 h. Major civil engineering work has been performed in 2004–2007 to upgrade the safety conditions of the interacting structures of the free-way, the water-collection systems and the laboratory.

LNGS is operated as an international laboratory. In the process of approval of the proposals, an International Scientific Committee, appointed by INFN, advises the Director. Underground space and other resources are allocated to experiments for a definite amount of time, in order to guarantee turnover. The rich experimental programme includes dark matter searches, with LIBRA, CRESST2, XENON, WARP; Double Beta Decay with COBRA, CUORE, GERDA; Solar neutrinos (and geo-neutrinos) with BOREXINO; Supernova neutrinos with LVD; Nuclear astrophysics with LUNA2; CNGS with OPERA and ICARUS. A special facility is dedicated to low-radio-activity measurements. The laboratory also supports several experiments on geology, biology and environmental issues. Almost all of the experiments are second-generation ones and have been approved for several years of data taking. The scientific user community is 752 strong, involving scientists from 26 countries.

6. Coordination in the Europe Union

The directors of the four EU underground laboratories (LNGS, LSM, LSC and BUL) initiated actions to co-ordinate activities and to optimise the use of the resources, taking into account the different characteristics of the infrastructures. In the 6th "framework programme" the ILIAS project (Integrated Large Infrastructures for Astroparticle Science) was submitted successfully to European Commission (EC) by ApPEC, the European inter-agency committee for astroparticle physics. The continuation of this program (a new proposal called ILIAS-Next has been submitted to EC) and the continuation of the coordination among the four underground labs has been favoured by ASPERA. Created by ApPEC and funded by the EC through the 7th Framework Programme, ASPERA is a network of national government agencies. In the 7th FP, EC also funded a Design Study project (LAGUNA) focusing on the design of an European infrastructure able to host underground new large-volume instruments with a fiducial mass of 100 kt to 1 Mt, depending on the technology, for neutrino physics and astronomy and proton decay search.

7. BNO. Baksan Neutrino Observatory (Russia)

7.1. http://www.inr.ac.ru/INR/

The Laboratory is operated by the INR of the Russian Academy of Sciences. It is managed as an observatory, with very long-duration experiments, without defining their duration. It is the oldest facility in the world, built specifically for scientific research. M. Markov, the Head of Nuclear Physics Division of the Academy of Sciences of the USSR, obtained in 1966 a special Decree of the Soviet Government, and construction of the Baksan Neutrino Observatory started under Mount Andyrchi in the Caucasus. A new village, called 'Neutrino', was built as a part of the original project in a previously empty space with personnel providing the necessary services (heating station, water-supply system, first medical help, transportation, safety, etc.). The staff directly related to science is 50–60. The scientific activity started under the leadership of Alexander Chudakov and George Zatsepin. The access is horizontal via two dedicated tunnels, with train transportation.

A large hall, $24 \times 24 \times 16\,\mathrm{m}^3$ in volume, 300 m deep, hosts the Baksan Underground Scintillation Telescope. BUST has been ready to observe neutrinos from galactic supernovae since 1978. The Laboratory of the Gallium Germanium Neutrino Telescope hosting SAGE, has a volume of $60 \times 10 \times 12\,\mathrm{m}^3$ at a vertical depth of 2100 m. In this lab the muon flux is $3.03 \pm 0.19 \times 10^{-5}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The neutron flux ($E > 1$ MeV) is $1.4 \times 10^{-3}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The Rn activity is 40 $\mathrm{Bq\,m}^{-3}$ with a fresh air input of 60 000 $\mathrm{m}^3\,\mathrm{h}^{-1}$.

The construction of a larger and deeper hall, about 40 000 m^3 in volume, was started in 1990, and stopped in 1992, when the Soviet Union collapsed. Further fate of this not finished construction is presently under discussion. Low-background Chambers with a volume from 100 to 300 m^3 are used for the R&D of dark matter and double beta decay search as well as for gravitational wave search and for some geophysics measurements. The number of users is 30–35.

