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Physics (almost) without accelerators

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Summary. — In this paper I will review the Astroparticle Physics activities carried out by Istituto Nazionale di Fisica Nucleare, the main Italian organisation dealing with basic research in Physcs. I will focus the paper on few selected highlights and in particular on the activities of the Gran Sasso Laboratory.

PACS 96.50.S- – Cosmic rays.
PACS 29.40.-n – Radiation detectors.
PACS 14.60.Pq – Neutrino mass and mixing.

1. – Introduction

INFN is the main physics research institution in Italy, its activity encompassing a broad range of research topics. The activities are organised in five main lines [1]. The so called "Line 2" deals with "Physics without accelerators", and is divided into five sub-lines, namely:

– Neutrino Physics

– Dark Matter

– Cosmic Rays

– Gravitational waves

– General Physics

As we will see, some of the activities are not completely devoid of the use of accelerators, hence the title of this paper. The first four lines are generally known as "Astro-particle" physics, as they combine aspects of both astrophysics and particle physics. The term was first introduced by our colleague V. Berezinski of the Gran Sasso Science Institute. Because of the need of special environments to carry out research in astroparticle physics, the experiments are often located in remote places. For example, the Pierre Auger Observatory [2], the largest array for the observation of high energy cosmic rays, needs a large (3000 km^2), flat surface, with minimal light pollution, and was hence built in the Argentinian pampa [2]. On the other hand, air-Cherenkov telescopes need less surface

Fig. 1. – The Gran Sasso Laboratory. Left: the underground laboratory layout and occupancy. Right: the external infrastructures.

but have to be placed at relatively high altitudes and in clear skies. The MAGIC [3] observatory is in fact located on a mountain top in the island of La Palma (Canary Islands). Neutrino observation needs typically deep underground or underwater environments: the ANTARES and NEMO [4, 5] experiments are complex installations of photomultipliers arrays in the depths of the Mediterranean sea. Finally, the observation of primary cosmic rays particles implies direct observation from the top of the atmosphere or from space, like the FERMI-GLAST [6] observatory, the PAMELA [7] and AGILE [8] satellites or the AMS experiment [9, 10].

Some of the studies carried out in astroparticle physics, and in particular neutrino studies and dark matter searches, need especially "quiet" environments, where the radioactive background is minimised. The Gran Sasso Laboratory (LNGS), located at about 100 km NE of Rome, is an underground facility where the cosmic radiation intensity is about 10^6 times lower than on the Earth's surface. There, some of the world's best experiments for neutrino physics and rare events search are located, and there I will focus the rest of this review.

2. – The Gran Sasso Laboratory

The Gran Sasso Laboratory is presently the largest underground infrastructure dedicated to basic research. It is comprised of three large experimental halls, interconnected by a network of tunnels, for a total volume of about 180000 m^3 excavated below 1400 m of limestone rock, equivalent (as shielding power for cosmic rays) to a flat overburden of 3100 m of water. Figure 1 (left) shows a schematic view of the laboratory with the present occupancy. Figure 1 (right) shows a view of the external facilities (offices, machine shop, warehouse, guesthouse) located in the Gran Sasso National Park. The Gran Sasso Laboratory is a unique infrastructure, where the *cosmic silence* allows scientists to perform a variety of experiments, not only of particle physics and astrophysics, but also of fundamental physics, biology and geology.

3. – Solar neutrinos

Neutrinos are abundantly emitted by the Sun, their flux at Earth being approximately $6 \times 10^{10}\,\text{cm}^{-1}\,\text{s}^{-1}$. They are produced in the Sun's core (within 0.24 solar radii) via a fusion reaction chain whose bulk is constituted by the process: $p + p \rightarrow d + \nu_e + e^+$. Neutrinos coming from this reaction may have up to 0.4 MeV of energy. Neutrinos of

