LSC

Laboratorio Subterráneo de Canfranc

ANNUAL REPORT | 2013

EDITING

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Thanks to all who have helped towards the making of this editorial project

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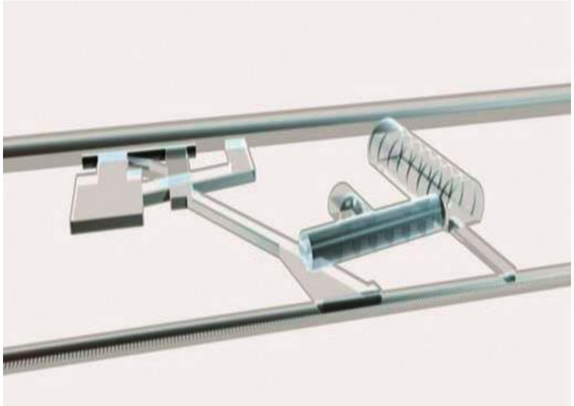


DIRECTOR'S STATEMENT

The Laboratorio Subterráneo de Canfranc is the second largest deep underground scientific laboratory in Europe. It is run by a Consortium between the Spanish Ministerio de Economía y Competitividad, the Government of Aragón and the University of Zaragoza.

It offers underground facilities shielded from the natural cosmic rays radiation to fundamental physics and astrophysics and locations of unique characteristics for geology, biology and environment sciences to researchers from all over the world.

Six experimental infrastructures proposed by groups of users from international universities and laboratories are already working or under construction, but more underground space is still available for new proposals. In addition an extension project for a nuclear astrophysics facility is under study.

Laboratories, offices and meeting rooms are also available on the surface. In addition, the LSC provides the following services to non-scientific users:

- Materials Radiopurity measurements with very low background HPGe detectors (RMS).
- Radiopure copper parts manufacturing service using electroforming techniques (CES).
- Underground clean room class 1.000 (ISO 6) and class 10.000 (ISO 7) (CRS).
- The conference room for institutional meetings with 98 seats.

We welcome both new scientific proposals, which can be hosted in the still free underground space, and requests for services. We do not fix any deadline for that. Just address to the web site or call. The International Scientific Committee of LSC will analyse the scientific proposals, giving its advice to the management based only on the scientific excellence, while the Access Committee will process the requests for services.

This Report describes to non-specialists the LSC infrastructures, science and the experimental activity of the external users up to 2013. It is based on the annual reports submitted by each experiment, which have been edited by the LSC. *Any inexact element introduced in the editing should be credited to LSC.*

Prof. Alessandro Bettini

Canfranc Estación, 31.1.2014

1 INTRODUCTION

Physicists have developed a theoretical description of the elementary building blocks of matter and of the basic forces of Nature, called the standard model. We have tested with increasing precision all its predictions at the energies that are reachable with the accelerators. A fundamental element that was missing, the Higgs boson, was discovered at CERN in 2012, when the new LHC collider had reached the energy necessary to produce it. Presently, work is being done to double the LHC energy to explore the phenomena that may occur at that scale. But we already know that it will not be sufficient. Underground laboratories, like LSC, provide scientific information that is complementary to that obtained in laboratories with accelerators, like CERN. Indeed, the first elements of physics beyond the standard model came from underground experiments.

The Universe originated about 14 000 million years ago in an enormous explosion, the Big Bang. The corresponding energy, the Planck energy scale, is fifteen orders of magnitude, meaning a one followed by fifteen zeros, larger than the LHC energy. In addition, we know that the different forces of Nature seem to become equal, to become unified as we say, at energies that only about one hundred time smaller than the Planck scale. We will never be able to reach it with an accelerator. We need another way. Phenomena characterised by a high-energy scale do, in fact, happen naturally even at the lower energies of every day. But the higher is their intrinsic energy scale the more rarely they happen.

Underground laboratories, in particular the LSC, are dedicated to the search for these natural, but extremely rare, nuclear and subnuclear phenomena. This search requires very low radioactive background environment. Taking an analogy, we all have observed with astonishment and admiration the innumerable population of stars in the dark heavens of the night. But we don't see stars during the day, even if they are still shining. Starlight is much fainter than that sunlight. To be able to see the weak luminous signal from a star we need darkness, the absence of the strong "background" of the sunlight. Similarly we cannot hear the chirp of a cricket in the noise of a freeway, but we need silence. We cannot detect the signals of very rare nuclear decays in presence of the much higher natural radioactivity background. This background noise is due to cosmic rays, falling on the surface of the earth and to decays of radioactive nuclei present, in traces, in all materials. Deep underground, under the Tobazo Mountain, the cosmic ray flux is reduced by a factor of one hundred thousand.

Other scientific sectors can profit of the unique location of the underground infrastructures. Geodynamics has the possibility to measure extremely small changes in the stress of the rock deep inside the mountain, as those due to the passage of the Moon, and very small accelerations and velocities in the depth, as those due to very small seismic events.

Underground, the experiments are protected by the "noise" due to human activity and atmospheric phenomena present on the surface.

Biologists can look for very peculiar type of microorganisms living in the dark inside the rocks.

2 A BIT OF HISTORY

Canfranc is a village in the central Pyrenees, at 1195 m of altitude in the high Aragón valley at a few kilometres from France, connected to it through the Somport pass. The latter, "el Puerto de Somport", and Canfranc itself are part of the (Aragon's) Camino de Santiago.

In consideration of its position, which is strategic for the connection between Spain and France, important civil works were performed in the first decade of 1900 for the construction of a railway between the two Countries. At Canfranc Estación large civil and deforestation works were done to host a huge International Station (Fig. 2.1); a tunnel was excavated to reach the French side. It is 7875 m long, 4.75 m wide and 6 m high. The king of Spain, Alfonso XIII, inaugurated the railway in July 1928, between the two World wars. The train operation ended in March 1970, when an accident destroyed a bridge in the French sector, which was never repaired.

In 1985 A. Morales and the Nuclear and High-Energy Physics Department of the Zaragoza University, started a project for the exploitation of underground space in the dismissed train tunnel for possible low background experiments, protected from the cosmic radiation. Their first infrastructure is shown in Fig. 2.2. It consisted in a car, to which the reels had been changed to make it apt to move on rails, and a trailer containing the radiation detectors and the instrumentation to characterise the tunnel along its length.

The first laboratory was lodged in a pair of existing small service cavities on the two sides of the train tunnel at 780 m from the Spanish entrance. Both have been now refurbished and integrated in the new LSC and called Lab

Fig. 2.1. The Canfranc station

780 L and Lab 780 R. Each consists of a small hall (12 m^2) leading, through opposite stairs, to two tunnels, parallel to the main one, of a total length of about 70 m.

At the beginning of the 1990s the Spanish and French governments decided to excavate a road tunnel close and parallel to the dismissed train tunnel. The latter became a safety escape route, having the two tunnels being connected by a series of by-passes.

In 1994, taking advantage of these works, a new experimental hall, 118 m^2, at 2520 m from the Spanish entrance was excavated. The hall hosted in the following years a number of experiments, on dark matter and neutrino physics. Along the years more than fifty scientists from twelve institutions from eight countries have participated in the LSC Scientific Programme. Also this hall has been integrated in the new LSC, after refurbishment works. It is called Lab 2500.

The action of A. Morales continued further. Strong of the success of two decades of research and of his determination, he convinced the Spanish authorities to build between the two tunnels a new, still larger laboratory, with fully international standards and all the necessary underground services. The depth is 850 m under Mount Tobazo. The facility, now called Lab. 2400, was completed in 2006. However, one year later signs of rock instabilities started to appear and the laboratory was closed. The Zaragoza University performed a complete revision of the original project and the rock support structures necessary to completely guarantee the safety of the personnel and of the properties were installed.

Fig. 2.2. The first Zaragoza Laboratory at Canfranc

Figs. 2.3. Excavation works

3 STATUS

A Consortium between the Spanish Ministerio de Economía y Competitividad, the Government of Aragón and the University of Zaragoza manage the LSC.

The staff is small, 12 people, to cover the essential services: administration and secretariat, safety, prevention and installations, low background service, chemistry and clean room service, mechanics, electricity, informatics and support to physics.

The protocol of access with the Tunnel de Somport (Ministerio de Fomento) foresees the access to the LSC via the road tunnel, to which a bypass connects with a dedicated entrance leading to gallery 12, and the exit through the safety tunnel. Both actions are communicated via radio to the tunnel control.

The "experiments" in an underground laboratory are complex and sizeable structures, which are designed and built by "Collaborations" of scientists, all external in the case of LSC, belonging to Universities and scientific laboratories. Typically, several years of R&D are necessary, followed by a few years for construction and finally many years to collect the data.

A fully international Scientific Committee of nine renowned scientists, which meets twice a year, helps the management in the processing of the proposals and in the monitoring the development of the experiments. The following experiments have been approved to date: ANAIS, ArDM and ROSEBUD on dark matter, NEXT on neutrino physics and GEODYN on geodynamics. Two other projects are ancillary to experiments in other laboratories: BiPo for the SuperNEMO proposal at the Modane laboratory in France and SUPERKGd for the SuperKamiokande experiment in Japan. In addition, the CUNA proposal for an underground nuclear astrophysics facility is under discussion.

The total number of users in 2013 has been 281, from 20 countries.

LSC is presently run purely as a service to external users. As such up to now, and differently from similar scientific institutions, it does not have an internal scientific staff neither a programme of doctorate or post-doctorate fellowships. However, several PhD students belonging to the users groups work at their experiments not only in their sites but also at LSC. Six of them have reached the PhD degree in 2013.

Workshops and Conferences are organised at LSC. In 2013 LSC organised or hosted:

- the International Meeting of the NEXT Collaboration
- the third "Jornadas de Gerentes de ICTSs"
- the meeting of Grupo de Cristales Líquidos y Polímeros University of Zaragoza
- the School on "Neutrino Physics and Astrophysics", one of the European Doctorate Courses of the ISAPP (International School on Astroparticle Physics)

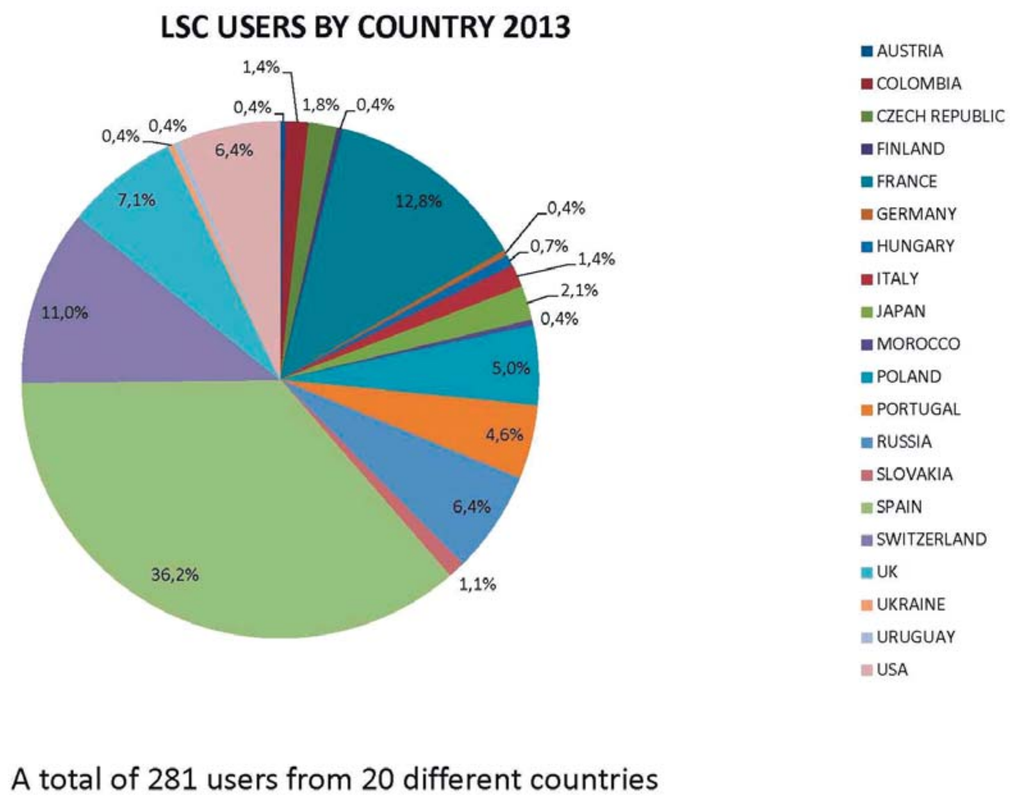


Fig. 3.1. LSC users by Country in 2013

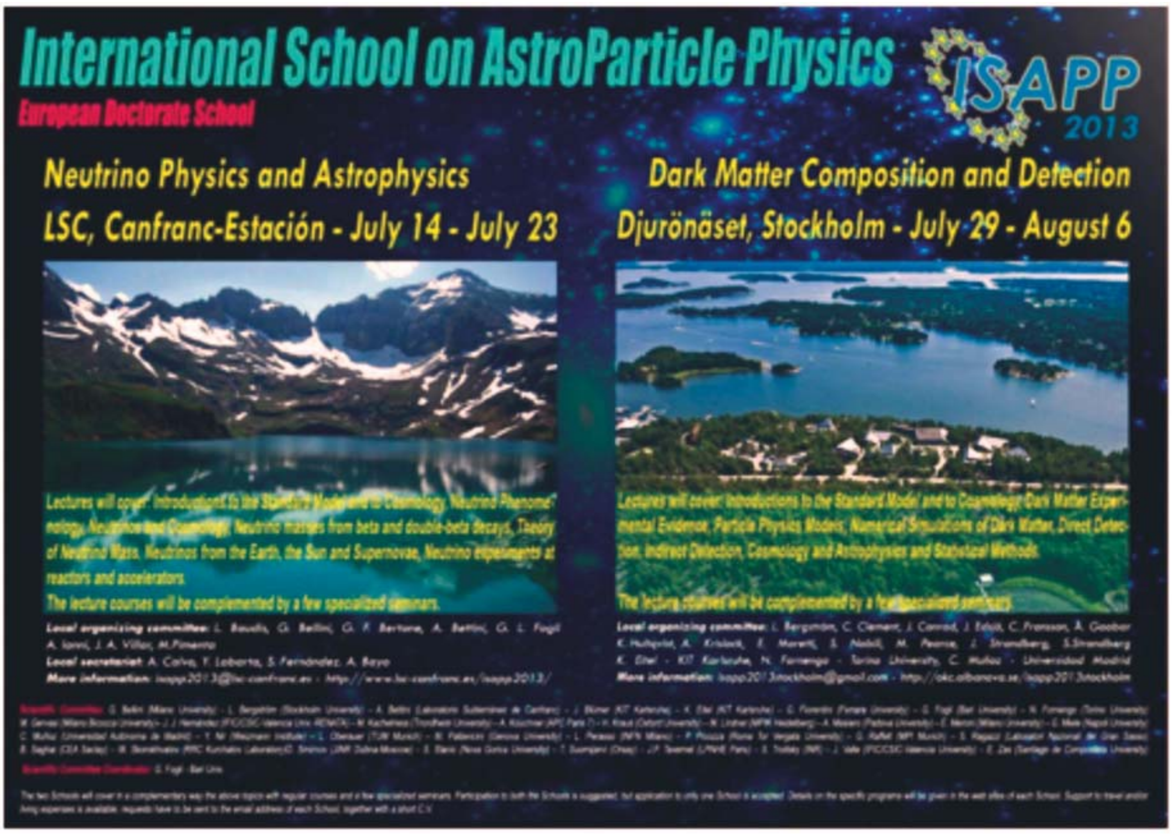


Fig. 3.2. The poster of the ISAPP School on Neutrino Physics and Astrophysics

The LSC is running a programme of visits, with almost 1100 visitors in 2013.