8. INO. India based Neutrino Observatory (India)

8.1. http://www.imsc.res.in/~ino/

One of the two experiments that first observed atmospheric neutrinos in 1964 was located at 2700 m depth in the Kolar Gold Mine in India. The India based Neutrino Observatory is the project to create an underground laboratory in southern India. It will be located near the PUSHEP hydroelectric pumping station, under a 1300 m rock overburden. The construction was foreseen to be completed by 2012. Since the proposed site is at Singara in the Nilgiri Biosphere Reserve in the prime elephant and tiger habitat, a detailed Environmental Managing Plan was carefully prepared and submitted to the local (Tamil Nadu) and central Governments. Actions by environmental organisations finally lead the Indian Government to reject the proposed site. The search for another location and its characterisation will delay the project by at least one year.

The lab will be organized with international laboratory standards with a Scientific Advisory Committee, services to the users, environmental, safety, security and outreach activities. Two main underground cavities are foreseen: Lab1 with a volume of $26\times135\times25(\mathrm{h})\,\mathrm{m}^3$ and Lab 2 with $53.4\times12.5\times8.6(\mathrm{h})\,\mathrm{m}^3$ plus connection tunnels and services. Access will be horizontal through a dedicated 2 km tunnel. The surface campus will host: a $1400\,\mathrm{m}^2$ building for administration, offices, shops, etc., a $2750\,\mathrm{m}^2$ building with a lecture hall and a guest house and a residential complex with 20 quarters. Personnel will be 50–100.

The main foreseen experiment is ICAL, a 50 kt (with possible expansion to 100 kt) magnetized Fe tracking calorimeter (MONOLITH like) for atmospheric and very long base-line accelerator neutrinos. It will occupy only a fraction of Lab1. R&D for a double beta decay experiment is under progress.

9. CDUSEL. China Deep Underground Science and Engineering Laboratory

Recently, a project for the world's deepest, and possibly largest underground laboratory has been launched in China [4], taking profit from the infrastructures of the Ertan Hydropower Development Company (EHDC). Twenty-one hydroelectric power stations are planned on the Yalong river, for a total of 30 GW. A system of tunnels 17.5 km long will cut a big U-turn of the river, under the 4193 tall Jingpin mountain. This has a flat cross section providing 2500 maximum rock overburden and more than 1500 m for 70% of the directions. The access will be horizontal, from the two sides.

Two small experimental halls $5\times5\times30\,\mathrm{m}^3$ are under construction. Ventilation, laboratory grade power supply and Ge counters with their shielding will be installed. Measurements of the muon flux (expected to be very low indeed, $20\,\mathrm{m}^{-2}\,\mathrm{yr}^{-1}$), of the neutron flux and of the radon concentration in the air will be performed. The laboratory will be designed as an international facility, opening the discussion to the world community. A working group, including scientists and engineer from major Chinese institutions and Universities, as well as EHDC, was established, chaired by H. Chen.

10. Kamioka Observatory (Japan)

10.1. http://www-sk.icrr.u-tokyo.ac.jp/index_e.html

The Kamioka Observatory is operated by the Institute for Cosmic Ray Research, University of Tokyo. It was established in 1983 by M. Koshiba as Kamioka Underground Observatory. The original purpose of this observatory was to conduct the KamiokaNDE experiment, to which Super-Kamionkande followed. The present facilities have been designed for Super-K, the largest existing underground experiment. Enlargement works are being developed, in order to accommodate more experiments. The KamLAND experiment is operated by the Neutrino Centre, Tohoku University. Buildings for offices and computer facilities are available on the surface. The staff members are 13 scientists, two technical support units, one for administration.

The coverage is 1000 m and the muon flux is $3\times10^{-3}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The thermal neutron flux is $8.25\pm0.58\times10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, the non-thermal is $11.5\pm1.2\times10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The ventilation is $3000\,\mathrm{m}^3\,\mathrm{h}^{-1}$. The access is horizontal by car, with no interference with the mining activity. The underground structures are as follows: Hall SK (50 m diameter) hosting Super-Kamiokande, to be continued for 15 years, at least. Clean room ($10\times5\,\mathrm{m}^2$) with XMASS prototype. Hall 40 (L-shape, $40\,\mathrm{m}\times4\,\mathrm{m}$ arm) hosting the purification tower for XMASS and the NEWAGE experiment on dark matter. Hall 100 (L-shape, $100\,\mathrm{m}\times4\,\mathrm{m}$ arm) with CLIO, a prototype of Gravitational Antenna (to be terminated in 2013) and a Laser displacement detector. The new Hall A ($15\times21\,\mathrm{m}^2$) hosting XMASS 800 kg (until 2012) with space available for another experiment. The new Hall B ($6\times11\,\mathrm{m}^2$) hosting CANDLE on double beta decay, to be occupied until 2012. Small areas are available in the dismissed mine. The scientific users are more than 200 in number. A budget request for the underground large cryogenic gravitational antenna LCGT has been submitted.