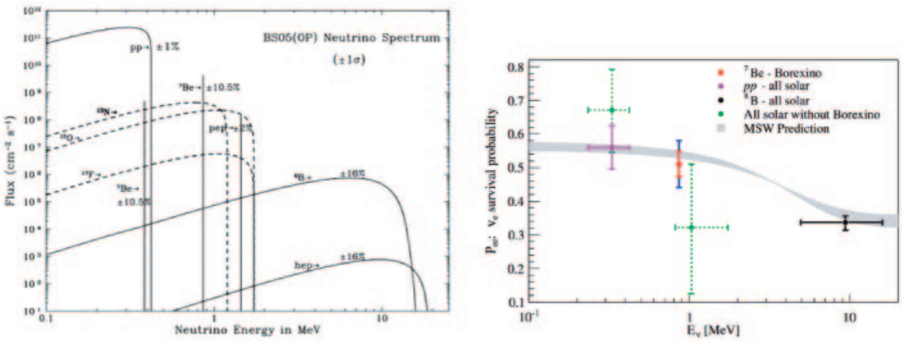

Fig. 2. – Left: the solar neutrino energy spectrum, from [11](CNO cycle not shown). Right: low energy solar neutrino measurements and the MSW prediction, from [20]

higher energies (up to 18 MeV) are emitted by other reactions, but with intensities that are orders of magnitude smaller than *pp* neutrinos (see fig. 2).

In 1964, Ray Davis [12] proposed an experiment to detect solar neutrinos to verify the supposed energy production mechanism of the Sun. A few years later, B. Pontecorvo proposed instead to use solar νs as a beam to study whether these particles exhibited behaviours consistent with a nonzero rest mass. The same experiment could therefore be aimed to astrophysics and particle physics at the same time, a perfect, *ante litteram* example of astropatricle physics. As any beam experiment, knowledge of the source is essential, and Pontecorvo was then pessimistic: *Unfortunately, the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos* [13]. However, thanks to the efforts of J. Bahcall and others [11, 14] the knowledge of the Sun and its neutrino flux became eventually precise enough to allow predictions. The "solar neutrino problem" was just about to start: from Davis's chlorine experiment on, all experiments [15, 16] failed to find the correct flux. Eventually, the picture became clear thanks to the SNO experiment at Sudbury (Canada) [17]. Because of their nonzero rest mass, the mass and weak interaction eigenstates of neutrinos do not coincide, making it possible the process of "neutrino oscillations". Because of this effect, a fraction of the νs emitted by the Sun fails to be detected by experiments sensitive to ν_e only. Neutrino oscillations are correctly described by the Mikheyev-Smirnov-Wolfenstein model [18, 19] that yields a precise prediction for the low energy solar neutrino spectrum (see fig. 2, from [20]), that cannot be checked by water Cherenkov or chlorine detectors due to their high threshold (around 5 MeV). The Borexino experiment was built to address this issue, and is presently the only solar neutrino detector operating at Gran Sasso [20]. Borexino detects solar neutrinos via elastic scattering on electrons in 270 t of hyper-pure liquid scintillator seen by 1,350 photomultiplier tubes (see fig. 2). The fiducial volume is surrounded by 1000 t of non-scintillating mineral oil, enclosed in a stainless steel sphere thait is contained, in turn, in a vessel containing 2100 t of demineralised water. This "graded shielding" approach allows to reach, in the sensitive volume, enough radio-purity to disentangle the weak solar neutrino signal from the otherwise overwhelming background. Borexino is able to see the lowest energy part of the solar neutrino spectrum, and more specifically the 862 keV line of the ^{7}Be decay (see fig. 2). Despite a lengthy start due to technical reasons, Borexino has been in full scientific production for

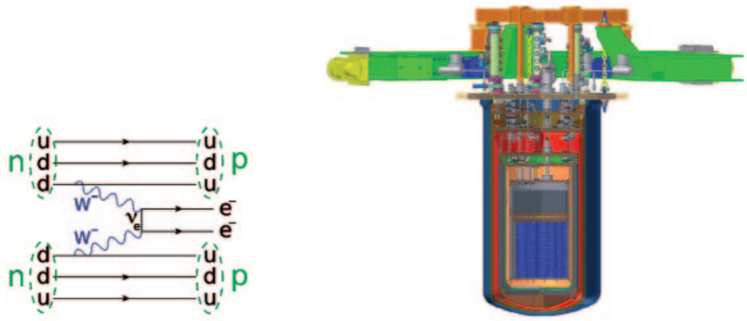

Fig. 3. – Left: diagram of a zero neutrino double beta decay. Right: Drawing of the CUORE array inside the cryostat.

