Highlights from Gran Sasso Laboratory

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Abstract. The Gran Sasso National Laboratory of INFN, between the cities of L’Aquila and Teramo, Italy, is a research infrastructure mainly dedicated to astroparticle and neutrino physics. It offers the most advanced underground Laboratory in terms of dimensions, complexity and completeness of its infrastructures. A review of the main experiments carried out at LNGS - devoted to neutrino and to nuclear astrophysics - will be given, together with the most recent and relevant scientific results achieved.

1 LNGS  
Underground Laboratories are the main infrastructures for astroparticle and neutrino physics to explore the highest energy scales not accessible with accelerators, by searching for extremely rare phenomena. INFN Gran Sasso National Laboratory (LNGS) is the largest underground laboratory in the world devoted to astroparticle physics. It is one of the four INFN National Laboratories and it is a worldwide facility for scientists working in one of the twenty experiments currently set there. Located between L’Aquila and Teramo - at about 120 km far from Rome - 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 about 180.000 m³ and a surface of 17.800 m². Access to experimental halls is horizontal and it is made easier by the highway tunnel. Halls are equipped with all technical and safety plants required for the experimental activities and to ensure proper working conditions. For instance ventilation plants allow, in normal conditions, a change of air in less than 3 hours, and air radon content is kept in the 20-80 Bq/m³ range. The 1400 metre-rock thickness above provides a cosmic ray flux reduction by one million times; moreover, the flux of neutrons in the underground halls is about thousand times less than on the surface, due to the very small amount of uranium and thorium of the Dolomite calcareous rock of the mountain. 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 90 people; besides, more than 950 scientists from 29 different Countries take part in its experimental activities.

2 Physics at LNGS  
At LNGS, many of the experiments currently underway or to be started soon are looking at fundamental and fascinating questions which are still unanswered. What is the Universe made up of and, in particular, Dark Matter? In this area, are we any nearer to open a door to a physics that goes
beyond the Standard Model of particle physics? What is the intimate nature and what are the latest characteristics of the neutrino and what role have they played in the evolution of the Universe? What do we know of the interior of the Sun and the stars, of the mechanisms that produce energy and how they evolve and die? What do we know about the interior of our own Earth, can we find out more through the study of geoneutrinos? LNGS research activities thus range from neutrino physics to dark matter search, to nuclear astrophysics, but also to geophysics, biology and fundamental physics.

3 Neutrino Physics

The study of the intrinsic properties of neutrino is of prime interest in elementary particle physics and has provided by now the only experimental evidence of phenomena beyond in the Standard Model of elementary particles by measuring neutrino oscillations. In order to properly comprehend the mechanism of the oscillation, various neutrino sources, both natural (the Sun or other stars) and artificial (particle accelerators) can be used.

Besides, the study of a phenomenon as the neutrino-less double-beta decay could allow us to find out if the neutrino overlaps with its antiparticle, thus providing a very significant answer towards the comprehension of the evolution of the Universe. Finally, neutrinos from the cosmos are very important messengers which transport fundamental information to understand the functioning of the stars as energy sources, their evolution and what happens when they “turn off”.

LNGS activities range among various aspects of the neutrino physics study.

3.1 BOREXINO and solar neutrinos

Borexino is a large unsegmented liquid scintillator detector built for real time measurement of low-energy solar neutrinos. The inner part of the detector is a Stainless Steel Sphere (SSS) 13.7 m in diameter that represents both the container of the scintillator and the mechanical support of the 2200 PMTs. Within the sphere, two nylon vessels separate the scintillator volume in three shells of increasing radiopurity. The SSS is enclosed within a large tank filled with ultrapure water that represents a powerful shielding against external background and is used as a Cherenkov muon counter and muon tracker. The experiment can then rely on an optimal energy and spatial resolution together with a very low energy threshold (40 KeV).

The main goal of the experiment is the detection of the monochromatic $^7$Be neutrinos, even if the extreme radiopurity of the detector resulted in a broadening of the scientific goals. Borexino now aims at the spectral study of other solar neutrino components, such as the CNO, pep and, possibly, pp.