The T2K experiment is starting now. It is a third generation neutrino oscillation experiment on an intense off-axis beam of ν_μ produced at the J-PARC facility at 295 km distance from the SuperK detector. The main goal is to search for the ν_μ to ν_e oscillation and to measure θ_{13}.

11. SNOlab (Canada)

11.1. http://www.snolab.ca/ also http://www.sno.phy.queensu.ca/

The SNO experiment has completed its glorious life and its cavity, $200\,\mathrm{m}^2$ area, is now being freed for further experimental activity. To these, new structures have been added to form a new laboratory, the SNOlab: a Main hall of volume $18\times5\times(15$ to 19.5 height$)\,\mathrm{m}^3$, a service hall of about $180\,\mathrm{m}^2$, a number of narrow (6–7 m) volumes, called "ladder labs" and, more recently, the "cryopit". This hall is designed to cope with the safety issues surrounding large volumes of cryogenic fluids. The total area is $7215\,\mathrm{m}^2$, of which $3055\,\mathrm{m}^2$ is available for the experiments; the total volume of the lab is $46\,648\,\mathrm{m}^3$, of which $29\,555\,\mathrm{m}^3$ will be available for the experiments. The access is vertical, through the shaft of the working mine, available daily. All the laboratory will be clean, class 1500.

On the surface a $3159\,\mathrm{m}^2$ building hosts a clean room, laboratories, staging and assembly areas, office space (60 users), meeting rooms, control rooms, an IT server room, an emergency generator, high-speed network link off site, high-speed network link surface/underground, safety structures and management. Staff will be of 30 full-time people.

The rock coverage is 2000 m under a flat surface. The μ flux is $3\times10^{-6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, the thermal neutron flux is $4.7\times10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, the fast neutron flux is $4.6\times10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The radon in the air is $120\,\mathrm{Bq\,m}^{-3}$. The ventilation in the smaller lab spaces provides 10 air changes per hour, in the larger ones, 5 air changers per hour.

The scientific programme includes PICASSO, searching for dark matter (2 kg) with the super-heated bubbles technique, which is running and SNO+ to be hosted in the former SNO cavity; it will be based on liquid scintillator for low energy solar neutrinos, geoneutrinos and double beta decay, by dissolving ^{150}Nd in the liquid. Dark matter search includes DEAP/CLEAN with noble liquids, which is getting ready to install prototype, and a LoI from superCDMS with bolometers. More LoIs are expected to be reviewed by the Experimental Advisory Committee.

12. SUL. Soudan Underground Laboratory (USA)

12.1. http://www.soudan.umn.edu/

The underground structures include: the Soudan lab ($20\times7\times10(\mathrm{h})\,\mathrm{m}^3$) that hosts: (a) CDMSII, expected to run until 2009;

(b) a low-background counting facility that currently occupies $5 \times 5 \times 3\,m^3$ and will expand to $25 \times 14 \times 14(h)\,m^3$, if funded. The MINOS lab that hosts: (a) MINOS that occupies $35 \times 16 \times 14(h)\,m^3$ and is expected to run a few years more with a 2-year decommissioning period at the conclusion; (b) the high-purity copper fabrication facility that occupies $4 \times 6 \times 3(h)\,m^3$ and expects to run for at least another two years. The users are 265 in number.

The access is vertical via a two-compartment slightly angled shaft. Diameters in excess of 1 m and lengths in excess of 10 m pose a problem. Access outside normal operating hours is possible. There is an access charge paid to the host institution, Soudan Underground Mine State Park. Normal laboratory safety requirements are in place. The laboratory coexists with an historic State Park, which offers mine tours during the summer months to the public, and winter tours to school groups. Some tours utilize a visitor's gallery available in the MINOS laboratory. There is no active mining activity.