years. The ^{7}Be line has been observed [20] with high precision as well as the flux of neutrinos of the weak "pep" reaction ($p+e^- + p \rightarrow {}^2H + \nu_e$). Those two measurements have now completely pinpointed the MSW model as the correct description for solar neutrino oscillations. Furthermore, Borexino has put the most stringent limit on the occurrence of the carbon-nitrogen-oxygen (CNO) cycle in the Sun. Such cycle is a catalytic process that should occur in stars of more than 1.3 solar masses and is strongly dependent on the solar modelling [21]. Finally, Borexino has measured for the first time neutrinos coming from the Earth, giving birth to "geoparticle physics" [22]. A more detailed account of Borexino is given by the talk of N. Rossi in this same conference [23].

4. – Double beta decay

A "neutrinoless double beta decay" (0-ν DBD) may occur if neutrinos are Majorana particles, that is, they coincide with their own antiparticle. The Feynman diagram for such a process is shown in fig. 3. The rate of this process is proportional to the square of the effective Majorana neutrino mass. Therefore, the detection of this process would give some insights on the absolute value of the neutrino mass eigenstates. Because of the absence of neutrinos, the two electrons carry all the energy released in the process and the "smoking gun" of 0-ν DBD is a monoenergetic line. Two isotopes that may undergo 0-ν DBD are ^{76}Ge and ^{130}Te, with, respectively, 2039 keV and 2527 keV of energy carried by the electrons. Detectors aiming at seeing this rare -if at all existent- process, must therefore minimise the background in those energy regions. A longstanding program for the detection of 0-ν DBD is CUORE [24] that makes use of TeO_2 crystals arranged in "towers" that have grown, with time, in size and numbers. The program started back in 1997 with the Milano Double Beta Decay experiment [25] which made use of 20 crystals for a total of about 7 kg. The second milestone has been the successful CUORICINO experiment [26], with 44 crystals, that pushed the limit on the half life of ^{130}Te (via neutrinoless DBD) up to 2.8×10^{24} years. The bigger CUORE apparatus is now under construction, and will feature 40 towers and 988 crystals of $5 \times 5 \times 5\,\text{cm}^3$, enriched with 206 kg of ^{230}Te. CUORE will push the limit on the half life up of two orders of magnitude and reach a sensitivity for the Majorana neutrino mass of about 0.05 eV. Another experiment aimed to the detection of 0-ν DBD is GERDA [27, 28], that uses instead ^{76}Ge high purity diodes immersed in a liquid argon bath for cooling and shielding purposes, the whole system immersed in a 10 m diameter water tank. One of the goals of

GERDA is to verify a previous, controversial claim by the Heidelberg-Moscow experiment (also at Gran Sasso) [29] about the occurrence of 0-ν DBD in ^{76}Ge. The first phase of GERDA makes use of about 30 kg of Ge. That phase ended in the summer of 2013 and soon after the phase II will start with the addition of about 20 kg of enriched Ge and the implementation of a liquid argon active scintillation veto. The result of phase I yielded a lower limit on the half life of ^{76}Ge via 0-ν DBD of $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ years [30], a result that does not support the previous claim [29].

5. – Long baseline neutrinos

A flagship program of European neutrino physics is certainly the CNGS, the long baseline neutrino beam from CERN to Gran Sasso. The neutrino beam was started in 2006 and ended in 2012, after a total of about 18×10^{19} protons on target ("pot"). The goal of the CNGS program was to single out τ neutrinos in the beam made mostly of muon neutrinos (with small contaminations of anti-ν_μ and ν_e). At LNGS, two main experiments are dedicated to the beam observation the ICARUS-T600 liquid argon detector [31] and OPERA [32]. The latter experiment detects neutrino charged current interactions with the "emulsion cloud chamber technique" (ECC). This technique makes use of photographic emulsion sheets sandwiched between 1 mm lead plates. 150000 "bricks" of ECC are present in OPERA, about 30 of them hit each day by a neutrino interaction with the CNGS beam on. The relevant brick is identified in real time by an active scintillation detector system (Target Tracker) and subsequently developed and analysed through a complex process. The analysis of OPERA has so far found three events compatible with the appearance of a τ neutrino. The first was found in 2009 ($\tau^- \to \rho^- \nu_\tau$), a second one in 2011 ($\tau^- \to 3$ hadrons) and a third one in 2012 ($\tau^- \to \mu^-$). OPERA was also able to put a limit on non-standard $\nu_\mu \to \nu_e$ oscillations as suggested by the LSND experiment [33, 34].

