Subnuclear Physics: Past, Present and Future
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Origin and Status of the Gran Sasso INFN Laboratory

Lucia Votano

Laboratori Nazionali del Gran Sasso
dell'Istituto Nazionale di Fisica Nucleare, Italy

Abstract

Underground laboratories are the main infrastructures for astroparticle and neutrino physics aiming at the exploration of the highest energy scales – still inaccessible to accelerators - by searching for extremely rare phenomena. The Gran Sasso INFN Laboratory, conceived by Antonino Zichichi approximately 30 years ago, is the largest underground laboratory in the world devoted to astroparticle physics. The main characteristics of the Gran Sasso Laboratory together with an overview of its broad scientific activities will be reviewed.

A brief history of the Gran Sasso Laboratory

The proposal to build a large underground Laboratory under the Gran Sasso massif was submitted in late 1970s by the then President of INFN Antonino Zichichi. At that time the tunnel under the Gran Sasso mountain of the Rome-Teramo highway was under construction and this was a unique opportunity for the excavation of large halls of an underground laboratory at a reasonable price.

The Italian Parliament approved the ‘Gran Sasso Project’ and its funding in 1982. By 1987 the civil engineering works were completed and in 1989 the first experimental apparatus, MACRO, started its data taking. Looking back on those past thirty years, the advances we have made in understanding the fundamental laws of nature and the evolution of the universe as well as the extraordinary growth of astroparticle physics can be clearly observed.

Fig1. Excavation of the experimental halls of the Gran Sasso Underground Lab.

An ever-increasing number of physicists joined this sector, which represents one of the most fascinating and challenging deal of the physics research. Technologies developed in accelerator apparatuses were first adopted; later on the search for very rare events, the need of increasing sensitivity and efficiency and the complexity of the analysis have called for the development of ever more cutting edge technologies. At present experimental apparatuses dedicated to astroparticle physics have mass, dimensions and technological complexity comparable to that used in the Large Hadron Collider (LHC). Astroparticle physics would not have been able to make such a massive and rapid progress without the great infrastructures necessary for this kind of study that only the facilities of underground laboratories can offer.

Having planned and built such a large and well equipped laboratory as early as the late 1970s, has brought Italy to have a leading role in this field, since then.

INFN Gran Sasso National Laboratory (LNGS) is the largest underground laboratory in the world for astroparticle physics. It is one of the four INFN National Laboratories and it is an international facility housing twenty experiments. Located between L'Aquila and Teramo, the underground structures are on one side of the highway tunnel (10 km long) which crosses the Gran Sasso massif (A24 Teramo-Rome Highway) and consist of three huge experimental halls (each one 100 m long, 20 m large and 18 m high) linked by service tunnels, for a total volume of ~180.000 m^3 and a surface of ~18.000 m^2.

The 1400 metre-rock thickness above provides a cosmic ray flux reduction by one million times; moreover, due to the very small amount of uranium and thorium of the Dolomite calcareous rock of the mountain, the flux of neutrons in the underground halls is about thousand times less than on the surface.

Outside, next to the highway tollgate of Assergi, an area of more than 23 acres hosts the external laboratories, the Computing Centre, the Directorate and various Offices. Presently LNGS staff consists of about 90 people; besides, more than 950 scientists from 29 different Countries take part in its experimental activities.

Neutrino Physics

The study of the intrinsic properties of neutrino is of prime interest in particle physics and one of the main research topics of the present scientific program of the Laboratory where various neutrino sources, both natural (the Sun, stars and the Earth) and artificial (particle accelerators) are used.

Solar neutrinos

The Borexino experiment at LNGS detects low energy solar neutrinos by means of their elastic scattering on electrons in a large volume liquid scintillator apparatus. Collecting the scintillation light with a large set of photomultipliers makes real-time detection of all events. The very low intrinsic radioactivity of the scintillator and of the materials surrounding it allows a clean spectral separation between the neutrino signals and the residual background.