Low energy neutrinos of all flavours are detected by their elastic scattering of electrons while electron antineutrinos by means of their inverse beta decay on protons or carbon nuclei. As the shape of the energy spectrum of recoil electrons is the only signature available for neutrinos, $\gamma$ or $\beta$ background events due to natural radioactivity cannot be distinguished from the signal on an event by event analysis, but only through their spectral shape. This fact, together with the low event rate expected, demands an extreme radiopurity of the detector and actually the inner core of Borexino is 9-10 order of magnitude less radioactive than anything else on Earth.

After the first result published in 2007 with a 30% precision, and the second one in 2008 with 10% precision, the best value for the interaction rate of $^7$Be neutrino published in 2011, corresponding to 750 days of data, is $46\pm 1.5 \text{stat} \pm 1.3 \text{syst} \text{ counts/(dayx100t)}$, with 4.3% accuracy [2]. The expected signal for non oscillated solar $\nu_e$ in the high metallicity model is $74 \pm 4 \text{ counts/(dayx100t)}$, while in the MSW-LMA scenario of solar neutrino oscillation, it is $48\pm 4 \text{ counts/(dayx100t)}$, in very good agreement with the Borexino measurement. In this scenario, neutrino oscillations are dominated by matter effects above 3 MeV and by vacuum effects below 0.5 MeV. The $^7$Be neutrinos lie in the lower edge of this transition region. Borexino has also been able, for the first time in a liquid scintillator detector, to detect $^8$B neutrinos above 3 MeV [1]. The first simultaneous measurement of the neutrino survival probability $P_{ee}$ in the vacuum and in the matter enhanced oscillations regions is of great importance and could be improved in the near future.
Thanks to the extreme high radiopurity achieved, the high photon yield, and the large number of free target protons, Borexino is also a very sensitive detector for antineutrinos in the MeV energy range where geo-neutrinos lie. Geo neutrinos are electron antineutrinos produced in $\beta$ decays of $^{40}\text{K}$ and of several nuclides in the chains of long-lived $^{238}\text{U}$ and $^{232}\text{Th}$ present in the Earth. They are direct messengers of the abundances and distribution of radioactive elements within our planet. By measuring their flux and spectrum it is possible to reveal the distribution of the natural radioactive isotopes and to assess the radiogenic contribution to the total heat balance of the Earth. Nowadays the existence of large mass scintillation detectors made their detection feasible. KamLAND has opened the way to geo-neutrino detection in 2005 while in 2010 the geo-neutrino observation has definitely been performed by Borexino [3]. The best estimate of the geo-antineutrinos has been determined with an unbinned maximum likelihood analysis of the twenty-one $\bar{\nu}_e$ candidates that passed all selections cuts, including the reactor $\bar{\nu}_e$ that represent an irreducible source of background. The KamLAND 2008 and Borexino 2010 combined analysis gives an evidence at more than 5$\sigma$ for the detection of geoneutrinos.

3.2 CNGS and OPERA

Started in 2006, the project CNGS 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 $\nu_\mu \rightarrow \nu_\tau$ channel. Neutrino oscillations at the atmospheric scale have been studied up to now through atmospheric and accelerator neutrinos in disappearance mode, while the direct observation of flavour transition through the detection of the corresponding lepton has never been observed before OPERA first evidence. The challenge of the OPERA experiment is then the detection of the short lived $\tau$ lepton produced in the charge current interaction of $\nu_\tau$. Detection of tau neutrinos in the beam CNGS, originally constituted by muon neutrinos only, provides the first direct evidence of the so called ‘oscillation’ mechanism of these particles. The $\nu_\mu$ beam from CERN is optimized for the observation of $\nu_\tau$ CC interactions, the average energy being 17 GeV. With a total CNGS beam intensity of 22.5x10$^{19}$ protons on target, about 24.300 neutrino events would be collected. The experiment should observe $\approx$10 $\nu_\tau$CC events for the present $\Delta m^2_{23}$ allowed region with a background of less than one event.

The huge apparatus mainly consists of 150.000 'bricks' made up of lead layers interleaved with nuclear emulsions, historically called Emulsion Cloud Chamber (ECC). OPERA is an hybrid detector made of a veto plane followed by two identical super modules (SM) each consisting of a target section of about 625 tons made of 75.000 bricks, and of a scintillator Target Tracker Detector (TT) to trigger the read-out and to localize neutrino interactions within the target, followed by a muon spectrometer. The observation of a first $\nu_\tau$ candidate event in the experiment has been reported in June 2010 based on the analysis of part of the data taken during 2008 and 2009 runs.