With the same beam, a precise measurement of the neutrino speed was attempted by OPERA with an initial misleading result suggesting superluminal neutrinos. That puzzling result prompted all the experiments of Gran Sasso, together with the CERN, to perform high accuracy measurements of the neutrino velocity [35-37] confirming that neutrinos do not violate Einstein's special relativity. For more updates of ICARUS and OPERA see also [38, 39].

6. – Dark Matter

The search for massive, weakly interacting particles (WIMPs) in underground laboratories is justified by several hints of the existence of "Dark Matter". The idea of "direct detection" [40] is based on the possibility to detect the nuclear recoils originated by the rare interactions, if any, of the DM particles with the target nuclei. Two kinds of interactions can be envisaged, a scalar coupling ("spin independent" — SI), where the WIMP couples to the nucleus as a whole ($\propto A^2$), or a vector coupling ($\propto J(J+1)$) normally referred to as "spin dependent" (SD). The expected rate of interaction is

$$R \approx N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle, \quad (1)$$

where N is the number of target nuclei in the target; ρ_χ the density of DM particles; m_χ the mass of the DM particle; $\sigma_{\chi N}$ is the cross section for WIMP-nucleus elastic

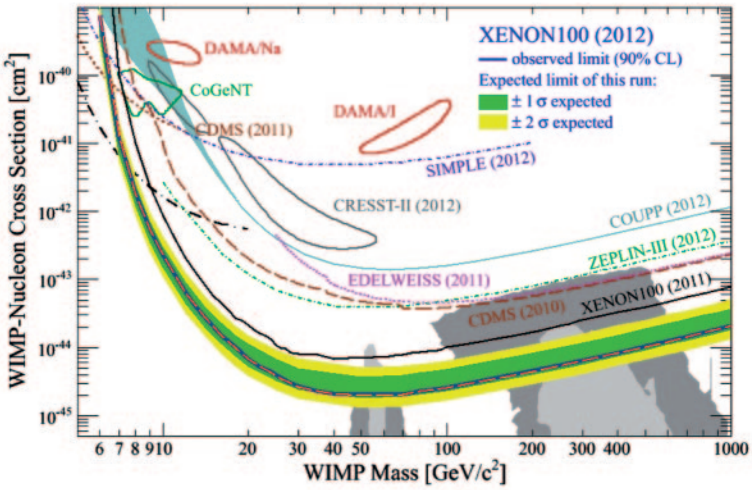

Fig. 4. – Current experimental situation of direct dark matter searches in the framework of spin-independent, WIMP-nucleus elastic interaction. Figure taken from [49].