Overall, nearly 3000 people have visited the laboratory since visits started in 2010.

Numbers of visits at LSC in different years

4 INFRAESTRUCTURES

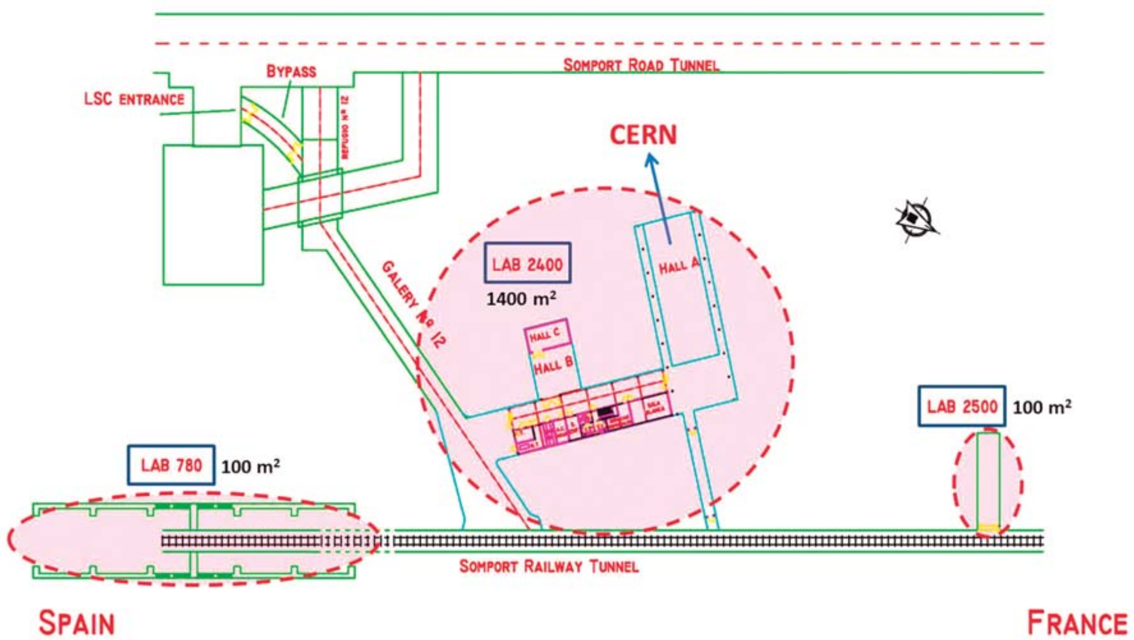


Fig. 4.1. Map of the underground infrastructures

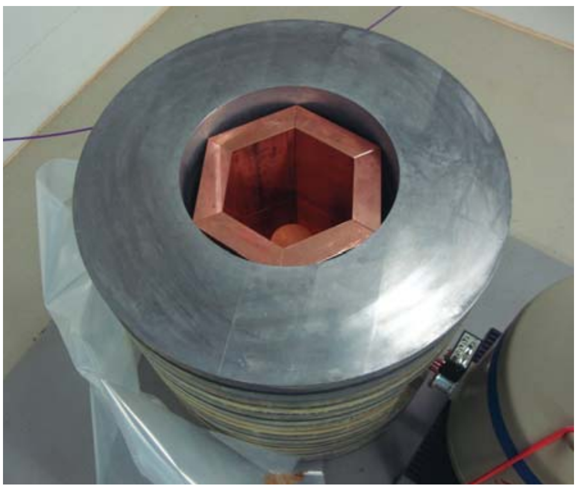
Fig. 4.1 shows a map of the underground infrastructures of Lab 2400. Hall A, measuring $40 \times 15 \times 12$(h) m^3, is shown in Fig. 4.2. The structure of ArDM can be seen on the right and the platform were NEXT will be installed at the end of the hall.

Hall B of $15 \times 10 \times 8$(h) m^3 hosts ANAIS and ROSEBUD in two separate huts as shown in Fig. 4.3.

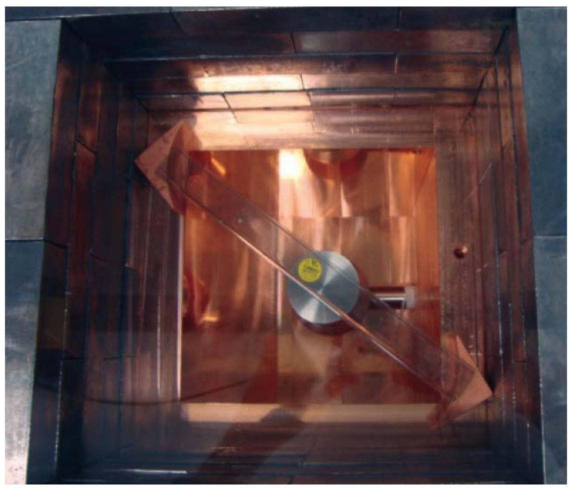
Fig. 4.2. Hall A

Fig. 4.3. The ANAIS & ROSEBUD huts at Hall B

Fig. 4.4. Hall C with the Ge counters



One counter while being mounted inside the copper and lead shields



Inside a Ge counter

The farther from the entrance part of Hall B, Hall C, is separated by a wall. It hosts seven hyper pure germanium counters with their lead and copper shields from the ambient radioactivity, shown in Fig. 4.4. The radiopurity service is open also to external users.

A further service is the underground clean room of 45 m^2 and Services for 215 m^2 shown in Fig. 4.6. It provides class 7 services, class 6 in a sector, both to the LSC experiments and external users.

An aisle was built perpendicular to the halls. It is divided horizontally in two parts: the left one connects the entrance to the halls; the right one has two floors, hosting the services (high and low tension, water treatment, technical gases storage and distribution, toilets, a small mechanical workshop, etc. and offices for the researchers).

Fig. 4.8 shows the Lab 2500, which lodges three more hyper pure germanium counters and R&D activities of the Zaragoza Nuclear Physics Group. More space is available for future experiments of external users.

The complex of underground structures, Lab 2400, 2500, 780 L and 780 R and the corresponding accesses correspond to a total area of about 1600 m^2 and a total volume of 10 000 m^3.

The surface building of approximately 1800 m^2 is shown in Fig. 4.9.

Fig. 4.6. The underground clean room

Fig. 4.7. The service aisle

Fig. 4.8. Lab 2500

Fig. 4.9. The service building on the surface

It hosts headquarters, administration, a library, offices (Fig. 4.10), a meeting room (Fig. 4.11), laboratories, storage areas and a mechanical workshop, safety structures and management.

Fig. 4.10. Inside the building

Fig. 4.11. Conference hall

The laboratories are specialised for electronics, informatics, physics and chemistry. The physics laboratory has been recently equipped with a counter of alpha and beta activity of small samples. The chemistry laboratory is equipped with a sophisticated copper electroforming facility developed at Zaragoza. The reason for that is the following. Copper is widely used a by the experiments to shield from the ambient gamma radiation. However, it usually contains very small traces of radioactivity itself. To avoid even those we have to build the copper structure "atom by atom" by drifting the atoms in an electrolyte. The process is called electroforming.

Surface and underground laboratories are linked with optical fibres lines. The high-speed connection to the Internet is provided by the Aragón Government, by means of radio bridges to the "Red de Investigación de Aragón".

Fig. 4.12. Electroformed pieces

5 CHARACTERISTICS

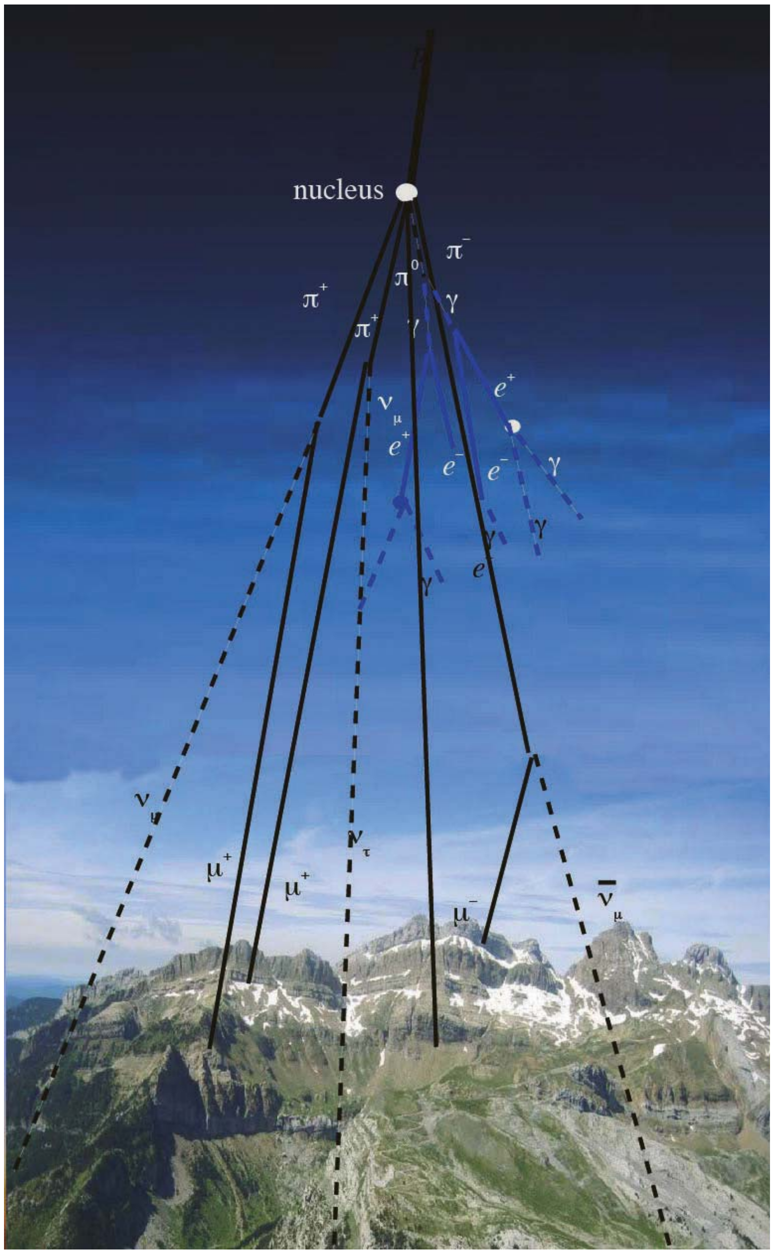
There are a number of characteristics of an underground laboratory that must be known and taken under control to allow proper design, planning and operation of the experiments.

In order to further increase safety, a dedicated structure of optical fibres to monitor continuously the rocks stability has been designed and is continuously working. It is made of 18 optical fibres, 5 m long with associated humidity and temperature sensors, measuring the distance between their extremes with a sensitivity of a few micrometres.

The Laboratorio de Bajas Actividades (LABAC) of the Zaragoza University, in collaboration with the LSC services, performs systematic radiological analysis of different samples of water collected in various positions of the underground and surface laboratories. The analyses are done via gamma spectroscopy and analysis of the total alpha and beta indices. Biological and chemical analyses are also performed.

Radioactivity is a natural phenomenon that has sources everywhere.

Cosmic rays are charged particles, mainly protons but also nuclei and electrons, coming from the universe and penetrating the atmosphere. In the atmosphere, hitting a nucleus, they may produce a cascade of unstable secondary particles. Deep underground only the most penetrating components survive. These are the almost invisible neutrinos and the muons. The latter are charged particles similar to electrons with a larger mass. The muon flux decreases, but does not disappear, with the rock overburden.



Not to scale artist view of a cosmic ray interaction in the atmosphere producing various primary and secondary particles. Neutrinos penetrate the rocks undisturbed, muons are gradually absorbed.

At LSC it is one hundred thousand smaller than on the surface. Muons have high energies, much higher than those of the nuclear decays.