While the main goal is the detection of the monochromatic ^{7}Be neutrinos, Borexino is now able to explore the 1-2 MeV region of the solar neutrino spectrum with unprecedented sensitivity and to study other components, such as the CNO, pep and pp. In 2011 Borexino measured the ^{7}Be solar neutrino rate with accuracy better than 5%, rejecting the hypothesis of no oscillation for ^{7}Be solar neutrinos at 4.90 C.L. More recently they have published the first observation of solar neutrinos from the basic pep reaction and the upper limit, the lowest ever published, for the CNO production in a star has been established.

Borexino is a very sensitive detector for geo-neutrinos too. Geo-neutrinos are electron antineutrinos produced in β decays of ^{40}K and of several nuclides in the chains of long-lived ^{238}U and ^{232}Th present in the Earth crust and mantle. They are direct messengers of the abundances and distribution of radioactive elements within our planet.

CNGS project

The CNGS (Cern Neutrino Gran Sasso) project consists of an artificial neutrino beam produced by the protons accelerator SPS of CERN and directed towards Gran Sasso. The main experiment of Gran Sasso National Laboratory devoted to CNGS neutrino detection is OPERA. The goal of the experiment is the detection of neutrino oscillations in direct appearance mode through the study of $\nu_\mu \leftrightarrow \nu_\tau$ channel; The challenge of the OPERA experiment is, in fact, the seeking of tau neutrinos in the beam CNGS originally constituted by muon neutrinos only, providing the first direct evidence of the so called ‘oscillation’ mechanism of these particles.

The detector consists of 150.000 ’bricks’ made up of lead layers interleaved with nuclear emulsions, historically called Emulsion Cloud Chamber (ECC) and electronic detectors to localize neutrino interactions within the target. The observation of a first ν_τ candidate event in the experiment has been reported in June 2010, followed by a second candidate in 2012 and the third one in March 2013.

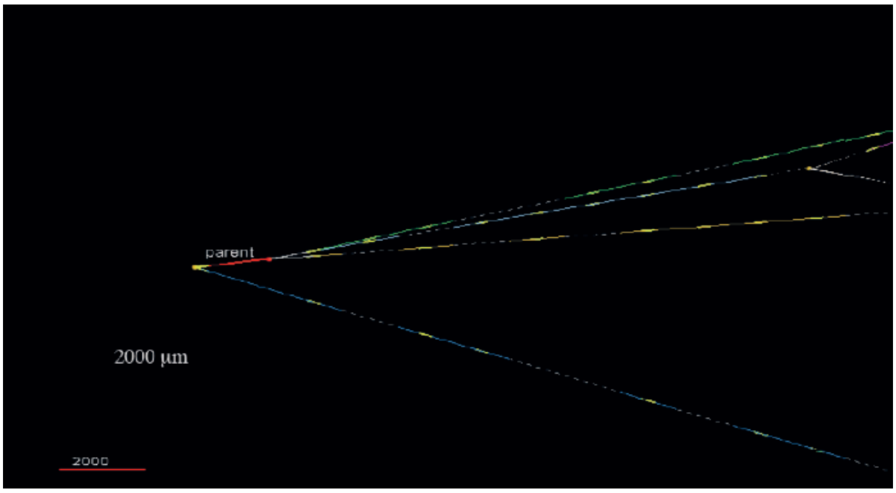

Fig 2. Second observation of tau neutrino in the OPERA experiment – April 2011

Another experiment able to detect CNGS beam is ICARUS, an innovative apparatus consisting of a big mass (about 600 tons) of liquid Argon, at a temperature of -186 °C. In particular conditions and by means of proper devices this liquefied gas is able to act as an extraordinary particle detector, allowing a 3D reproduction of any interactions of charged particles inside its volume. The commissioning of ICARUS was successfully completed in 2010 and in May the first CNGS neutrino events were recorded. ICARUS is now continuously collecting data from CNGS.

Such a massive liquid argon experiment running in an underground laboratory is, so far, the most important milestone for the LAr-TPC technology towards the design of a much more massive multikiloton LAr detector.

Neutrino less Double-Beta Decay

Neutrino less double-beta decay is a process by which two neutrons in a nucleus undergo beta decay by exchanging a virtual Majorana neutrino, emitting an electron each. This would violate lepton number conservation ($\Delta L = 2$) and would necessarily require neutrinos to be Majorana particles; therefore this represents a unique tool to test this hypothesis and nowadays, thanks to the discovery of neutrino oscillations, this makes it the object of a renewed interest. The LNGS program exploits complementary approaches concerning isotopes and technique.