The appearance of the $\tau$ lepton is identified in OPERA by the detection of its characteristic decay topologies, either in one prong (electron, muon or hadron) or in three prongs. The detection of decay topologies is triggered by the observation of a track with a large impact parameter with respect to the primary vertex. In the event samples analysed so far, one candidate has been identified with measured characteristics fulfilling the selection criteria a priori defined for the $\nu_\tau$ interaction search. The primary neutrino interaction consists of seven tracks, one of which showing a visible kink. Two electromagnetic showers caused by $\gamma$-rays, associated with the event, have been located. The event passes all cuts with the presence of at least one gamma pointing to the secondary vertex, and it is therefore a candidate to the $\tau \to \pi^0 \text{prong}$ hadron decay mode. The invariant mass of the two detected gammas is consistent with the $\pi^0$ mass value. The invariant mass of the ($\pi^-\gamma\gamma$) system has a value compatible with that of the $\rho(770)$. The two main sources of background to this channel are: the decay of charmed particles produced in $\nu_\mu$ interactions, estimated for the analyzed sample to 0.007
±0.004syst and the one prong inelastic interactions of primary hadrons produced in νμ interactions, estimated to 0.011 [4].

By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ. If all τ decays modes which were included in the search are taken into account, the probability to observe one event due to the background fluctuation is 4.5%; this corresponds to a significance of 2.01 σ. OPERA data taking will continue at least up to 2012.

3.3 CNGS and ICARUS
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 [5]. 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 with unique imaging capability, and spatial/calorimetric resolutions.

3.4 The research of neutrinoless double beta decay
Neutrino oscillation experiments have clearly shown that neutrinos do oscillate and that they are massive, though this is not enough to determine the nature of such mass (Dirac or Majorana) and to determine the absolute mass scale. In fact neutrino oscillation experiments can only measure the absolute value of the difference of the square of the neutrino masses while two different hierarchical mass arrangements of neutrino masses (Direct and Inverted), besides the obvious quasi-degenerate option, are possible. Many theories beyond the standard Model suggest a mass generation mechanism that implies a Majorana character of neutrinos.

Neutrinoless 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 (ΔL = 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.

From an experimental point of view, the only available information is carried by the daughter nucleus and the two possible emitted electrons and then the possible measurable quantities are: sum of the electron energies, single electron energy and angular distributions, identification and/or counting of the daughter nuclei.

In most cases the experimental signature rely on the electron sum energies and on the discrimination of the different distribution expected for: a continuous bell distribution for ββ2ν, and a sharp line at the transition energy for ββ0ν. Energy resolution and level of measured background are the critical issues.

In 2001 evidence for a ββ0ν signal has been claimed by a small subset (KHDK) of the HDM (“Heidelberg-Moscow”) collaboration at Gran Sasso National Laboratory. The result is based on a re-analysis of the HDM data. Such a claim has raised some criticisms that cannot be dismissed though as none of the existing experiments is able to rule it out. Therefore there is great interest on next generation and more sensitive experiments.

3.4.1 GERDA
GERDA [6] is designed to search for ββ0ν-decay of 76Ge using high purity germanium detectors (HPGe), enriched (~ 85%) in 76Ge, 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 experiment is scheduled to proceed in two phases. For Phase I, eight
reprocessed enriched HPGe detectors from the past HdM experiments (~ 18 kg) and six reprocessed natural HPGe detectors (~ 15 kg) from the Genius Test-Facility will be deployed in strings. At the expected background rate of $10^{-2}$ cts/(kg keV y) at the Q-value of the $^{76}$Ge decay (2.039 keV) the resulting sensitivity after one-year exposure for the half-life of the neutrinoless double beta decay is $2 \times 10^{25}$ y. This is sufficient to confirm or refute the existing claim from KHDK. In Phase II new diodes, which are able to discriminate between single- and multi-site events, will be added to increase the active mass up to 37.5 kg. The expected background reduction down to $10^{-3}$ cts/(kg keV y) will allow to increase the sensitivity to the half-life of the process by one order of magnitude for the total exposure of 100 kg y. In this case it would be also possible to probe the effective neutrino masses ($m_{\nu}$) at the level of 150 meV.