Small quantities, traces, of radioactive isotopes are everywhere, in the rocks, in the water, in the air, and in our own bodies. Radioactive nuclei may decay in three main ways called α, β and γ decays, corresponding to the emission alpha particles (that are helium nuclei), electrons or photons respectively. Alpha particles emitted in the rocks and in the concrete are often captured by another nucleus, which is unstable and will decay emitting a neutron. In each case the energies are up to a few MeV (millions of electronvolt).

Radon is a radioactive noble gas coming from uranium and thorium in the environment, in particular the walls and the water. Several isotopes of the Rn decay chain are dangerous to the experiments. Some of them, which may be α, β or γ emitters, stick on the surfaces and may contribute substantially to the background. The Rn activity in the air, both on the surface and underground, has large fluctuation both periodic (daily, seasonal, yearly) and non-periodic. The Rn concentration underground depends also on the characteristics of the input duct and on the rate of air substitution. LSC input air system is ancillary to that of the freeway, exploiting the space between the pipes that bring air to that and the concrete lining of the corresponding civil structures. A 250 m long vertical pit takes the fresh air at Rioseta on the mountain. Rn activity was measured at a reference time as 15 Bq/m^3 at Rioseta and 38 Bq/m^3 at the bottom of the pit. To reach the LSC, the air further runs through a horizontal, 500 m long corridor. At the same reference

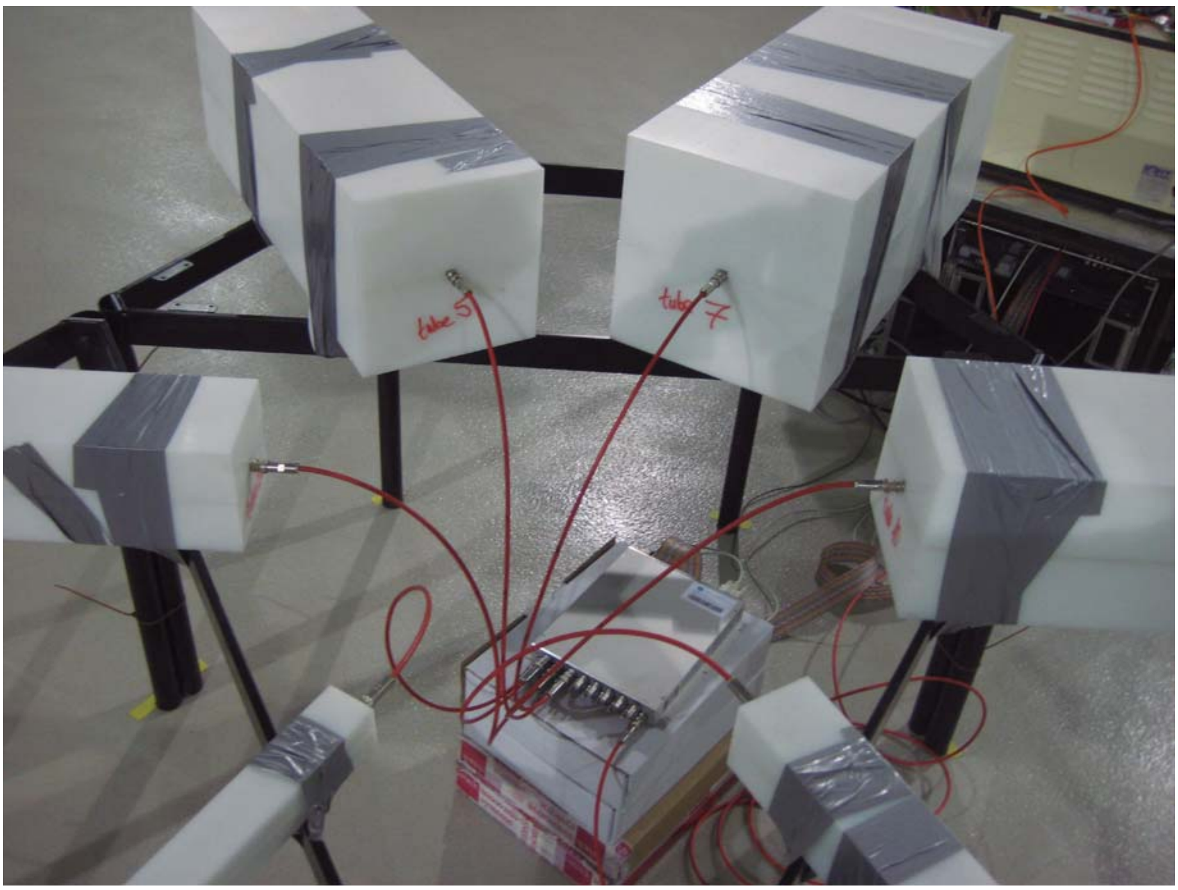


Fig. 5.1. Six ^{3}He proportional counters in Hall A (CUNA Collaboration)

time Rn activity was 70 Bq/m^3 at the LSC entrance. Systematic measurements showed that in the experimental halls Rn activity is equal to that at the entrance, indicating that there is no appreciable further contribution from Rn emanation from the surfaces, with a fresh air input of 11 000 m^3/h. The specific Rn activity inside the laboratory varies between 50 and 80 Bq/m^3.

The neutron background level underground is also smaller than at the surface, where is typically about 100 n/(m^{2}s) at sea level. The CUNA Collaboration has measured the neutron flux and energy spectrum in the range between 1 eV and 10 MeV. They used a set of six ^{3}He proportional counters (Fig. 5.1), of the set-up that will be mentioned in the CUNA chapter, inside polyethylene matrices of different thickness. In such a way the neutron background rate was measured simultaneously at different energy ranges. The total flux in the centre of Hall A resulted to be (3.44±0.35)x10^{-2} n/(m^{2}s), about thirty times less than on the surface.

These neutrons coming from the concrete of the wall wander in the halls making up a sort of very diluted gas. To have an idea, we have of the order of hundred neutrons in the total volume of Hall A. They are very few indeed, but enough to be dangerous for the experiments. Shields of neutron absorbing materials are built around the experiments for protection.

The gamma ray spectrum has been measured by the LSC low radioactivity service. Its total flux is 120 gammas/(m^{2}s). This is small, but, once more, experiments must build shields to

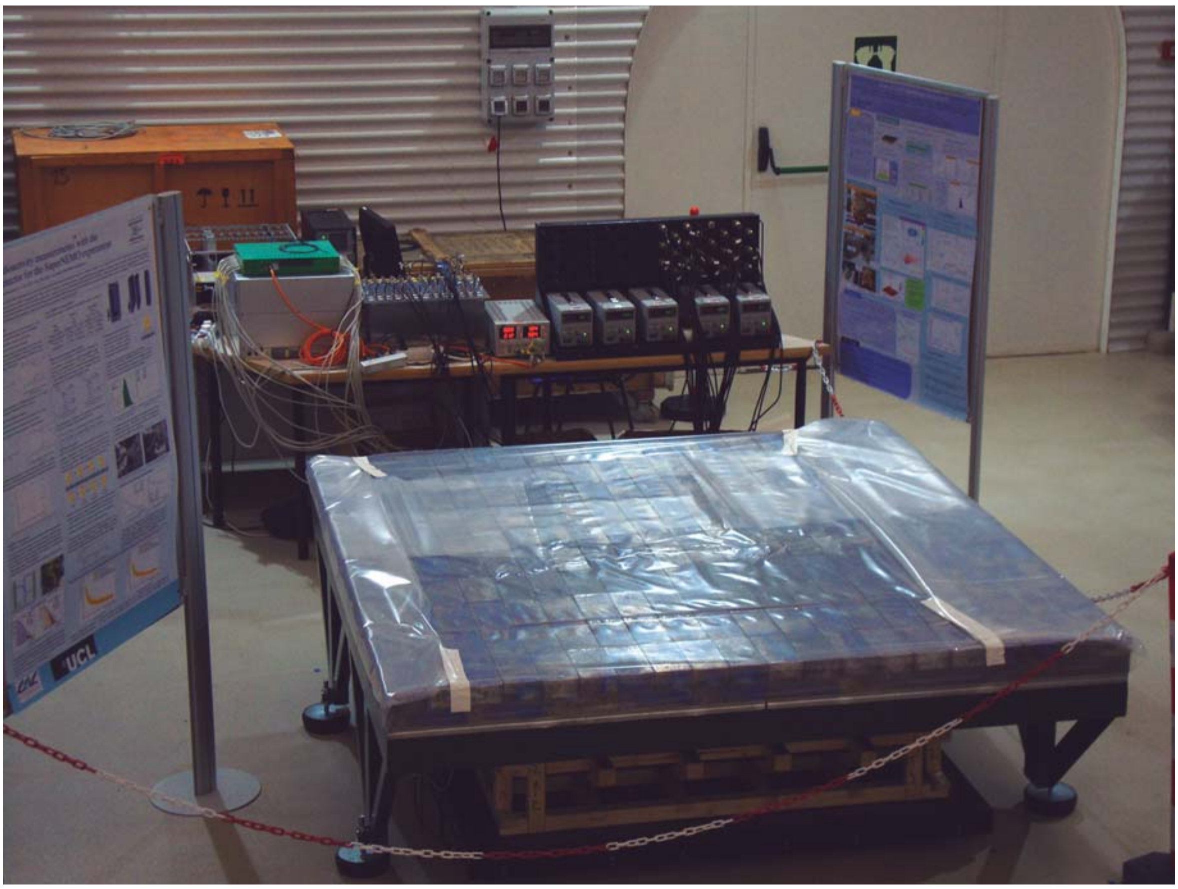


Fig. 5.2. Muon monitor

protect themselves.

The total muon flux integrated over the angles was measured to be $3\text{-}5 \cdot 10^{-3}$ m^{-2} s^{-1} in 2006, depending on the location. New measurement of the muon flux as a function of the angles is undergoing with a segmented telescope designed and built by the Moscow Institute of Physics and Technology.

Knowing the background fields, the experiments can design their shielding to reduce the background effects to acceptable values. However, the materials of the shields and of the experiments themselves contain radioactive traces. In practice every single component must be screened to determine any small trace of radioactive isotopes. The already mentioned low radioactivity service of LSC helps the experiments in this fundamental activity.

We can have an idea of the issue considering the following example. Our body is radioactive, but we live happily with it. Potassium (K) amounts to about 2 per mille of our body, hence a person of 70 kg contains 140 g of potassium. About one on 10 000 of the K nuclei are the ^{40}K isotope, which is radioactive. These 17 mg produce 44 Bq, meaning 44 decays per second. Of these 89% are β and 11% are γ. The body absorbs the former, while the majority of the latter radiate out. We emit about 5 gammas per second.

As a comparison, consider the ANAIS experiment, which is made of sodium iodine (NaI) crystals. If a dark matter particle would hit a nucleus this would recoil, ionising a few atoms and producing a small flash of light, which we can detect. However, potassium is chemically similar to sodium, which remains in traces in the crystal after chemical treatment. A fraction of the ^{40}K decays gives a flash of light equal to the searched one, a background signal we say. Consequently, the potassium traces in the crystal must be reduced at an acceptable level. This is one hundred thousand times smaller than the 2 per mille of the human body.

6 THE SCIENCE

The scientific programme of the LSC is mainly on astroparticle physics, dark matter searches, neutrino physics and geodynamics.

NEUTRINOS

The known elementary constituents of matter can be grouped in three groups, called "families". Each family is composed of two quarks, a charged lepton and a neutrino. The charged leptons of the three families are the electron (e), the muon (μ) and the tau (τ); the corresponding neutrinos are the electron-neutrino (ν_e), the muon-neutrino (ν_μ) and the tau-neutrino (ν_τ). We say that the pair of leptons of each family has electron-flavour, muon-flavour and tau-flavour respectively. Each particle, quarks, charged leptons and neutrinos have an antiparticle. The standard model assumes that neutrinos born with a flavour keep that forever. The conclusion was based on experiments done at accelerators with neutrino beams having lengths of the order of one kilometre.

Experiments in underground laboratories have studied neutrinos over much larger distances. Their sources are natural, rather than artificial: the interactions of cosmic rays in the atmosphere and the nuclear fusion reactions in the centre of our Sun. These experiments have shown that neutrinos change flavour if enough time is given them to do so. This phenomenon is called oscillation from one flavour to another and can happen only if the neutrinos have non zero masses. The oscillation times are so long because neutrino masses are small, much smaller than those of the other elementary particles. But neutrinos can give us other surprises.

As the electron has an antiparticle, the positron, so the antiparticle of the electron neutrino is the electron-antineutrino (and similarly the others). The charge of an antiparticle is opposite to that of its particle, i.e. electrons are negative and positrons positive. Even if they have no electric charge, in the standard theory, neutrinos and antineutrinos are assumed to be different particles, distinguished by the so-called lepton charge. But there is another possibility, outside the standard theory, i.e. that neutrino and antineutrino are one and the same particle, as originally imagined by Majorana in 1937.