The overburden is 700 m of rock. The muon flux is $2 \times 10^{-3}\,m^{-2}\,s^{-1}$. The neutron interaction rates are approximately $10\,kg^{-1}\,d^{-1}$ (from U/TH, low energy) or $0.01\,kg^{-1}\,d^{-1}$ (muon generated in the rock). The radon concentration is seasonal, varying from $300\,Bq\,m^{-3}$ in the winter to $700\,Bq\,m^{-3}$ in the summer. The mine has natural ventilation, about $550\,m^3\,h^{-1}$ for the level of the laboratories. Half of this is diverted to ventilate the MINOS and Soudan spaces. This results in a complete air change every 110 s.

The major facility on the surface is a building of approximately $650\,m^2$ with offices, a kitchen and sanitary facilities. The laboratory has a staff of 9, including secretarial and accounting assistance and network and computer maintenance personnel. It is staffed 10 h/day, 5 days per week, but the staff is on-call during the balance of the time and responds to requests for emergency access.

13. DUSEL. Deep Underground Science and Engineering Laboratory (USA)

Solar neutrino physics started in the Homestake mine in South Dakota with the experimental work of R. Davis and the theoretical sun model developed by J. Bahcall. After a long and complex process, in spring 2007, NSF selected amongst several proposals the Homestake mine in South Dakota as the site in which the Deep Underground Science (physics, biology, and geology) and Engineering Laboratory (DUSEL) should be designed. The project foresees a funding by NSF of about 250 M$ for the facility plus a contribution to the initial set of experiments, costing about 250 M$. In addition, to prepare the site, SD provides 46 M$ on its own and 70 M$ from a donation by T. D. Sanford. NSF is expected to fund with 15 M$ the design of the facility, which will take three years. For the time being, the facility is a SD State Laboratory, funded primarily from SD-controlled money. Water constantly flows into the mine at a rate of 1.2 Mt/yr. Pumps had stopped in spring 2003. Rehabilitation work started in January 2007, securing the level at 1450 m depth with pumps at 1600 m.

On the surface several existing buildings will be rehabilitated for about $10\,000\,m^2$ to host offices, support structures and laboratories. A major science education centre has been funded by Sanford. The initial staff is estimated to be 30–50 strong, to increase to 100–150 when the State Lab will become DUSEL. The Scientific Committee has been established with an USA composition in 2006.

Laboratory spaces will be built separately for biology, geology and physics. Service and R&D structures (e.g. electroforming) will be available for physics at a 100 m deep level. Two main campuses are foreseen for physics at about 1450 and 2200 m deep. Each will contain a number (4 and 3 respectively) of standard modules of $50 \times 20 \times 15\,m^3$ plus service areas. A staged construction of the upper campus using SD and private funding is foreseen. For the lower campus, NSF and Congress approval will be necessary.

14. Conclusions

There are several underground facilities in the world, but only a few are managed as international laboratories, with a truly international Scientific Committee, full-scale services, turnover of the experiments. New laboratories and upgrades of existing ones are being created along these lines. New sub-critical facilities should not be created.

The physics programme for the next decades appears to be extremely rich and challenging, including the following fundamental questions:

- What is the nature of neutrinos, Majorana or Dirac particles?
- Are lepton and baryon numbers conserved?
- What is the absolute neutrino mass scale and its hierarchy?
- What is the value of θ_{13}?
- What is the nature of dark matter?
- Do we understand completely the solar neutrino physics? (Berillium and pp neutrinos).

Experiments on dark matter and double beta decay will reach the ton to multi-ton scale in the next several years. Presumably no more than one megaton-size detector will be built with a wide physics programme ranging from proton decay, to CP violation on a high intensity neutrino beam, to supernova neutrinos. The community is still far from consensus on the technique and the site (the optimum distance from the source will depend, in particular, on the value of θ_{13}).

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References

[1] A. Bettini, The world undeground science facilities. A compendium, arXiv:0712.1051.
[2] A. Bettini, Journal of Physics: Conference Series 120 (2008) 082001.
[3] E. Coccia, Underground laboratories: cosmic silence, laud science, in: TAUP 2009 Proceedings.
[4] K. Kang, et al., Journal of Physics: Conference Series 203 (2010) 012028.