GERDA experiment

GERDA (The GERmanium Detector Array) is designed to search for *2β0ν*-decay of ^{76}Ge using an array of high-purity germanium detectors, enriched (~ 85%) in ^{76}Ge, directly immersed in LAr, which acts both as shield and as cooling medium. The cryostat is located in a stainless steel water tank providing an additional shield against external background. GERDA is presently operating eight enriched coaxial detectors (approximately 15 kg of ^{76}Ge). Moreover five new enriched BEGe detectors have been tested and deployed in GERDA at the beginning of July 2012. The background reached is approximately 17x10-3 cts/(keV kg y), which is about a factor of 10 lower than for previous experiment HdM and close to the design goal of 10x10-3 cts/(keV kg y). About 30 new custom-made enriched BEGe detectors will be deployed in the next phase (additional 20 kg of ^{76}Ge).

CUORE experiment

The CUORE experiment (Cryogenic Underground Detector for Rare Events) aims at the detection of *2β0ν*-decay through TeO_2 crystals acting as bolometer detectors: the energy from particle interactions is converted into heat and measured via the resulting rise in temperature. Recently the Laboratory has received additional 120 lead bricks (4 tons) from an ancient Roman ship that sunk off the coast of Sardinia 2.000 years ago. CUORE is in the construction phase at LNGS and is expected to start operation in 2015. The first tower CUORE-0 has been recently commissioned.

Dark Matter search at Gran Sasso

There are compelling evidence from astrophysical and astronomical observations that about one-quarter of the energy density in the universe is composed of non–baryonic and non-relativistic (cold) massive component larger than the one observable through telescopes, due to a not-yet-identified particle. It is called Dark Matter because it neither emits nor absorbs radiation and thus it is invisible to our eyes and instruments. It is supposed to be five times more abundant than ordinary matter, which only constitutes 5% of our Universe.

One of the most well known hypotheses is that these massive particles constitute a widespread halo permeating our galaxy as well as others. There are different techniques that could be able to discover Dark Matter. One of the most common candidate for CDM are Weakly Interactive Massive

Particles (WIMPs) predicted by super symmetric theories (SUSY), searched for at LHC looking for their appearance in collisions; while space-experiments are looking for the detection of CDM by looking for WIMP annihilation signatures from the centre of the Sun or from the centre of the galaxy, the direct detection of DM candidates is only possible in underground laboratories.

LNGS houses experiments devoted to search for dark matter candidates through their direct detection. These experiments put Gran Sasso Laboratory at the forefront of this kind of study.

DAMA/LIBRA experiment

The DAMA/LIBRA experiment is mainly based on the development and use of low background scintillators and the main aim is the direct detection of DM particles in the galactic halo by investigating the model independent annual modulation signature.

The experiment has been operational since 2003 with 250 kg of extremely radio-pure NaI (Tl) crystals. The most recent published results confirmed the annual modulation of the very low energy signals induced in the detector, already observed in the previous lower mass experiment DAMA. Such modulation is identical to the one that the relative motion of the Earth through the huge amount of dark matter halo of our galaxy is supposed to cause. The interesting result has produced a lively debate inside the scientific community as well as the production of theoretical models able to conciliate such results with the absence of positive signals by other experiments.

XENON100 experiment

After the successful results of the 10 kg scale detector XENON10, a second-generation experiment exploiting the two-phase time projection chamber (TPC) technique based on liquid xenon (LXe) is now operating at LNGS. The two-phase detector XENON100 experiment contains 170 kg of xenon, 65 kg of which constitute the active part while the remaining acts as a shield. A key feature of the detector is its ability to localize events with millimetre resolution in 3 dimensions, which further allows selecting only the innermost 48 kg as ultra-low background.

After the result published in 2011 from 100.9 live days of data, the present improved running conditions of XENON100 allowed to further push the sensitivity of XENON100 that smoothly continues data taking. Recently the XENON collaboration has published the analysis of 225 more days of data accumulated in 2011 and 2012. They see no evidence for the existence of WIMPs: the two candidate events being observed are statistically consistent with one event being expected from background radiation. Compared to their previous 2011 result, the world-leading sensitivity has again been improved by a factor ~5.

