Physics of the Dark Universe 4 (2014) 36–40

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

New underground laboratories: Europe, Asia and the Americas

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ARTICLE INFO

Keywords:
Underground science
Neutrino physics and astrophysics
Dark matter
Cosmic radiation
Geodynamics
Deep underground life

ABSTRACT

Deep underground laboratories provide the low radioactive background environment necessary to explore the highest energy scales that cannot be reached with accelerators, by searching for extremely rare phenomena. In addition, these laboratories provide unique opportunities to sectors of other fields: geodynamics, rock mechanics, hydrology and the study of life under extreme conditions.

Underground laboratories of different size and depth exist in all the regions. This article is focussed on future perspectives, reviewing the newer facilities, those still under project and the space becoming available at the older laboratories. We shall not discuss the existing or proposed facilities dedicated to detectors of long base line experiment with reactor or accelerator beams.

1. A bit of history

The first experiments underground date back to the 1960s. They were performed very deeply in mines. In 1965 the first "natural" neutrinos, produced by cosmic rays interactions in the atmosphere were discovered, almost at the same time, by two groups working in the Kolar Gold Mine in South India [1] at a depth of 2700 m and in the East Rand Property Gold Mine in South-Africa [2] at a depth of 3200 m. A cavity in the Homestake Mine in S. Dakota in the USA was the site of the fundamental experiment by R. Davis [3], who first detected in 1968 neutrinos from the Sun. The observed rate resulted about three times smaller than that calculated by J. Bahcall [4]. As we have gradually learned, with other experiments underground since then, this was the first evidence for physics beyond the Standard Model.

A hall in a mine is not however a laboratory. The first full-fledged underground laboratory is the Baksan Neutrino Observatory (BNO). In 1966, under the action of M. Markov, the Academy of Sciences of the USSR obtained a Decree of the Soviet Government for the construction of the underground and surface facilities. Scientific activity started under the leadership of G. Zatzepin and A. Chudakov. The underground laboratory, including a horizontal access tunnel, was excavated and built under the mount Andyrchi in the Caucasus.

In 1979 a double tunnel was under construction for a freeway under the Gran Sasso Mountain in central Italy. A. Zichichi, then President of the INFN, saw the unique opportunity of building a world-class underground laboratory (LNGS) with a broad spectrum of potential scientific programme, including a future neutrino beam from CERN. In 1982 the Parliament approved and funded the construction, which was completed in 1987, at a very low cost.

In 1983 M. Koshiba established the Kamioka Underground Observatory, in a modern working mine with horizontal access, to host the KamiokaNDE water Cherenkov detector. Later on its bigger successor was built, SuperKamiokande, which in 1998 [5] discovered neutrino oscillations in the muon-neutrinos from the atmosphere, complementing the Davis and Bahcall discovery. Several other facilities were built after those, of different sizes and at different depths.

I have been requested to limit this review to the recently built facilities and to those under project, and to the underground space available in the older ones. For a more complete review I refer to a set of articles I have co-ordinated [6] in 2012 on: BNO [7], Canfranc (LSC) [8], Kamioka [9], Modane (LSM) [10], LNGS [11], SNOLab [12], SURF [13], and the Indian INO [14], Chinese CJPL [15] and South-American ANDES [16] projects. The introductory article [6] includes also brief descriptions of the smaller laboratories: CUPP in Finland, SUL in Ukraine, Y2L in Korea, Oto Cosmo in Japan, Sudan and WIPP in the USA.

2. Characteristics

The deep underground laboratories (DULs) differ from many points of view.

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http://dx.doi.org/10.1016/j.dark.2014.05.006

Depth is an important parameter, because the μ flux and the fluence of the μ-induced spallation neutrons decrease with increasing depth. However, these are only two of the background components and do not contribute substantially to the background budget below about 1500 m of rock overburden in the majority of the cases. On the other hand muons are also useful for calibration purposes.

In the design of a laboratory, halls of different sizes may be foreseen. 15–20 m diameters *and* heights are needed for water shields (e.g. in dark matter and double beta searches) and for large liquid scintillator detectors, as those necessary for solar and geo-neutrinos. Large heights require, in particular, thick enough layers of good quality rock.

Horizontal access has many advantages over the vertical one, which typical in some mines. It allows drive-in to the experiments, the installation of large pieces of apparatus built on the surface and reduced operation costs. In one case, BNO, the access tunnel was built on purpose, in other (LNGS, LSC, LSM and ANDES) is (or will be) provided by a road tunnel. Notice however, that in this case a unique window of opportunity exists, during the construction of the tunnel itself, before it is opened to the traffic. The Kamioka observatory is in a mine, with horizontal access. Hydroelectric power stations offer similar opportunities (CJPL, INO, CUNPA). SNOLab and SURF have vertical access, in mines, operational for the former, dismissed for the latter. The operation costs are higher for vertical access. However, in the case of SNOLab the mine contributes in-kind in sectors like safety, security, access.

The support facilities on the surface differ widely between the DULs, both in the laboratories and workshop and in the quantity and skills of personnel.