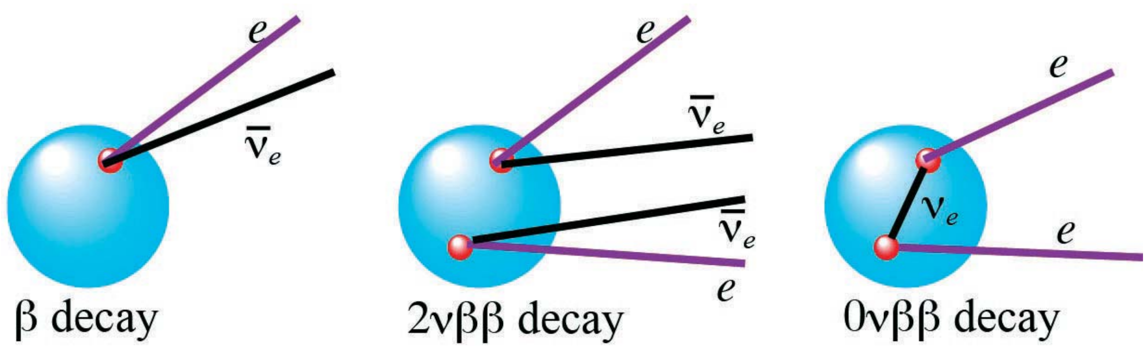


Fig. 6.1. a) Beta decay, b) 2νββ), c) 0νββ

How can we distinguish between the two possibilities? Several nuclei are unstable and experience beta decay. A neutron decays into a proton, emitting an $e^-\bar{\nu}_e$ (electron electron-antineutrino) pair. For some nuclei the beta decay is forbidden for energetic reasons but another decay path, the double beta decay (2νββ), is allowed. Two neutrons decay at the same into two protons emitting two $e^-\bar{\nu}_e$ pairs. The double beta decays have very long lifetimes, 10^{19}-10^{21} years, but are still a process foreseen by the standard theory. If the neutrino and antineutrino are the same particle another process is possible, the neutrinoless double beta decay (0νββ). Also in this case, two neutrons decay into two protons but only the two electrons are emitted. There is only one neutrino, which remains inside the nucleus, being exchanged between the two decaying neutrons. This is possible because in this case neutrino and antineutrino are the same. No experiment has reliably detected neutrinoless double beta decay, but limits have been given, which are in the range of 10^{25} years, namely 10^{15} times the age of the Universe.

How can we explore so long times? We can do that because the decays are statistical processes: if the half life is say 10^{25} yr one in 10^{25} nucleus would decay in a time of the order of one year. The experiments of the present generation aim to explore up to 10^{26} years. This means looking for a few events per year in a kilo-mole of substance, which is 6 x 10^{26} nuclei. Notice that we know exactly the energy released to the two electrons in the decay. We then measure the sum of the two electrons energies as accurately as possible. However, backgrounds are always present and can also simulate the signal. Extremely good energy resolution and extremely low background index are the necessary features for the search.

At LSC the NEXT experiment, presently under construction, will search for 0νββ of ^{136}Xe.

DARK MATTER

Enormous progresses have been done in elementary particle physics, in cosmology and in astrophysics, but we still do not know of what, for the largest fraction, the Universe is made of. About 68% of the mass-energy budget is made of something that accelerates the expansion rate. It acts as a pressure or energy pervading the vacuum. We call it dark energy, but we do not know what it is.

The remaining 32% is matter, but only 5% of that is luminous, the other 27% is invisible and called dark. This conclusion comes from many different observations at different epochs of the history of the Universe. One of them is the measurement of the rotation speeds of Galaxies. Newton's law tells us how the rotation speed of an object is related to the mass around which it is orbiting. So we can calculate the mass of a galaxy from the rotation speed of a gas cloud orbiting around it. We find that the masses of the galaxies are

Fig. 6.2. Collision of two clusters of galaxies, showing the presence of dark matter. Picture from NASA

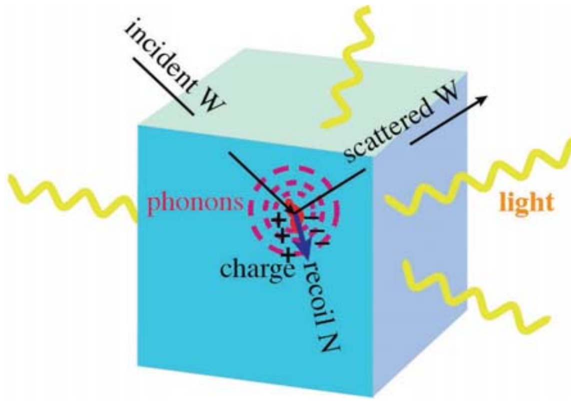


Fig. 6.3. Principles of WIMP detection

much larger than their luminous mass. Fig. 6.2 gives another example. It is a composite image of two clusters of galaxies that have just (on cosmic scale) crossed each other (bullet cluster). NASA made it (http://apod.nasa.gov/apod/ap060824.html) combining optical and X-ray observations, which give the "visible" matter and "gravitational lensing" observations that give the total matter. One sees that visible matter (red) slowed down interacting while crossing, while dark matter (blue) did not.

None of the known particles can explain dark matter. Dark matter particles have no charge and only weak interactions. In this they are similar to neutrinos. Neutrinos are indeed present in the Universe, but their mass is too small to contribute substantially to the budget. Dark matter particles must have bigger masses, but we do not know how big. We expect values between several GeV (the proton mass is about 1 GeV) and a few thousands GeV. They are generically called WIMPs, for "Weakly Interacting Massive Particles". A theoretical extension of the standard model, the supersymmetry, or SUSY for brief, does indeed foresee a good candidate of WIMP, the neutralino. The theory gives also indications on the neutralino interaction cross section (meaning probability to interact) with nuclei. It should be very small, like for neutrinos, but how small we do not really know.

If WIMPs exist they should fill our Galaxy, and the Earth should sail through them while moving in its orbit. To detect them we use materials such as a crystal (as ANAIS) or a liquid (as ArDM). When, very rarely, a WIMP hits a nucleus, this recoils and we try to detect the energy it releases to the medium. The recoiling nucleus will ionise some atoms, producing free charges (electrons), excite other atoms, which will emit light (photons), or produce vibrations of the crystal (phonons). In our experiments we try to detect those secondary particles. However, any small trace of natural radioactivity may produce similar effects and sophisticated techniques must be developed to distinguish this background from the signal.

There are two basic strategies. The most commonly followed is to build the experiment in such a way that the background is reduced to zero in the experimental window. This is achieved by measuring the radioactive traces in all the components of the experiment, before assembling them, and developing a "background model" by numerical simulation. A period of data taking follows providing a certain "exposure", which is the product of the sensitive mass by the exposure time. Our background model foresees zero background events. If we see no events, we conclude that there is no signal and we can put limits on the cross section as a function of the WIMP mass.

The second approach searches for a characteristic signature of the WIMP signal. Our detector moves in the Galaxy with the Earth, in the WIMPs "sea". The Earth velocity in the Galaxy varies during the year. In June the Earth's movement in its orbit is in the same direction of the velocity of the Sun in the Galaxy. Consequently the Earth velocity relative to the Galaxy is maximum. It is minimum in December when the two velocities are opposite. As a consequence, the WIMP interaction rate should vary periodically over the year with maximum in June. The modulation is only several per cent, but should be observable. This signature looks to be a powerful means to distinguish the signal from the backgrounds. Unfortunately, however, several ambient parameters, like Rn activity and humidity, have also annual periodicity.

GEOLOGY

The LSC is located at depth in one of the most seismically active areas in Western Europe, at the Pyrenean chain that marks the boundary between the European plate and the Iberian microplate. Besides, the underground tunnel environment ensures a very low level of noise perturbations, either of natural or cultural origin. In addition, the dismissed train tunnel and several service tunnels give opportunities to have access to underground rocks.

HYDROLOGY

Rain water and water from snow melting gradually penetrate deep inside the mountains and sooner or later exit to the rivers. Looking to these phenomena from deep underground offers a unique opportunity to hydrologists.

BIOLOGY

Life is present practically everywhere on Earth, including environments in which it develops under extreme conditions, in particular deep underground. One can try to answer questions like:

- How deeply in the earth does life extend?
- What makes life successful deep under the surface?
- What can life underground teach us about how life evolved?

The LSC and the nearby service tunnels, some of which have been dismissed from human activity, can offer access to search for "dark life" in the bulk of the rocks. For example new groups of bacteria (phyla) have been discovered deep underground in the Henderson mine in Colorado in 2006.

7 ANAIS

http://gifna.unizar.es/anais/

ANAIS is a project to search for dark matter looking for the annual modulation of the counting rate expected as a characteristic signature of dark matter. As a matter of fact, the only experiment that has reported positive evidence so far is DAMA/LIBRA at LNGS. The evidence has never been confirmed by experiments with much larger sensitivity. However, this apparent contradiction cannot be considered definitive, because different techniques and different target nuclei have been employed. A confirmation or confutation of the DAMA/LIBRA positive result can only come in a model independent way by using similar detectors, namely NaI scintillating crystals, in extremely low background conditions. ANAIS aims at using an array of up to 250 kg of such detectors.

Along 2012 a prototype crystal, called ANAIS-0 (9.7 kg), grown by the Saint Gobain Company and encapsulated at the University of Zaragoza, was in operation at the LSC. The main goal was the setting up and tuning of the shielding, electronic chain and acquisition and analysis software for ANAIS. A new electronic chain based on the VME and NIM standards was installed in 2012. New data acquisition software was tested and the corresponding analysis software was developed and adapted to the new acquisition format while keeping the previously developed protocols and analysis parameters.

Very important progress was achieved in the development of strong filtering protocols to remove anomalous events in the low energy region, in the understanding of the radioactive backgrounds in ANAIS-0 and in the building of a background model able to reproduce the measured background. Results derived from the ANAIS-0 data taking were published and presented in important international and national conferences.

Particularly important for ANAIS are the potassium traces in the NaI crystals that must not be larger than 20 ppb (parts per billion). Crystals are grown from a NaI salt powder, which has to be screened as a first step. A sample of powder produced on purpose by Alpha Spectra Inc. (AS) was measured in the radiopurity service of LSC between October 2011 and January 2012. The potassium content was found below the sensitivity limit of the Ge counter, namely <90 ppb. Two crystals, 12.5 kg each, were then ordered to AS, to determine the potassium content, with increased sensitivity, by the identification of the ^{40}K decay by the coincidence method that we shall mention. Growing and encapsulation protocols were suggested by the Zaragoza group and accepted by the AS company.

By May 2012 both crystals were grown and the encapsulation started in the Colorado facilities of AS. Final dimensions of the crystals were 4.75" in diameter and 11.75" in length. They were encapsulated in Oxygen Free High Conductivity (OFHC) copper and designed to have a Mylar window in order to allow low energy calibrations. In October 2012 encapsulation procedure finished and the detectors were sent to the LSC by surface transportation, rather than by flying, in order to minimize activation induced by cosmic rays. They were received at the end of November 2012 and installed almost immediately, after coupling them to the photomultipliers (PMTs) in the LSC clean room. The available shielding, electronic chain and acquisition software from ANAIS-0 were used. Data taking started in December 2012. We will refer to this set-up as ANAIS-25.

In parallel, 42 PMT units were ordered to Hamamatsu and the 25 electronic modules required to complete the electronic chain for the 20 modules experiment. The PMT model finally chosen shows excellent performance in quantum efficiency and low radioactive background, according to results derived with ANAIS-0.

The main goal of the ANAIS-25 set-up was to carry out a measurement of the ^{40}K bulk content of the AS NaI crystals, as well as a general background assessment of the modules. The 40K content was determined using the coincidence between the gamma line at 1461 keV in one detector and the X ray at 3.2 keV in the other, a signature characteristic of the isotope. The conclusion was a 40K specific activity of 1.25 ± 0.11 mBq/kg corresponding to 41.7 ± 3.7 ppb of potassium. This result means an improvement of an order of magnitude with respect to ANAIS-0 and it is very close to the ANAIS goal of 20 ppb potassium.

Other radioactive traces that are alpha emitters contribute to the background. Alpha events appear in the higher energy part of the spectrum. A specific digitization line was developed, and used in parallel to the standard electronics chain, for better identifying the alpha events by Pulse Shape Analysis. The total alpha rate in both crystals is about 280 kg^{-1} day^{-1} (3.15 mBq/kg). This value is much higher than that of ANAIS-0 prototype and is an important drawback for reaching ANAIS background goals. This high alpha rate could be due to contaminations of ^{222}Rn during growing or machining of the detectors. After a few weeks, only ^{210}Pb would remain. Conversations with Alpha Spectra about the possible origin of the high ^{210}Pb - ^{210}Po contamination started very soon after its discovery. As a result, a new 1 kg bare crystal was ordered and soon delivered to analyse the evolution of the alpha rate and to try to

Fig. 7.1. Two NaI detectors being installed in their Cu and Pb shields

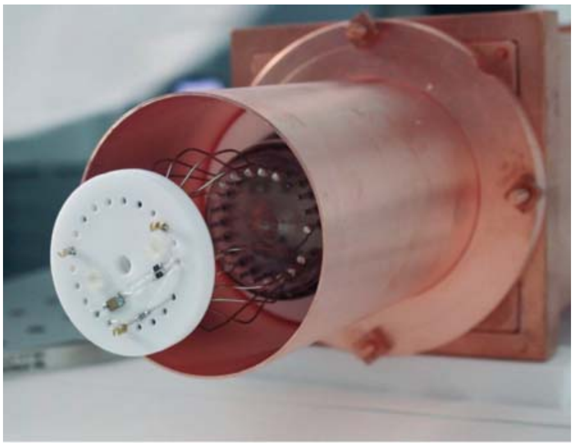


Fig. 7.2. The photomultiplier inside the copper housing, after coupling to the NaI crystal

Fig. 7.3. Working on a NaI detector at LSC clean room

determine the origin of the contamination. The rate was found to increase with time, showing that equilibrium in the decay chain has not yet been reached. The detector was mounted at the University of Zaragoza and installed at the LSC in August 2013. Work is still in progress.

The number of photoelectrons per unit of deposited energy (phe/keV) was measured, with a preliminary result of about 15 phe/keV. This excellent value is attributed to the much better optical coupling between crystal and quartz windows in the ANAIS-25 modules and the excellent optical quality of the crystal. The trigger efficiency was evaluated with the 3.2 keV tagged events from ^{40}K. Most of the events attributable to ^{40}K decay triggered our acquisition: 99% of the events above 1.5 keV in one crystal and more than 97% in the other. This result points at the ability of ANAIS to lower the energy threshold below 2 keV.

