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Gran Sasso laboratory: Present and prospects

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Summary. — Research activities carried out at the underground Gran Sasso laboratory are reviewed.

PACS 13.15.+g – Neutrino interactions.
PACS 29.40.Mc – Scintillation detectors.
PACS 23.40.-s – β decay; double β decay; electron and muon capture.
PACS 95.35.+d – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Description

The Gran Sasso underground laboratory has been operational since 1987. Gran Sasso laboratory at present is the largest worldwide underground research facility with a total excavated volume of 180000 cubic meters. The average rock coverage is 1400 m, which gives a cosmic rays flux reduction of a factor 10^6. The cosmic muon flux underground is about $1\,\mu/\text{m}^2/\text{hour}$. The laboratory is divided into three main experimental halls, each about 100 m long, 20 m wide and 18 m high. A number of service tunnels are present. The laboratory has a horizontal access which allows the possibility to drive underground. A comprehensive description of the Gran Sasso laboratory can be found in [1] (see also: `http://www.lngs.infn.it`).

The research carried out at Gran Sasso covers:

- Neutrino Physics with long baseline projects, solar neutrinos, terrestrial and core collapse neutrinos and neutrinoless double beta decay
- Direct Dark Matter investigation
- Nuclear Astrophysics
- R&D for low counting detectors and rare processes
- Cosmic muons physics
- Environmental physics underground.

At present Gran Sasso hosts some 20 experiments deployed in the main halls and service tunnels. A number of achievements has been obtained at Gran Sasso. Some of the results established are the best worldwide. In particular, we recall the main results established on:

- evidence of neutrino oscillations both in appearance (OPERA [2]) and disappearance (OPERA and ICARUS [3]) with the CERN-Gran Sasso neutrino beam (the beam was stopped in 2012)
- atmospheric neutrino oscillations with MACRO [4] before the year 2000
- solar neutrinos with Borexino [5] at present and GALLEX/GNO [6] before 2001
- terrestrial electron anti-neutrinos (so-called geo-neutrinos) with Borexino
- double beta decay search with GERDA [7] and CUORE (under construction) [8], in the past by HdM experiment [9]
- direct dark matter search with DAMA/LIBRA [10], XENON-100, XENON-1t (under construction) [11], CRESST [12] and DarkSide-50 [13], in the past by WArP as well [14].
- nuclear astrophysics with LUNA-400 [15]
- core collapse supernova neutrinos with LVD [16] and Borexino
- world records on a number of rare processes bounds such as Violation of Pauli Principle and nucleon decay.

Gran Sasso laboratory is well suited for rare processes search due to the low environmental background. ^{238}U and ^{232}Th are at the level of 5 and 0.3 Bq/kg, respectively. The radiogenic neutron flux ($> 10\,\mathrm{MeV}$) is at the level of $10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The cosmogenic neutron flux is a factor of 10 smaller. The gamma rays flux ($< 3\,\mathrm{MeV}$) is about $1\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

2. – Neutrino physics

In this review we do not take into consideration results from OPERA [2], ICARUS [3], Borexino [5] and GERDA [7] discussed elsewhere in these proceedings. In this context we underline that the energy for neutrino sources studied at Gran Sasso ranges from sub-MeV for solar neutrinos to tens of MeV for supernova neutrinos, to tens of GeV for accelerator and atmospheric neutrinos. In the study of neutrino oscillations what matters is the energy and the baseline between the source and the detector. At Gran Sasso the baseline changes from hundred of kilometers for accelerators and reactors, to ten thousand kilometers for up going neutrino induced muons, to one A.U. for solar neutrinos, to the extreme case of core collapse neutrinos. In 1987 neutrinos from a core collapse in the Great Magellanic Cloud at about 50 kpc were observed on Earth in three different detectors: Kamiokande-II, IBM and Baksan. The Gran Sasso Laboratory with LVD and Borexino is a supernova neutrino observatory.

At present the picture of neutrino oscillations is rather well established using Gran Sasso laboratory results as well.

Another source of neutrinos observed at Gran Sasso are neutrinos from radioactive long-lived elements in the crust and mantle, so-called geo-neutrinos, and the electron anti-neutrinos produced in nuclear reactors. Due to the baseline ($> 1000\,\mathrm{km}$ on average) and the energy ($< 10\,\mathrm{MeV}$) the effect of oscillations for these neutrinos is a simple reduction factor of about 50%.

In the future neutrino oscillations at Gran Sasso will be studied with a short baseline ($\sim 10\,\mathrm{m}$) experiment which makes use of neutrinos produced by e-capture in ^{51}Cr [17]. Moreover, in the case a new neutrino beam will be built, a large liquid argon detector (10 kton), as an example, could be installed underground for CP violation searches and mass hierarchy.