scattering; $\langle v \rangle$ is the speed of the Earth with respect to the DM halo. The expected rate of the order of one event per 1 t per year. The typical recoil energy would be of the order of 10 keV. Such a low rate of extremely low energy events would never be detectable in any above ground location. The underground environment takes advantage of a reduced, but definitely not zero, residual flux of high energy muons [35]. The residual muons and associated neutron flux, and the radioactivity of the rocks motivate the need for further shielding of the apparatuses looking for DM interactions. The typical DM detector has an "onion-like" shielding structure where each layer targets a specific background. Water or polyethylene, given their hydrogen content, stop neutrons and, if the water is made active with photomultipliers, also may tag muons and associated particles. High purity copper and lead, typically placed in the inner layers, stop gamma radiation to enter the detector. Finally, discrimination techniques, based either on the shape of the pulses or on the use of multiple detection channels (scintillation light, ionisation charge or phonons) further enhance the signal to noise ratio, allowing to single out samples of nuclear recoil events with high efficiency. The current experimental scenario is shown in fig. 4. This is the usual plot where many experiments compare their results in the space of WIMP-nucleus elastic cross section *vs.* WIMP mass. This implies the assumption of an interaction model that may distort the true comparison of different results. In fact, in the same figure we can see positive results (see DAMA, CRESST) along with exclusion curves from other experiments. The DAMA-LIBRA experiment [41, 42] uses scintillation light, with 250 kg of high-purity NaI organised in a matrix of 25 crystals seen by photomultipliers. The whole setup is characterised by extremely stable conditions that allow to reach a threshold as low as 2 keV. DAMA-LIBRA observes a seasonal variation of the event rate with a maximum around end of May and one year phase. This modulation is indeed what is expected from the relative motion of the Earth with respect to the DM halo [43]. DAMA-LIBRA's signal is now firmly established over more than 8 years. However, to accept this as a true DM signal, an independent confirmation would be needed.

CRESST [44] is a cryogenic experiment using about 10 kg of target in the form of calcium tungstate ($CaWO_4$) cylindrical crystals with a mass of 300 g each. Each crystal is equipped with two readout channels, made with Transition Edge Sensors [45]. The bottom sensor acts as a phonon detector, while the top one, thanks to a layer of silicon light absorber, detects scintillation photons. The scintillation yield of heavier particles tends to be lower, and this allows to single out nuclear recoils from the electron background. CRESST published [44] the result of the analysis of 730 kg days. They saw 67 events in their acceptance region, with an expected background of about 44 events. If interpreted as a true signal, it would mean a WIMP of a mass around 20–50 GeV (see fig. 4). Improvements of the detector setup are under way, specifically addressing some of the sources of background.

7. – Charge and light: double phase TPCs

Time projection chambers with noble liquids such as Ar and Xe are powerful and easily scalable detectors. The detector's core system is a cryostat containing the noble liquid with a layer of gas at its top. Both phases are exploited by this technique, as explained below. An interaction in the liquid produces direct scintillation photons (S1) and ionization electrons. An electric field is applied across the volume with appropriate potentials on a series of electrodes, drifting ionization electrons away from the interaction zone. Electrons which reach the liquid-gas interface are extracted into the gas, where another scintillation signal (S2), proportional to the ionisation charge, is produced. Both the S1 and the S2 scintillation signals are detected by photomultiplier tubes. The ratio S2/S1 produced by a WIMP (or neutron) interaction is different from that produced by an electromagnetic interaction, allowing a rejection of the majority of the gamma and β particle background. This detection principle has been adopted both with liquid xenon (LXe) and liquid argon (LAr). There are important differences between the two liquids that make them complementary targets. At the Gran Sasso Laboratory, two collaborations make use of this technique, DarkSide [46] (with argon) and XENON. I will focus the XENON program, currently considered the most advanced. The present detector, XENON100, is characterised by a careful selection of all detector materials regarding intrinsic radioactivity, a xenon target with lower ^{85}Kr contamination, a novel detector design leaving only low radioactive components close to the target, and by an improved passive shield. Furthermore, XENON100 features an active LXe veto. The energy response of LXe at low recoil energy has been measured with a dedicated setup [47]. XENON100 has set the most stringent limit for a very large range of WIMP masses [48, 49] and is currently the highest sensitivity LXe TPC in operation. The current limit has a minimum of $2 \times 10^{-45}\,\text{cm}^2$ at 55 GeV and 90% confidence level (see fig. 4 [49]).

While the XENON100 detector is still running, the next generation detector, XENON1T, with a fiducial mass of about 1t and a total mass of 2.5 t, has been designed. XENON1T will be installed in the Hall B of the Gran Sasso Laboratory, starting in 2013.

8. – Conclusions

The field of astroparticle physics is an extremely diverse and exciting playground, where the discovery of new physics may be just around the corner. The Gran Sasso Laboratory of INFN is the world's biggest and best equipped infrastructure for astroparticle and underground physics. In particular, given the number and quality of the experimental activities, it might be the place where the discovery of the nature of dark matter will happen.

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