Other work is in progress, and new results are expected to be delivered soon. In August 2013 the first five units of the selected PMTs were received at LSC for radiopurity screening. A layer of plastic scintillator counters was installed in summer 2013 all around ANAIS-25, to detect penetrating muons. Events seen in ANAIS-25 in temporal coincidence with a muon will be "vetoed" to avoid the interference due to the latter. The long life scintillation in NaI(Tl) crystals has been studied. Results of the activity have been published in international journals and presented in the most important conferences of the sector.

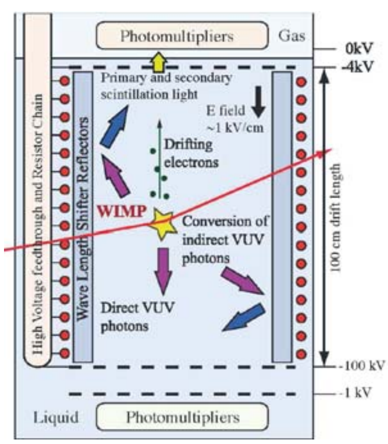
8 ARDM

http://www.ipp.phys.ethz.ch/research/ArDM

The ArDM (Argon Dark Matter) Experiment aims at direct Dark Matter search based on a ton-scale liquid argon (LAr) double-phase time projection chamber (TPC). Elastic scattering of Dark Matter particles (hypothetical WIMPs) off target argon nuclei is measurable by observing photons from scintillation and free electrons from ionisation, which are produced by the recoiling nucleus interacting with neighbouring atoms. The ArDM detector is designed to measure both signals in its double-phase (liquid-vapour) TPC operation mode. The ionisation electrons, produced in the liquid, drift up to the liquid surface and are extracted into the saturated argon vapour above the liquid, thanks to strong electric fields of the order of one thousand volts per centimetre (this requires a very high voltage of ~100 kV in the system). The extracted electrons further interact with argon gas atoms producing secondary scintillation light (S2). Its intensity is proportional to the charge. The S2 light is detected by photomultipliers (PMTs) and gives the ionisation charge. The primary scintillation light (S1) is recorded promptly by the same PMTs. The time interval between S1 and S2 (the electrons drift time) is proportional to the distance from the event vertex to the liquid surface, and is used to know precisely the vertical coordinate of the event. The two horizontal coordinates are reconstructed from the distribution of the S2 photons falling onto the two-dimensional PMT array. Full 3D position information is so obtained. This working principle of the ArDM detector is sketched in Fig. 8.1, with a diagram of argon scintillation processes.

Due to the very small WIMP-nucleus interaction cross-section very rare events are expected. Typical kinetic energy of recoils is in the range of 10–100 keV. The signal is therefore quite elusive and requires an experiment in a deep underground location such as LSC. Besides, very good background discrimination capabilities and good detector shielding are indispensable.

Noble liquids such as argon and xenon are two of the best options for large-size Dark Matter experiments because they have high



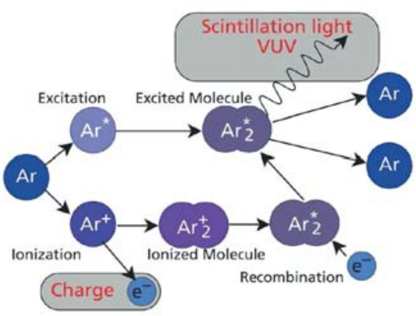


Fig. 8.1. Principles of the liquid Ar two-phase TPC

scintillation and ionisation yields that are essential for the detection of such low energy events and they are commercially available in large quantities, so that ton-scale detectors can be conceived. These provide simultaneously detector mass and self-shielding against external sources of background, two features essential for the detection of rare events. Our choice of argon as target material was motivated by the following arguments.

1. The event rate in argon is not very sensitive to the recoil energy threshold (the minimum detected one) due to finite nuclear sizes (on the contrary, for xenon the event rate is reduced at high recoil energies). To understand the orders of magnitude, assume a standard distribution of WIMPs in the Galaxy and consider typical values of 100 GeV for the WIMP mass and 10^{-44} cm2 for the WIMP-nucleon cross-section. With energy threshold of 30 keV the rate on argon is one recoil event per day per ton of argon.
2. Argon is much cheaper than any other noble gas. Consequently, an even larger (multi-ton) scale detector that might be required for the future is conceivable.
3. The scientific relevance of obtaining data with both argon and xenon is given by the fact that recoil spectra are different, providing an important crosscheck in case of a positive signal.
4. The charge to light ratio and the pulse shape of the S1 signal provide efficient discrimination against gamma and beta electron recoil backgrounds.

An important aim of ArDM thus is to demonstrate the feasibility of an argon-based ton-scale experiment with the required performance to efficiently detect WIMP induced nuclear recoils and sufficiently discriminate backgrounds for a successful WIMP detection.

A one-ton ArDM prototype initially was built on surface at CERN (Geneva, Switzerland) and was operated successfully in cryogenic (−186°C at 1 bar) liquid argon. The vacuum and cryogenic infrastructure, the detector control and the data acquisition systems were then transported to LSC in February 2012 and installed underground in Hall A.

In Fig. 8.2 a picture of the ArDM installation is presented. The blue platform built for the installation, the cryogenic vessels and the polyethylene neutron shield structure (white) can be seen.

For a safe underground operation ArDM has a full control system, which monitors and regulates actively the different subsystems of the experiment. The control system is based on a programmable logic controller and is integrated in an array of seven racks as shown in Fig. 8.3. It monitors all the pressures, temperatures and liquid argon levels in the ArDM detector and its cryogenic system. It also regulates the vacuum system, the cooling of the liquid argon, the argon purification and the power supply of the high voltage generator.

In February 2013 the upgraded ArDM detector with a new light readout system was installed at LSC. A picture of the new detector

Fig. 8.2. ArDM experimental structure

Fig. 8.3. The ArDM control system

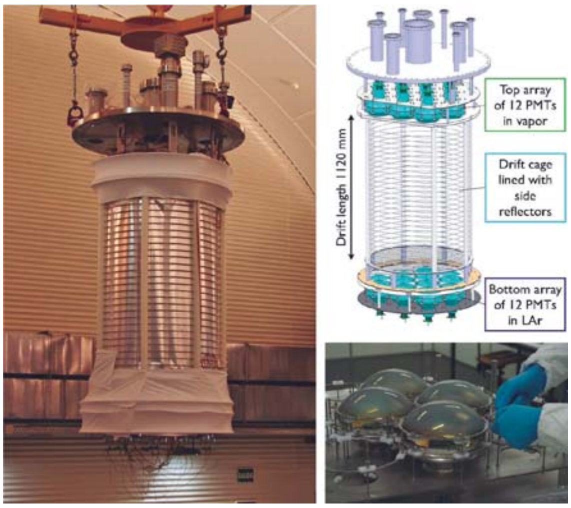


Fig. 8.4. Components of ArDM

hanging on the crane in Hall A, being installed into the detector vessel, is shown in Fig. 8.4 together with its drawing and a close-up view of one of the PMT arrays. The new detector has total of 24 cryogenic 8-inch PMTs in two arrays, one in the vapour phase above the target/drift volume (called "drift cage") and the other below immersed in liquid argon. The PMTs are not sensitive directly to the scintillation light in argon, which is far in the ultraviolet (λ=128 nm). The light wavelength is shifted up to become detectable by coating the windows in front of the PMTs and the reflectors on the side of the volume with a chemical that absorbs ultraviolet photons and re-emits blue light (around λ=430 nm).

The detector is in the commissioning phase and a number of measurements have been done using argon gas at room temperature as the detection medium, showing good detection efficiency of the light readout system to the argon scintillation light as expected.

The ArDM data acquisition system also was upgraded during the year 2013. The new system is capable of handling a kHz-scale event rate that is expected in LAr, and can record data at a rate of ~300 MB/s. A new data storage system involving 192-TB hard disk is to be installed at LSC for physics data taking at this high data rate.

Substantial efforts have been undertaken also on the software for the physics analysis. Fully functioning data analysis framework has been developed and also a Monte Carlo simulation programme, involving the full detector geometry and all the physics processes. ArDM is ready to analyse physics data as soon as available.

Like many other LSC experiments, control and screening of neutron background is a critical issue for ArDM. For this purpose a systematic material screening campaign is actively being pursued at LSC, thanks to the strong support from the laboratory. Radioactivity of different detector components is being measured using the germanium facility of the underground lab. In addition, an in-situ neutron background measurement in Hall A of LSC has been started.

The ArDM Experiment is now fully ready for the first cryogenic liquid Ar operation and is in the process of a safety review by LSC regarding, in particular, the use of a large quantity (~2 t) of cryogenic liquid argon underground. After a successful commissioning and a full characterisation of the system during the first cryogenic operations, physics data taking for dark matter search is expected to start during the year 2014.

The ArDM Collaboration is composed of scientists from: ETH Zurich (Switzerland) and CIEMAT (Spain).

9 ROSEBUD

http://www.unizar.es/lfnae/rosebud/

ROSEBUD is a collaboration, between the Institut d'Astrophysique Spatiale (France) and the University of Zaragoza (Spain), which started in 1998. It was dedicated to the development optimization and characterization of scintillating bolometers to be used in nuclear and astroparticle physics experiments. Since 2006, both institutions are members of the EURECA collaboration, a large European effort in dark matter search, whose goal is to combine different detection techniques and target materials with a modular design in a unique low background cryogenic setup scalable up to 1 t total target mass. ROSEBUD has completed its programme in 2012 and proceeded with the decommissioning of the experimental set-up at LSC in March 2013.

A bolometer is a device operating as a calorimeter to measure the energy deposit produced by the interaction of a particle (a nucleus recoiling after having been hit by a WIMP, an electron ejected from its atom by a photon, etc.). It consists of a crystal (absorber), thermally coupled to a thermal bath, and a thermal sensor glued on it. It measures the energy deposited in the absorber through the corresponding temperature increase. This is so small to become observable only at extremely low temperatures, near absolute zero. That technique requires the use of a complex cryogenic system, including a dilution refrigerator, to reach temperatures down to 10-20 mK. Bolometers have many applications as particle detectors because, apart from their excellent performance (good energy resolution and very low energy threshold), this detection technique also offers a wide material (absorber) choice.

ROSEBUD has been a pioneer in the development of scintillating bolometers, in which also scintillation light is produced and detected. The contemporary detection of heat and light gives an excellent power to discriminate nuclear recoil from background. Scintillating absorbers are mounted in a double bolometer configuration to simultaneously measure the heat and t h e light. The second bolometer is a thin Ge disk (tens of micrometres in thickness) with the corresponding thermal sensor glued on it. Scintillation photons are absorbed on the disk.

The scintillating bolometers of ROSEBUD were produced and tested at the Institut d'Astrophysique Spatiale and mounted inside a copper frame thermally coupled to the mixing chamber of the refrigerator. The good performance detectors were moved and tested at Hall B of the LSC (until 2008 measurements were carried out at Lab 2500) in an ultralow radioactive background environment. The experiment was lodged in

Fig. 9.1. A scintillating bolometer. The light produced in the scintillating crystal (right) is absorbed in the Ge disk (left)

a hut acoustically isolated and vibrationally decoupled, which contains a 3x3x4.8 m^3 Faraday cage to avoid electromagnetic interferences. A shield from the environmental radioactivity surrounded the dilution refrigerator in the Faraday cage. The full shield consisted of, from inside to outside, 25 cm of Pb bricks, a 1 mm mu-metal foil, a PVC box sealed in which liquid nitrogen vapour was flushed to remove airborne radon and 40 cm of polyethylene for neutron shielding.

Scintillating bolometers have many applications in nuclear and astroparticle physics. The most relevant results of ROSEBUD are the following.

Dark matter. Scintillating bolometers are used in experiments for direct detection of dark matter profiting of the wide absorber choice and background rejection capability. ROSEBUD has carried out the first dark matter search based on light versus heat method with a $CaWO_4$ scintillating bolometer. It has also developed and tested detector prototypes of Al_2O_3 and BGO obtaining excellent performance. These materials could be incorporated as targets in the EURECA project. In addition, the light and heat response to nuclear recoils of several materials have been measured.

Neutron detection. ROSEBUD has developed and tested scintillating bolometers of LiF and ^{6}LiF that can be used to monitor the neutron flux inside the experimental shielding of a cryogenic dark matter experiments like EURECA through the resonance of the ^{6}Li(n,α) reaction.

In addition, several other measurements of very low level radioactivity have been performed: limits to natural α radioactivity of tungsten, measurement of the L/K electron capture ratio of ^{207}Bi and of the energy partition among heat, light and traps produced in the interaction of radiation with matter in several materials.