Underground space is the main mission of all the DULs. The corresponding allocation policies differ. Some laboratories do that on the advise of a fully international Scientific Advisory Committee, other are substantially controlled by the host Nation or Institution. Two different approaches are exemplified by LNGS, which has three large general purpose halls and allocates space, in general, for a defined period of time, and Kamioka that builds new halls “on demand” of new experiments.

Other differences are in the degree of internationality of the community, in the presence or not of other science (biology, geology, engineering, etc.), in the structure of the management, in the funding regulations, in the safety, security, environmental, technology transfer and accountability policies.

The capital investment necessary to build the laboratory infrastructures is obviously an important issue and needs to be accurately evaluated in the design phase. A number of test drills is necessary for a complete knowledge of the geology of the site. Notice that not all the rock types are suitable for excavation of stable cavities. All the costs of the project must be evaluated as accurately as possible and a proper risk analysis performed before submitting the project to the Funding Agencies. Missing to do so in a few cases in the past lead to loss of credibility.

It may be useful to have an order of magnitude idea, analysing the costs of the existing infrastructures. Site dependent factors can be sizeable, but, in general, the costs of excavation, once the starting ones are covered, are proportional to the volume and those for the rocks stabilization to the area of the surfaces. I give a few examples. The cost of the service equipped LNGS, which an excavated volume of 190,000 m^3, extrapolated to 2011 is of 57 M€, or 300 €/m^3. The project of an independent access tunnel, 6 m diameter, 5 km length, made in 1999 to be excavated wit a tunnel boring machine (TBM) lead to a cost evaluation, which extrapolated to 2011 is of 55 M€, or 220 €/m^3. The DOMUS project of LSM takes the opportunity of the excavation of a second road tunnel, for building a new experimental hall of about 14,000 m^3 plus access corridors, with a cost of 7 M€ evaluated on the basis of a unitary cost of 300 €/m^3. The cryopit at SNOLab has a volume of 40,000 m^3 and an area of 3500 m^2. Its cost was 15 M$Can, corresponding, once more, to about 300 €/m^3. The unitary cost is substantially lower for larger cavities as those of the LAGUNA study.

Only a fraction of the total volume is directly available to experiments. Corridors connecting the experimental halls may reach a substantial fraction of the total. Consequently, compact structures are cheaper, but require the availability of a large enough volume of good rock. For newly built infrastructures this can be searched for in the project phase, while may require substantial tunnelling to be reached in an existing mine (which are excavated for other purposes). Notice on purpose that refurbishing an existing mine tunnel is substantially more expensive than drilling a new one. Very high and difficult to evaluate in advance are the costs to rehabilitate an old infrastructure in an abandoned mine, corresponding to an increased project risk.

3. Monitoring

Progress in the underground experiments is strictly linked to the progress in background reduction. The background budget contains intrinsic components in the detector itself and its shields and external components due to the environment. The latter are different in different laboratories and must be known by the scientific users to be able to design their shields. The environmental background fields are the following.

Atmospheric muons. Their flux decreases almost exponentially with increasing depth from a few 10^{-3} m^{-2} s^{-1} at Kamioka and LSC (at about 2 km water equivalent) to a few 10^{-6} m^{-2} s^{-1} at SNOLab and CJPL. They induce background both directly, interacting in or near the detectors, and indirectly producing neutrons by spallation. The former can be suppressed by anti-coincidence. Muon flux varies during the year with a periodic modulation of a few per cent, with maximum in summer and minimum in winter, due to the variation of the atmospheric temperature and density. Muon flux can have substantial direction dependence that must be measured.

Neutrons. Neutrons come mainly from (α, n) reactions and fission of U and Th in the rocks and in the concrete used for stabilization. Their energy spectrum, which must be measured, decreases almost exponentially, but with several peaks, with increasing energy up to about 8 MeV. The fluence does not depend on the depth (if larger than 100 m or so), but depends on the local geology and on the concrete used for lining (and that consequently must be accurately selected). The flux ranges from a few to many 10^{-2} m^{-2} s^{-1}. Very low radioactivity concrete has been used at BNO to reduce the neutron flux down to 0.2310^{-2} m^{-2} s^{-1}. These neutrons can be shielded.

Higher energy neutrons, up to several GeV, are induced by the muons by spallation reactions in the environment, in the shields and in the experiment itself. Their flux depends on the depth and is typically two or three orders of magnitude smaller than for the low energy neutrons. However, only the externally produced component can be shielded and requires thick shields. The fast internal component can be reduced by anti-coincidence of the muon. This is done to four orders of magnitudes in BOREXINO. Metastable nuclei are more difficult; they can reduced increasing depth. The background is experiment dependent, being more severe if high-Z materials are used, in particular in the shield.

The gamma background field is due to nuclear decays in the environment, mainly in the rocks and in the atmosphere due to ^{222}Rn and daughters. Flux and energy spectrum must be measured. The flux is a function of the local geology and does not depend directly on the depth. Typical values are a few 10^4 m^{-2} s^{-1}.