3. – Direct dark matter searches

Presently, the most important aim in astroparticle physics is the experimental detection of dark matter particles. From astrophysics and cosmology there are strong indications of the presence of non-baryonic cold dark matter. Dark matter is distributed around galaxies in a so-called galactic halo. At Gran Sasso the direct search for dark matter is carried out by a number of experiments which aim to observe dark matter particles in the galactic halo: DAMA/LIBRA with high purity NaI scintillators; XENON with a two-phase liquid Xe TPC; DarkSide with a two-phase liquid Ar TPC; CRESST with $CaWO_4$ bolometer scintillators. DAMA and XENON have already been discussed in these proceedings [18, 19]. In the following we take into consideration DarkSide which makes use of underground LAr. In this case a 50 kg LAr two-phase TPC views by 38 3 inch PMTs is installed inside a stainless steel cryostat. The cryostat is inside a stainless steel sphere of 2 m in radius. The sphere is equipped with 110 8 inch PMTs and filled with a boron loaded liquid scintillator. The sphere works as a neutron veto to reduce the radiogenic background coming from the material the cryostat and TPC are made of. The signal from the TPC consists of a prompt scintillation event in liquid and a secondary event in gas after drifting the ionization electrons produced in the liquid phase. The different ionization of e-like background events and dark matter interactions allows to reject the background with a high efficiency. The neutron veto is installed inside a $1000\,\mathrm{m}^3$ water Cherenkov detector. Due to cosmogenic ^{39}Ar which is a β emitter with 1 Bq/kg activity, in DarkSide the argon is taken from underground CO_2 reservoir. The extraction and purification process allow to store LAr with less than 1% of ^{39}Ar with respect to standard argon. DarkSide-50 is presently taking data. The sensitivity of DarkSide-50 is 3 years of data taking is estimated to be $\sigma_{\chi p} \sim 10^{-45}\,\mathrm{cm}^2$ for $m_\chi = 50\,\mathrm{GeV}/c^2$.

In the dark matter sector, depending on the results from DAMA/LIBRA, XENON-1t, CRESST and DarkSide-50, further developments at Gran Sasso are foreseen with larger and reduced background set-ups. In the next few years we expect new results from XENON-1t, in construction, and DarkSide-50, in data taking. In particular, a DarkSide-3t is under consideration. Both XENON-1t and DarkSide-3t could reach a sensitivity of $\sigma_{\chi p} \sim 10^{-47}\,\mathrm{cm}^2$ for $m_\chi = 50\,\mathrm{GeV}/c^2$.

4. – Neutrinoless double beta decay

As far as neutrinoless double beta decay search is concerned, Gran Sasso laboratory is very successful. The search for neutrinoless double beta decay is a unique method to determine the nature of neutrinos, Dirac or Majorana particles, and probe the neutrino mass. The isotope under consideration in experimental activities at Gran Sasso are: ^{130}Te with CUORE, ^{76}Ge with GERDA and ^{82}Se with Lucifer [20]. Moreover, there are R&D activities with ^{116}Cd and ^{136}Xe. In the coming years the research in this field will focus on: 1) GERDA-II which aims to obtain a background at the level of 10^{-3} cts/keV/kg/year for 38 kg of ^{76}Ge; CUORE with a predicted background of 10^{-2} cts/keV/kg/year for 206 kg of ^{130}Te. Moreover, further developments with the present know-how and R&D activities on scintillator bolometers [20] can open new opportunities to push further the sensitivity for neutrinoless double beta decay.

5. – Nuclear astrophysics underground

Gran Sasso laboratory has an important tradition in nuclear astrophysics underground with the LUNA set-ups [15]. LUNA started taking data in 1999 with a 50 kV accelerator, proving the technique works successfully underground. LUNA aims to measure cross sections for interactions taking place in the core of stars. The cross section must be measured as close as possible to the Gamow peak to avoid extrapolation errors. For processes of interest in nuclear astrophysics Gamow peak energies range in 10–100 keV. Therefore, cross sections are of the order of 10^{-39}–10^{-33} cm^2 and this implies the need to go underground in order to reduce the background. In the year 2000 LUNA installed a 400 kV facility to measure fundamental cross sections for the pp and CNO burning cycles. At present LUNA is proposing a new installation with a 1 MV accelerator which aims to study the following processes: ^{12}C$(\alpha,\gamma)^{16}$O, ^{13}C$(\alpha,n)^{16}$O and ^{22}Ne$(\alpha,n)^{25}$Mg. In particular, ^{12}C$(\alpha,\gamma)^{16}$O is considered the "holy grail" of nuclear astrophysics. LUNA-MV should start taking data in 2016.

6. – Conclusions

The Gran Sasso laboratory has a number of leading experimental efforts in rare processes search for dark matter and neutrinoless double beta decay. These projects will lead the field in the coming years. Gran Sasso has a short term project with an artificial neutrino generator to be coupled with the Borexino detector, named SOX. This proposal aims to measure the electron-neutrino interaction at 1 MeV on a baseline of 10 m. Gran Sasso has also a strong and unique program on nuclear astrophysics. Due to the successful completion of OPERA and ICARUS, experimental space underground for new projects will be available starting in 2016 at Gran Sasso.

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