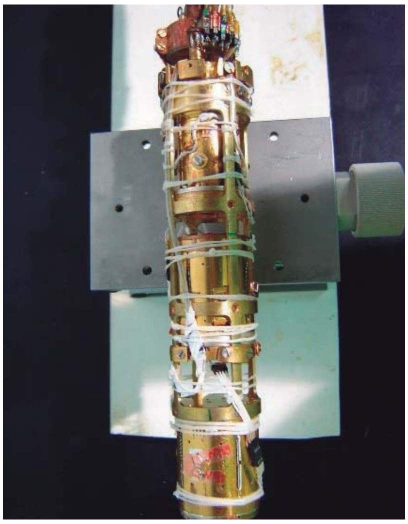


Fig. 9.2. Three scintillating bolometers mounted inside a copper frame thermally coupled to the mixing chamber of the dilution refrigerator

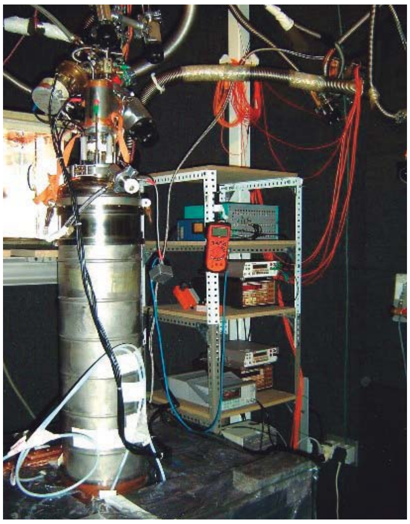


Fig. 9.3. Gas handling and pumping system for the dilution refrigerator

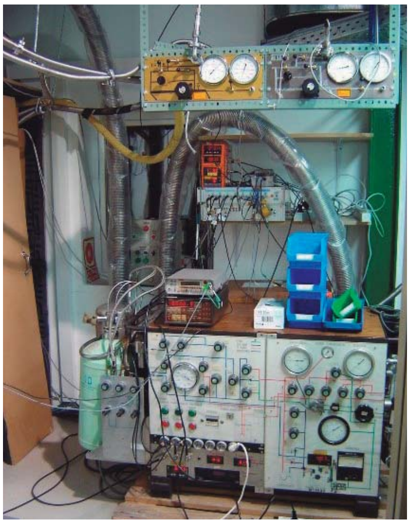


Fig. 9.4. The dilution refrigerator inside the Faraday cage with the shielding partially mounted

10 NEXT

http://next.ific.uv.es/next/

The NEXT experiment has the aim of detecting neutrinoless double beta decay (0νββ) in xenon gas, enriched in the isotope $Xe^{-136,}$ the one that decays double beta. The signature of such a decay is a peak in the distribution of the energy released by the two electrons in the decay, which must be constant, since no neutrinos are present to carry away part of the total energy. Thus, a good 0νββ experiment must be able to measure energy at a great level of resolution and have the capability of rejecting those background events with almost the same energy as the electrons of the decay.

NEXT consists of a high-pressure time projection chamber, that is, a vessel full of 100 kg of xenon gas at 15 bar, in which an electric field is applied, and of two different sensor planes. These are used one to measure the energy and the other to provide a "picture" of the event. Fig. 10.1 shows the principle of detection.

When a charged particle enters the gas, it releases its energy interacting with the gas molecules in two ways. On one hand, the molecules pass to an excited state and then go back to their normal state by emitting light, in the range of the ultraviolet wavelengths. This light (called scintillation) is registered by the sensors on one side of the detector and gives the starting time of the event. These sensors are photomultipliers, that are devices capable of converting light into electric current. On the other hand, the energy released by the particle can also extract electrons from the xenon atoms, through the ionization phenomenon. These electrons are drifted by the electric field all the way through the drift region until they enter a region of moderately higher field where they are accelerated and secondary scintillation (but not ionization) occurs. This process results in an amplification of the signal, which grows linearly with the electric field. The photomultipliers detect this secondary light, giving a precise measurement of the energy of the event. On the opposite side, the distribution of the light on another, denser array of silicon photomultiplier is, in every moment, a 2D picture of the event

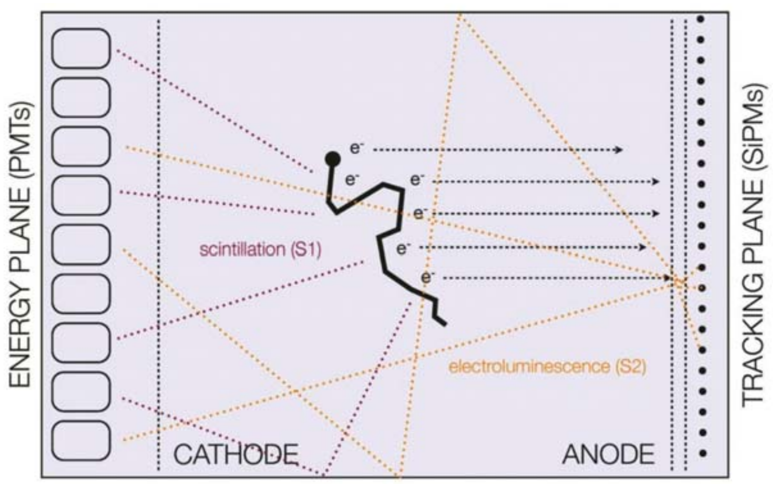


Fig. 10.1. The NEXT detection principle

Fig. 10.2. The NEXT-DEMO prototype at the IFIC Valencia

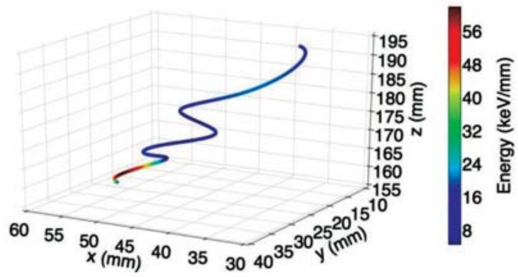


Fig. 10.3. An electron track reconstructed by NEXT-DEMO

at a given position along the axis. Knowing the starting time of the event, the absolute position along the chamber axis can also be reconstructed.

This novel concept meets the essential requirements of a $0\nu\beta\beta$ experiment mentioned above. As far as concerns the energy resolution, the fluctuation in the quantity of ionization electrons produced and secondary scintillation light are very low. On the other hand, in xenon at 15 bar it is possible to take advantage of the topological signature of the event: the two electrons of $0\nu\beta\beta$ leave a track with almost constant energy deposition and two big "blobs" of energy at the ends, caused by the more twisted walk that the electrons follow when they have low energy left. This signature is an excellent instrument for background rejection.

From 2009 to today an intense R&D program has been carried out by the Collaboration.

The feasibility of the technology has been demonstrated with the NEXT-DBDM and NEXT-DEMO prototypes, which have shown the excellent performance (energy resolution, electron reconstruction) of the apparatus, as well as the robustness of the EL technology. NEXT-DEMO has had the aim of testing the instrumental concept of NEXT: it is a chamber with the same proportions in size as the final NEXT detector, and holds 4 kg of natural (non-enriched) xenon at 10 bar. In Fig. 2, the detector inside the clean room is shown. NEXT-DEMO has been operating successfully for more than two years and has demonstrated (see Fig. 3):

a. operation stability, with no leaks and very few sparks, even at high voltages

b. energy resolution better than 1% once extrapolated to the energy of the $0\nu\beta\beta$

c. capability of reconstructing tracks.

In July 2013 the spokesperson of NEXT has obtained an Advanced Grant of the European Research Council (ERC). The LSC Scientific Committee has recommended that a first-phase of the NEXT detector, deploying 20 % of the sensors of the final apparatus is installed and operated at the LSC, with the double target of assessing the NEXT background model from the data themselves, and observing (measuring) the mode with two neutrinos double beta decay, which will allow a clear demonstration of the unique NEXT topological signal (observation of two electrons). As a consequence, the collaboration has decided to deploy a first stage of the NEXT detector, the NEW (NEXT-WHITE) apparatus (the name honours the memory of Professor James White, recently deceased and one of the key scientists of the NEXT Collaboration). According to our schedule, the construction of NEW, as well as the completion of the needed infrastructures at the LSC (which are the same for NEW and for the final apparatus, NEXT-100) can be carried out over a period of 12--15 months.

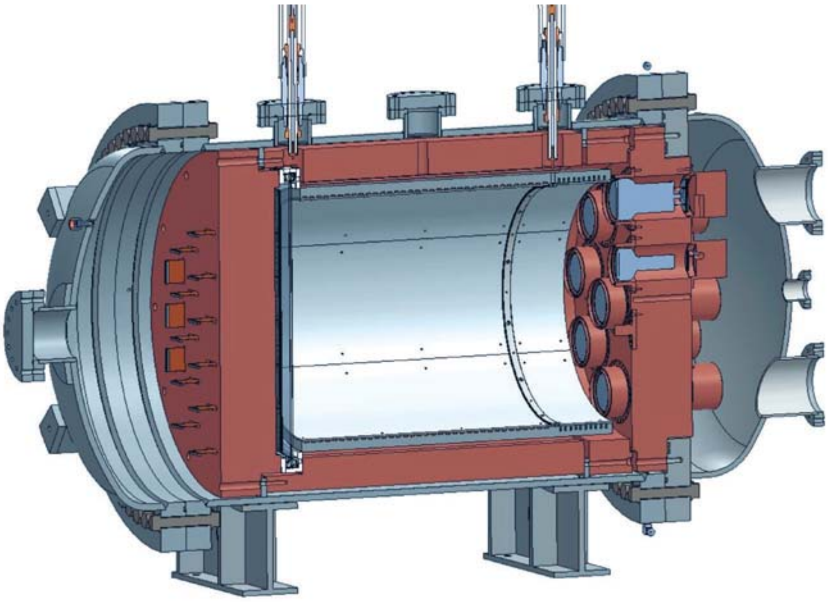


Fig. 10.4. The NEW chamber

It is therefore foreseen to commission and take data with NEW during 2015 and 2016, in parallel with the construction of the NEXT-100 detector. A scheme of the NEW detector is shown in Fig. 10.4.

Neutrinoless double beta decay, if it exists, is an extremely rare event, with a half-life greater than 10^{25} years. In order to be able to measure it, an experiment needs to shelter the detector from all the possible radiation that could produce a signature similar to the signal one. For this reason, NEXT is placed underground at LSC, where the earth itself blocks most of the cosmic radiation. Moreover, the materials used to build the detector must be extremely radiopure, in order not to introduce further radiation that can be confused with a double beta decay.

The installation of the NEXT final detector at LSC started in late 2012. The working platform has been put in place, as well as the gas system. During 2013 the seismically insulated central part of the platform, which will support the detector and its shield, has been designed together with the "castle" that will host the shield. These structures have been tendered and are under construction. They are expected to be ready in the spring 2014. The shield will consist of pure Pb bricks externally and pure copper, which is less radioactive then Pb, internally.

A screening campaign of all the materials to be used in NEXT is being performed by the LSC service, measuring the activity of each sample by means of germanium detectors.

The stainless steel vessel has been manufactured in Madrid, by the Spanish company Movesa, and has been delivered at LSC. The other components (the structure that creates the electric fields, the energy plane, the tracking plane, the feedthroughs...) are being designed and built by different parts of the NEXT Collaboration

The NEXT Collaboration is composed of scientists from: Universidad Antonio Nariño (Colombia), Universidad de Aveiro and Universidad de Coimbra (Portugal); JINR (Russia); IFIC - Instituto de Física Corpuscular, Valencia; Universidad Autónoma de Madrid; Universitat de Girona; Universidad Politécnica de Valencia, Universidad de Santiago de Compostela and Universidad de Zaragoza (Spain); Iowa State University, Lawrence Berkeley National Laboratories, Texas A&M University (USA)

11 BiPo

SuperNEMO is an experiment on $0\nu\beta\beta$ proposed for the future extension of the Modane underground laboratory (LSM) in France. The project foresees a source of 100 kg of ^{82}Se in the form of very thin foils. The electrons will be detected with gas detectors on the two sides of the foils, while their energy will be measured using organic plastic scintillators. These foils must be ultra radiopure in ^{208}Tl and ^{214}Bi, which are two isotopes produced from the decays of the natural radioactive ^{232}Th and ^{238}U isotopes. The required radiopurity of the selenium foils must be better than 2 μBq/kg in ^{208}Tl (less than 5 decays of ^{208}Tl per month and per kg of selenium) and better than 10 μBq/kg in ^{214}Bi. This level of radioactivity is so small that cannot be measured by the traditional gamma spectroscopy Ge detectors. Thus, the SuperNEMO collaboration developed the BiPo detector to qualify these double beta source foils. The BiPo detector needs to be hosted in an underground laboratory. It was proposed to and approved by LSC in the frame of the collaboration existing between European deep underground laboratories (LNGS, LSC and LSM).

In BiPo, the foil of interest is inserted between two thin ultra-radiopure plastic organic scintillators to detect the ^{214}Bi and ^{208}Tl contaminations both via the so called BiPo process. The ^{214}Bi isotope decays β emitting an electron, into ^{214}Po, which is an α emitter with a half-life of 164 μs. The ^{208}Tl isotope is measured by detecting its father, the ^{212}Bi isotope. The latter decays β (64%) into ^{212}Po, which is an α emitter with a half-life of 0.3 μs. In both cases the electron and, later, the α are detected by the scintillators of the two sides. The two modes are distinguished by the different delay between β and α. The experiment started with two prototypes, BiPo-1 and BiPo-2, which were necessary to develop the technique. Finally the BiPo-3 detector was built and installed at LSC.

The BiPo-3 detector is composed of two separate modules. Each one consists of 40 ultra radiopure plastic scintillator plates seen by low radioactivity photomultiplier tubes. The size of each scintillator is 300×300 mm^2 and 2 mm thick, for a total detector surface of 3.6 m^2. Each module is tightly closed by pure iron plates and installed inside a low radioactive shield contained in a large tight stainless steel tank. The two BiPo-3 modules have been installed at LSC in July and November 2012 respectively. The shield was completed in January 2013.

The first measurements were devoted to background measurements until May 2013. They showed an extremely low background for both modules, well within the requirements. It corresponds to a surface radiopurity of ~1 μBq/m^2 in ^{208}Tl and ~5 μBq/m^2 in ^{214}Bi.

These background levels correspond to sensitivities of the full BiPo-3 detector for a measurement of ^{82}Se SuperNEMO foils between 5 to 8 μBq/kg in ^{208}Tl and 15 and 30 μBq/kg in ^{214}Bi after 6 months of data collection, satisfying the requirements for the SuperNEMO source foils. If the background is low long times are needed to reach the necessary sensitivity.