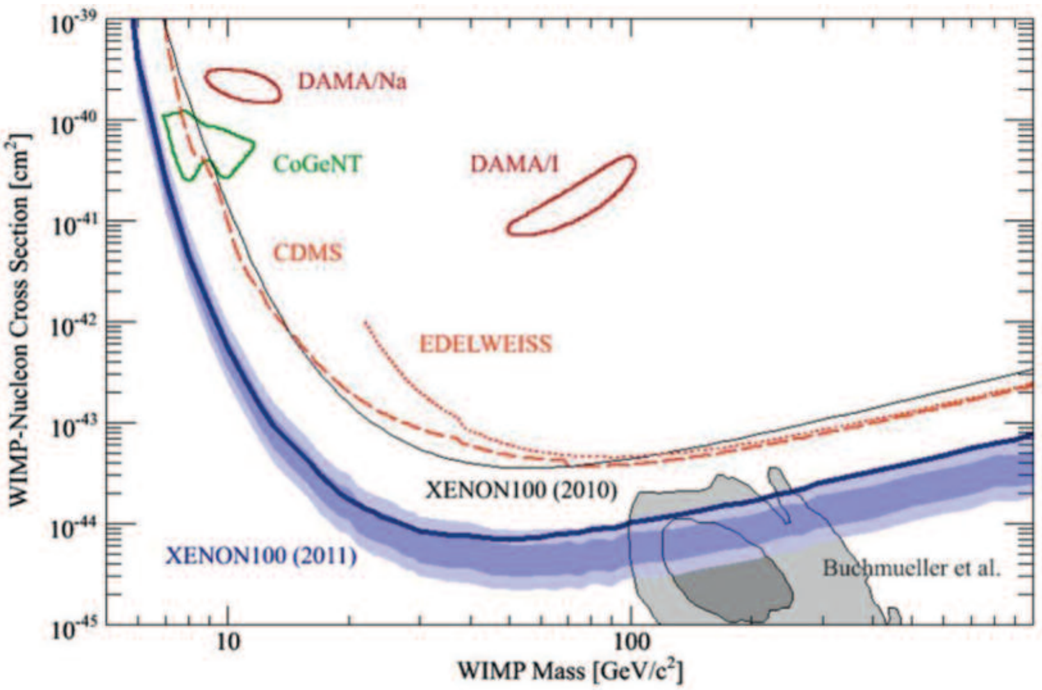

Fig 3. 2011 results: XENON100 Dark Matter Limit (90% CL)

In order to reach a lower sensitivity of about 5 X 10^{-47} cm^2 and/or to confirm a possible detection in XENON100, the collaboration will continue the Xenon program at LNGS with the XENON 1T detector having a total mass of 2.4 tons of LXe

XENON1T will be installed in the Hall B of the underground Laboratory and the construction should start in summer 2013.

CRESST experiment

The CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment is based on the bolometer technique with $CaWO_4$ crystals at a temperature of few mK as well as on the simultaneous detection of scintillation light and the heat resulting by the interaction of a particle with the crystals. One advantage of the cryogenic detectors developed for CRESST consists on the fact that they can measure the deposited energy calorimetrically, independently on the type of interaction. Combining the calorimetric measurement of the deposited energy with a measurement of scintillation light, a potentially high discrimination of the nuclear recoils from radioactive background can be obtained and the type of recoiling nucleus can be determined in a multi atomic target.

In 2011 CRESST has completed a long run and has submitted a paper with the analysis of data with a total exposure of 730 kg days. An excess of events has been found in the acceptance region where a WIMP signal would be expected. A new run with several detector improvements aimed at a reduction of the overall background is expected to be started soon.

Conclusion

The Gran Sasso National Laboratory of INFN, the largest underground laboratory in the world, holds the leadership in massive experiments with record performance and low-level background. The present scientific program of LNGS includes a very broad spectrum of competitive experiments (astroparticle, particle and nuclear physics), including the world-leading ones in the fields of solar neutrinos, accelerator neutrinos, double beta decay, dark matter and nuclear astrophysics.

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