The installation of the experiment in Gran Sasso Laboratory has been accomplished and now the experiment is in the commissioning phase. The first non-enriched Ge detectors have been deployed for a technical run aimed to perform background evaluation.

### 3.4.2 CUORE

The CUORE experiment (Cryogenic Underground Detector for Rare Events) [7] is the most recent and ambitious development of the ‘TeO$_2$ bolometers’ technique in which INFN has over than 20 years experience. In the bolometer detectors, the energy from particle interactions is converted into heat and measured via the resulting rise in temperature.

CUORE will consist of a rather compact cylindrical structure of 988 cubic natural TeO$_2$ crystals of 5 cm side (750 g), arranged into 19 separated towers (13 planes of 4 crystals each) and operated at a temperature of 10 mK. At such temperature, these detectors have an energy resolution of a few keV over their energy range, extending from a few keV up to several MeV. The measured resolution in the region of interest (2527 keV) is about 5 keV FWHM; a background level of the order of 0.01 c/keV/kg/y is expected by extrapolating the CUORICINO background results and the dedicated CUORE R&D measurements. Considering the high mass of the experiment, the CUORE predicted limit, after 5 years of running sensitivity, for the half-life is $2.1 \times 10^{26}$ y (90% C.L.) corresponding to $m_{\nu} \leq (24-83)$ MeV. CUORE will therefore allow a close look at the IH region of neutrino masses.

As well as being protected by the Gran Sasso rock, the apparatus is protected by a series of shields, including ancient Roman lead for the utmost reduction of residual radiation in the Laboratory and to allow the detection of the very rare decay. Very recently the Laboratory has received additional 120 lead bricks (4 tons) from an ancient Roman ship that sunk off of the coast of Sardinia 2.000 years ago. CUORE will be installed in the Gran Sasso National Laboratory and will start the data taking in 2014. The first CUORE tower, CUORE-0, composed by 52 bolometers, is under preparation and will start the data taking in 2011.

### 4 Nuclear astrophysics and LUNA

Nuclear astrophysics aims at the knowledge of thermonuclear reactions responsible for the stellar luminosity and for the synthesis of the chemical elements. In the energy region of interest (generally below 100 keV, lower than the Coulomb energy) the cross section undergoes an exponential decrease as the energy itself decreases. Its extremely small value has always prevented from direct measuring in a surface laboratory where background events, produced by the interactions of cosmic rays, are by far dominant.

In order to start measuring in this unexplored nuclear astrophysics region, LUNA collaboration has installed two accelerators - 50kV and 400kV - in the Gran Sasso underground Laboratory. The qualifying characteristics of both the accelerators are the very high beam current and the very small energy spread. High pure solid and gaseous targets have been developed, while silicon, ultrapure germanium and a segmented BGO detector have been used. The cross sections of the key reactions of the proton–proton chain and of the Carbon–Nitrogen–Oxygen (CNO) cycle have been measured by
LUNA right down to the energies of astrophysical interest [8]. Currently only the 400 KV accelerator is being used whereas the 50KV one has been dismissed in 2005. The measurement of key reactions of the He burning cycle is relevant at higher temperatures than reactions belonging to the hydrogen-burning studied by LUNA so far, and it requires high energy accelerators. The collaboration has recently submitted to LNGS Scientific Committee an update of a previous letter of intent for a research program devoted to the He burning reactions using a 3.5MV accelerator; in this very LoI the experimental conditions and neutron production rates have been re-evaluated and the machine characteristics have been better specified. A possible location at the LNGS interferometric zone has been agreed, a detailed technical study of the “B node” preparation in LNGS was completed, GEANT4 simulations for neutron fluxes calculations were accomplished and the layout and shielding of the accelerator are under study. Moreover a successful round table was organized at LNGS in order to gather new interested collaborators.

5 Conclusions

Neutrino and astroparticle physics would not been able to make the massive progress seen in the last thirty years without the necessary great infrastructures like underground laboratories. The present scientific program of the Gran Sasso Laboratory is at the top of its life thanks to a very broad spectrum of competitive experiments. Last years have been very successful: new experiments have come into operation and relevant scientific results have been published.

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