The superNEMO source foils will be composed by a mixture containing the isotope, held by a low density material sheet. Samples of these different components are being measured in two modules of BiPo since 2013 to assure their radiopurity before the final assembling of the source foils. The BiPo-3 detector is now a unique high-sensitivity planar detector, able to measure ultra high radiopurity of a large variety of materials with thin foil geometry. An example is the possibility to measure the radiopurity of substrates used in microelectronic devices and memories. Today the natural radioactive contaminations of these substrates are a limiting factor for computers.

Fig. 11.1. General view of the BiPo-3

Fig. 11.2. Assembling of one of the BiPo-3 modules in the underground clean room

12 SUPERKGd

SuperKAMIOKANDE is a large detector containing 50 000 t of ultra pure water in which the tracks of charged leptons, electrons and muons, produced by neutrino interactions are observed through the light they produce in the liquid, via the so-called Cherenkov effect. It is the successor, at the Kamioka Observatory under the Japanese Alps, of the smaller KamiokaNDE, the first neutrino telescope. The latter studied neutrinos from the sun and, for the first time, from a supernova explosion in 1987. This discovery led to the Nobel Prize for physics to Koshiba. SuperKamiokande started operation in 1996 and discovered neutrino oscillations in 1998. It is still producing very important physics and astrophysics results.

Even if SuperKAMIOKANDE is the biggest neutrino telescope in the world it can see supernova neutrinos only if the explosion happens in our Galaxy or in the nearby Magellanic Clouds. Such explosions unfortunately happen only a few times per century. However, neutrinos from the supernovae of the past epochs are still wandering around and can be detected. However, these relic supernova neutrinos, and antineutrinos, do not come as a burst during only several second as those from an actual explosion, but continuously and consequently are much more difficult to distinguish from backgrounds, in consideration of their rather low energies.

We can enhance the sensitivity of the detector by detecting the neutron produced together with the positron by the low energy antineutrinos. Dissolving in the water a salt of gadolinium can do this. Indeed the Gd nucleus has a large cross section (probability) for neutron capture, after which it decays with observable gamma rays. However, the Gd salt must be ultra clean from radioactive traces to avoid the risk to contaminate all SuperKAMIOKANDE making it blind to observations. A specific R&D programme is going on. It includes the construction of a test water detector at Kamioka and a systematic action of screening of the materials.

The LSC radiopurity service has an internationally recognised excellence both in the quality of the Ge detectors and in the related analysis software. The team of the Universidad Autonoma de Madrid (UAM) involved in the Super-Kamiokande experiment and its Gd R&D programme submitted the proposal, which was approved, of a series of measurements of different samples of Gd salts and other relevant materials.

After the results of the first measured batches, it was clear that the radioactive contamination of the Gd salts is a serious issue, being the current values not acceptable for the experiment. Thus, a thorough worldwide search of providers was started and it is still going on. It is already giving positive results: we have identified at least one factory able to produce radioactive clean enough Gd salt.

However the UAM works at the LSC have yet a long way to go. We have to achieve a control in the production such that cleanness of the delivered salts is routine. Two hundred ton of Gd salt will be dissolved in Super-Kamiokande at the final stage of the project. To ensure its cleanness and the constancy of the remaining contamination in this huge amount of material is a crucial part of the Gd project.

13 GEODYN

The LSC is located at depth in one of the most seismically active areas in Western Europe, at the Pyrenean chain that marks the boundary between the European plate and the Iberian microplate. Besides, the underground tunnel environment ensures a very low level of noise perturbations, either of natural or cultural origin. These features make it particularly suitable and interesting for hosting an advanced integrated geodynamic observatory, to monitor very precisely local and regional seismic activity and internal deformation processes.

The geodynamic facility in the LSC consists of a broadband seismometer, a strong-motion seismometer, two laser strainmeters, and two superficial continuous GPS stations. This multidisciplinary instrumentation allows advanced studies of geodynamic phenomena, both local and global, in a spectrum ranging from short period seismic waves to tectonic deformation. Hence, it is of great interest for a large community of researchers in Earth Sciences.

Management of the geophysical equipments is carried out in cooperation between expert teams from the Institute of Earth Sciences J. Almera – CSIC (seismic), the University of Salerno, Italy (laser interferometers) and the University of Barcelona (surface GPS).

The GEODYN LSC data is integrated in regional and European networks and databases, within large-scale projects as Topo-Iberia and Topo-Europe, as well as the research infrastructure programme EPOS (ESFRI road map), thus ensuring widespread scientific access to this LSC geodynamic facility.

Seismic component. The two sensors (Broad Band seismometer and accelerometer) and the data-logger installed on the Lab 780 are fully operational since June 2011, when the time synchronization was achieved by installation of the GPS time antenna outside, nearby the entrance of the tunnel together with a 800 m long optical fibre cable that brings the signal to the Lab 780. Moreover, since July 2011 the seismic equipment is connected to the internet, which allows remote checking of the components, as well as remote downloading of data. The status of parameters of this equipment, as well as the visualization of the

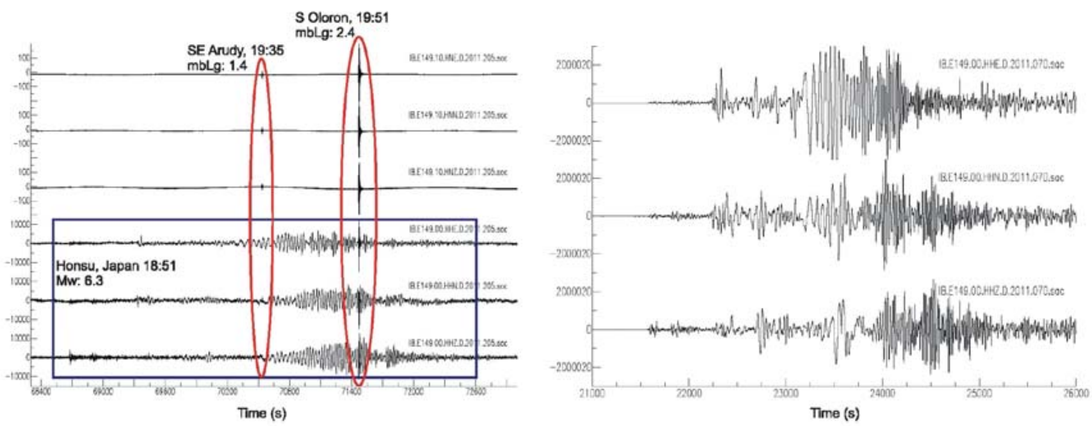


Fig. 13.1. Near and far seismic events

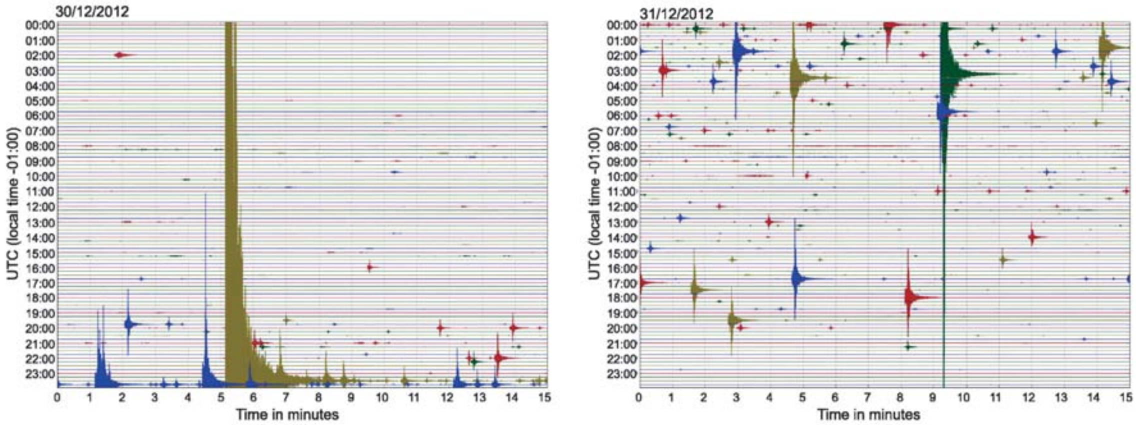


Fig. 13.2. Seismic crisis near Lourdes 2012-2013 as seen by GEODYN

three components is accessible online at the website: http://193.146.122.114:8083/pages/taurus/status.page. Fig. 13.1 shows examples of earthquakes recorded at GODYN seismic component. Left panel shows two local events in the northern Pyrenees, each at about 40 km distance from Canfranc, and a teleseismic event in Japan recorded very shortly in time (panel shows the 3-components of the accelerometer on top and of the BB seismometer at the bottom). Right panel: Major earthquake of Magnitude 9.0 in Tohoku-Japan (March 2011) recorded in the BB sensor. Record length: 5000 s (~1.4 h).

As another example we mention a seismic crisis in the French Pyrenees, about 40 km NE of LSC site. It was triggered on 30.22.2012 by a M= 4.7 event that took place SW of Lourdes town at 23h35 GMT. The main event was preceded at least by a dozen of precursors in previous hours, and followed by hundreds of aftershocks in the next few days, as will be shown in the day recording panels at the LSC site (Fig. 13.2). All the registrations show the much lower level of background due to human activities compared to the ones taken on the surface

The LASER interferometers. A laser interferometer gives information on the variations of the strain of the rock, namely is a strainmeter. This is done by measuring the strain component in its direction. In order to have the information of two perpendicular directions, two interferometers are located along bypass 16 and in Lab 780 L (Fig.13.3). They are operating since December 2011. The two strainmeters measure distance changes between two end points by means of Michelson-type optical interferometers. The two end points of each interferometer are anchored to the rock; their distance is about 70 m. Two photodiodes measure the intensity of the vertically and horizontally polarized components of one of the two outputs of each interferometer.

Fig. 13.3. The interferometer in Lab 780 L

Hydrological signals. During the routine processing of the seismic data we detected an unusual spectral signature, which does not correspond to the typical sources of seismic noise and which can also be recognized in the strain records. We calculated the spectrogram of the continuous dataset to better characterize those episodes, which have well-defined frequency content, extending from 2 to 8-10 Hz. Since early 2011 four main episodes have been identified, each one lasting 1-2 to 6-8 days. Fig. 13.4 compares seismic and meteorological data. The upper panel shows the daily rain in the meteorological station located nearby LSC. The middle panel shows in red the maximum daily discharge registered in the A271 gauge station. The lower panel displays the power density spectrum of the vertical seismic data recorded by the broadband seismometer, with reddish colours representing high-energy intervals. Black dashed boxes show the main hydrological events and their correlation with intervals of high levels of seismic energy in the 2-10 Hz band.

The occurrence of those episodes is neither regular in time nor linked to variations in the noise level in the micro-seismic band, occurrence of local or regional seismicity or changes in the cultural noise level. After checking against meteorological and hydrological data, including wind speed, rainfall amount and river discharge, we can relate those signals to variations in the discharge by the Aragon River, an Alpine-style river in the southern Pyrenees, located about 400 m from the GEODYN facility. This fact shows that the continuous seismic and strain monitoring of the upper section of an Alpine river allows investigating its hydrological evolution, even if the river discharges are modest.

Three types of river-generated seismic events have been identified, related respectively to moderate rainfall episodes, snowmelt season and large flooding events associated to severe storms. Each of those types has distinctive characteristics, which allow monitoring the hydrological features from the analysis of seismic data. The continuous recording of seismic and deformation data seems particularly suited for long-term studies on the characteristics of the snowmelt season in mountain basins, as it provides detailed information of the daily and seasonal cycles and it is not exposed to changes in the river channel geometry which may perturb

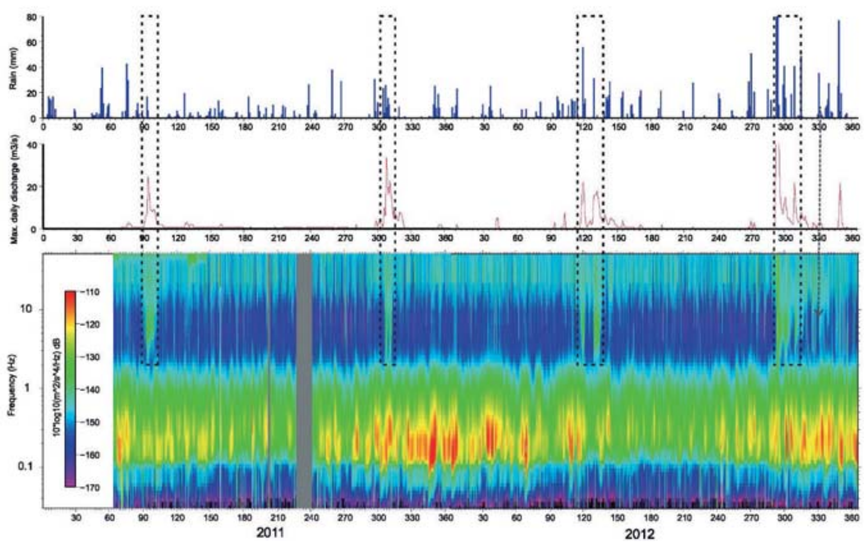


Fig. 13.4. Comparison between seismic and meteorological data. Time scale is expressed in Julian days

discharge measurements in a hydrological gauge station. During severe storms the frequency content has a characteristic pattern, which can be used to identify the occurrence of avenues. As seismic data can be transmitted in near-real time, this may provide a valuable tool for civil protection authorities.

The deformations detected by the laser interferometers during the periods of river-generated seismic noise can be explained by the effect of water infiltration through the uppermost crust and seem directly related to rainfall. A different deformation pattern has been detected for heavy and moderate rainfall episodes. In the first case, both instruments show extension, suggesting that the large volume of water infiltration results in pore pressure increase and global dilatation. Abnormal extension is then recovered following the consequent groundwater feeding to the Aragon river, which causes river discharge changes and pore-pressure decrease. For moderate episodes (less than 50 mm of accumulated rain) the water infiltration mostly follows the fault gouges, increasing the pressure inside them and resulting in compression along the direction perpendicular to the fault trend (Lab 780 L interferometer) and expansion parallel to it (bypass 16 interferometer).

Other recent results obtained by the interferometers relate to the observation of non-linear loading tides. The tidal forces arise from the gravitational forces of the Moon and the Sun. To a good approximation, we can model the tidal response of an Earth without oceans, namely only its solid part. We consider the SNREI (Spherical, Non-Rotating, Elastic and Isotropic) Earth model. Tidal forcing has a much longer period than any normal modes of oscillation of the Earth so that we can use a quasi-static theory, taking the response to be in equilibrium.

Earth tide observations also include the effects of the ocean tides. Even on a rigid Earth the redistribution of mass in the ocean tides would create signals from the attraction of the water; on the real Earth this redistribution also causes the Earth to deform. These induced signals are called the load tides, which combine with the body tide to make up the total tide.

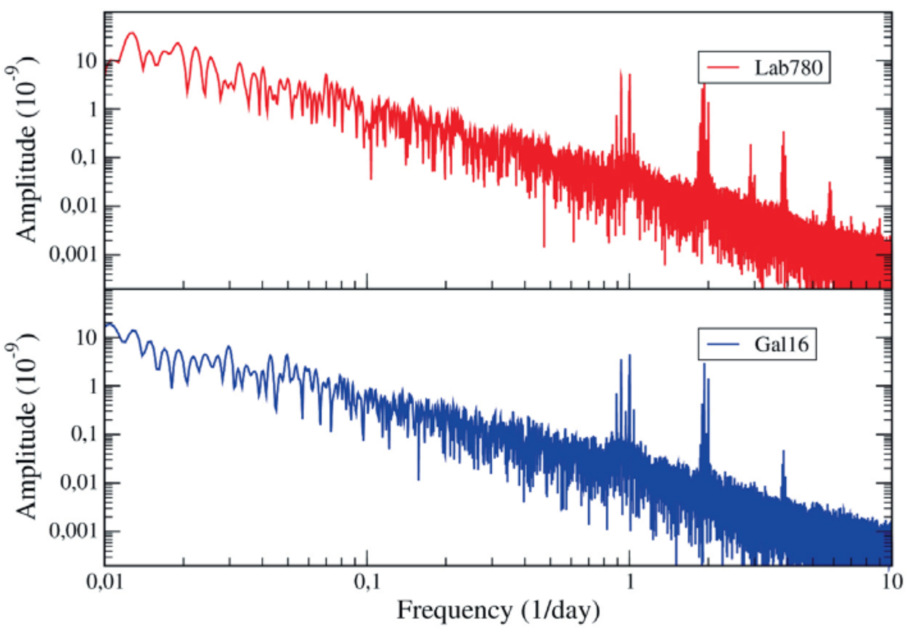


Fig. 13.5. Amplitude spectra of strain recorded by the two interferometers

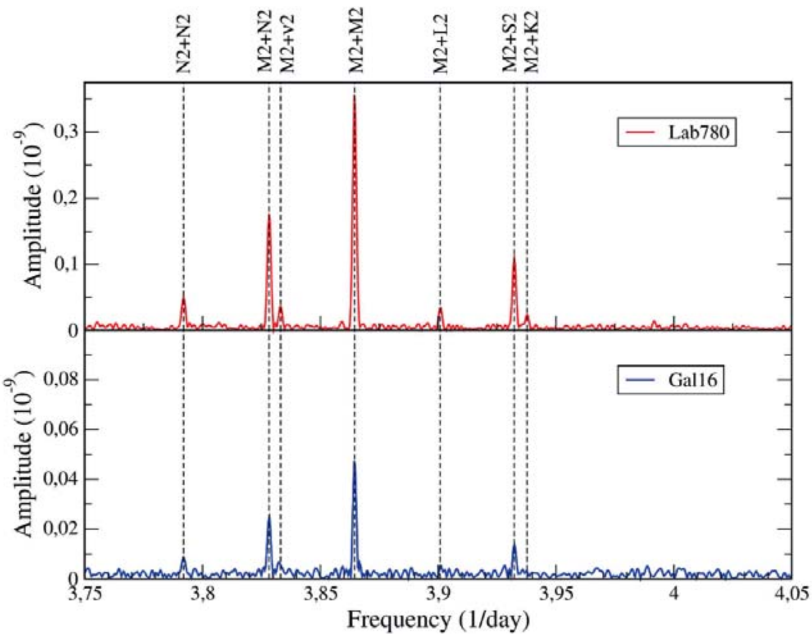


Fig. 13.6. Enlarged view in the fourth-diurnal band

Fig. 13.5 shows amplitude spectra of strain recorded by the interferometers installed in bypass 16 and Lab 780 L. Because of gaps, both records are actually about 1.5 years in length. Tidal lines are clearly visible up to the sixth-diurnal band (i. e., frequencies close to 6 cycles per day).

Figure 13.6 shows an enlarged view in the fourth-diurnal band. Body tides in the fourth-diurnal band are very small; visible lines relate to load tides. In the open ocean the tidal spectrum can normally be represented by a limited number of well-defined frequencies, primarily in the diurnal and semidiurnal bands. In coastal regions, however, the spectrum can become much more complex because the semidiurnal and diurnal frequencies are mixed with a large number of "shallow-water tides," having frequencies within the long period, diurnal, semidiurnal, terdiurnal, and higher bands. These new frequencies are a consequence of the nonlinear interactions between the tidal waves as they propagate in shallow water. Resonance or near- resonance responses add to the complexity of the tidal pattern and tend to intensify nonlinear effects. It is very difficult to extract other components than M4 in altimetry. Therefore, the only oceanographic data which could be used for validating non-linear ocean tidal models over the North West European continental shelf are tide gauges. However these instruments are often installed at coastal stations and may only be representative of very local effects. The analysis of strain data recorded by the two geodetic interferometers at LSC is one of the few methods to validate non-linear ocean tidal models on larger spatial scales. Signal-to-noise ratio for strain data appears even higher than for high accuracy gravity measurements.

The GPS component. Two continuous GPS stations are foreseen to monitor deformations around the tunnel area from outside. Basic elements for each station are a choke-ring antenna, the receiver-recorder, power system, communication-remote access to the equipment and accessories. The continuous GPS nets measure the displacement of a set of benchmarks with respect to a reference one; distance between benchmarks is of the order of kilometres. Up to now, the permitting procedures for the two envisaged GPS sites are still ongoing.

14 CUNA

During the Big Bang nucleosynthesis hydrogen, helium, and other trace elements were formed; these species became the constituents of the first generation of stars. From there on, more and more complex nuclear processes within stars are responsible for the synthesis of heavier species. It is in these nuclear furnaces where the chemical abundance pattern of the Universe was, and still is, shaped. Most of the known isotopes above iron are produced by neutron capture reactions that occur in significantly different astrophysical environments. On the one side, rapid neutron captures *(the r-process)* are believed to occur in Core Collapse Supernovae, while slow neutron captures *(the s-process)* occurs in red giant stars on the Asymptotic Giant Branch (AGB) phase producing the *main component* and in massive stars producing the *weak component.*

The s-process is thought to produce about half of the isotopes above iron. Nevertheless, an open question still remains, namely the source of the required stellar neutron flux to produce such reactions. Particularly important are the (α,n) processes, in which a nucleus, N, captures an alpha particle producing a nucleus, N', with three times more nucleons and a neutron. The process is written as N(α,n)N'. The most likely are the ^{22}Ne(α,n)^{25}Mg and ^{13}C(α,n)^{16}O reactions, depending on the specific scenario for the s-process. The reaction cross section is a quantity proportional to the probability of that reaction to happen.

The kinetic energies of the atomic nuclei in the stars correspond to the temperature of the region of the star where they are and are always very low for the nuclear standards. This energy range is called Gamow peak. Two nuclei approaching each other tend to repel themselves because are both positively charged and only rarely can reach the short distance necessary to the nuclear reaction to happen. Indeed, the cross sections depend on the energy and decrease very rapidly with decreasing energy, becoming extremely small in the Gamow peak. The measurement of the majority of the cross sections needed to understand the astrophysical processes cannot be done in the usual nuclear physics laboratories due to the interference of the cosmic rays that produce background interactions at rates much larger than the searched ones. We need to work in an underground laboratory. Since many years one such facility exists, the LUNA infrastructure at the Gran Sasso underground laboratory in Italy (LNGS-INFN). However, one facility is not enough to cover all the scientific programme, considering that the measurement of a single cross section takes several years of work. This is why the Canfranc Underground Nuclear Astrophysics (CUNA) project was developed.

An "Expression of Interest" titled *vvv* was submitted to the LSC in 2009 by Spanish groups and international partners. A full Letter of Intent was submitted in October 2012, endorsed by more than 50 international support letters. In parallel, the LSC performed preliminary studies for a new experimental hall to be excavated near to the existing underground facilities. The hall shall host a linear ion accelerator and the detectors of the various experiments that will use the facility along the years. The accelerator must have a few-MV maximum energy, to overlap with measurements at higher energies, high intensity and very high stability and reliability.

A high current accelerator is the workhorse of the proposed facility, the high beam intensity allowing for the low count rates to be measurable for the proposed relevant reactions proposed, although it may pose some challenges in terms of operation and target stability. In addition, controlled operation with low voltage ripple is of key importance, since it allows for the efficient use of the beam time and precise knowledge of the beam energy and intensity. The installation of two experimental stations with two beam lines, in order to be able to perform preparations in one of them while measurements proceed in the other, is envisaged.

An ion beam of sufficient energy becomes a source of neutrons through nuclear reactions. With alpha (and proton) beams of a maximum energy of 3 MeV the neutron production channels are open only for a limited number of stable isotopes. Numeric simulations have been performed to evaluate the neutron background attenuation in the rock. Results show that a metre of rock reduces the flux by three orders of magnitude. Consequently, the neutrons will not affect experiments installed in other halls. Moreover, neutrons should not escape from the entrance to the hall. To this purpose the entrance was designed trough a two-wall labyrinth with 2 m thick walls. The walls of the hall and of the tunnels are covered with 40 cm of concrete. With this configuration numerical simulations showed that the neutron escaping are not dangerous.

The CUNA collaboration has also studied the detection structures. The extremely low value of the cross sections requires both a high detection efficiency and a high discrimination capability for the reaction channel of interest. The core of the experimental programme proposed at CUNA is the (α,n) reactions. The use of a neutron counter based on ^{3}He proportional tubes embedded in a polyethylene matrix, acting as a neutron energy moderator, is the best-suited detector candidate. It unites detection efficiencies of the order of 50%, a very clean signature of neutron events and relatively insensitivity to other types of radiation. A detector of this kind, consisting of 20 tubes arranged in two

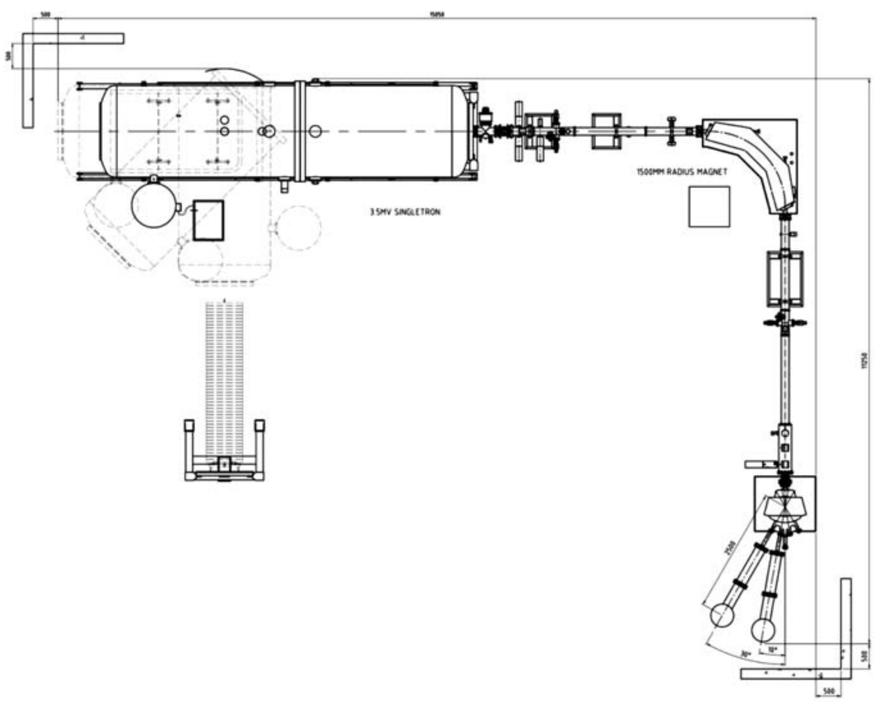


Fig. 14.1. A possible layout of the accelerator facility (3.5 MeV Singletron by HVee, The Netherland)

rings around a central longitudinal hole of radius 5.5 cm, has been recently built by a Spanish collaboration for the measurement of β-delayed neutrons, and could be easily adapted to the measurements at CUNA. Six of the tubes have been already used to measure the neutron background in the hall A of LSC.

Several workshops have been organized to discuss the feasibility, the Physics programme and the future prospects of the CUNA facility. They started by "Nuclear Astrophysics Opportunities at the Underground Laboratory in Canfranc" (February 2009) in Barcelona, followed by "Background and simulations for CUNA" (December 2010), in Zaragoza and finally "Nuclear Astrophysics at the Canfranc Underground Laboratory" in March 2012, at the Laboratorio Subterráneo de Canfranc. This international workshop was the latest in a series of meetings dedicated to exploring prospects for experiments in nuclear astrophysics at existing and nascent underground laboratories. A key goal was to further develop and discuss CUNA in an international context by soliciting the advice and opinions of leading nuclear astrophysicists outside Spain.

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Also a total of 22 Thesis related to the experiments have been developed.

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