The WArP Experiment

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Abstract. Cryogenic noble liquid detectors are presently considered one of the best options for WIMP Dark Matter searches, especially when extensions to multi ton scale sensitive masses are foreseen. The WArP experiment is the first one that exploits the unique characteristics of liquid Argon to make a highly sensitive search for WIMP Dark Matter candidates. In 2008, a double phase detector has been assembled in the Gran Sasso National Laboratory with 140 kg sensitive mass and a discovery potential in the range of $5 \times 10^{-45}$ cm$^2$ in the spin-independent WIMP-nucleon cross-section. In addition to standard neutrons and gamma-rays passive shields, WArP implements an 8 ton liquid Argon active shield with $4\pi$ coverage. The detector was commissioned and put into operation during the first half of 2009 for a first technical run. Detector design, construction and assembly are described, together with the very first results of this technical run.

1. Introduction

Increasing efforts are being made to unveil the nature of Dark Matter, especially since its existence was definitively certified by astrophysical and cosmological observations [1]. Several possibilities for Dark Matter constituency are seriously considered although a central role is presently played by direct WIMP searches due to the potential link with the SUSY hypothesis.

In the last ten years several technologies have grown up from the laboratory scale to full size experiments running or to be run in several underground locations [2]. Despite the increasing efforts...
made by the present experiments, the positive signal claimed by the DAMA Collaboration in terms of seasonal variations [3] still stands without an independent confirmation or clear disproof. In this scenario there are already many proposals for upgrades of the presently adopted technologies to sensitive masses of the order of few tons with increasing complexity in terms of shielding and background control in order to fully explore the predicted regions of the minimal SUSY hypothesis. Noble liquid detectors play a central role in this future scenario due to their potentiality for the instrumentation of very large sensitive masses. WArP is the very first experiment that exploits the characteristics of Liquid Argon (LAr) for direct Dark Matter searches.

The WArP technology was established in several years of R&D studies. They were started at CERN at the beginning of the nineties with pioneering works with liquid Xenon in the framework of the general R&D activities of the Icarus experiment [4]. When the concept of double phase chamber as a tool for direct Dark Matter searches was put forward [5], around the mid of the nineties, we opted for argon as our primary choice for a number of reasons [6]. As a liquid scintillator, argon has a very good light yield: about 20 eV are required, for a relativistic electron, to produce a scintillation photon, just slightly lower than the one of liquid xenon [7]. Scintillation light is emitted at 128 nm wavelength, in the Vacuum Ultraviolet Region, and specific methods have to be implemented to wave shift and efficiently collect it. Contrary to liquid xenon the fast (singlet) and the slow (triplet) components of the scintillation light are very widely separated: the fast component is emitted with a decay time of about 7 ns while the slow component has a decay time of about 1400 ns [8]. This separation allows for very efficient identification of nuclear recoils against gamma and beta backgrounds by means of pulse shape discrimination with methods similar to the ones commonly in use with specific organic scintillators. Liquid argon has a very high electron mobility, it is available in large quantities at low cost and can be easily purified from electronegative impurities allowing for very long drift distances, of the order of several meters, for free electrons as amply shown by the results obtained by the Icarus Collaboration [9]. On the other side, argon is contaminated by $^{39}$Ar, a β active isotope with 269 years half-life and end point at 565 keV; $^{39}$Ar is produced by interaction of cosmic rays in the upper atmosphere and is giving a β activity in commercially available liquid argon of about 1 Bq / kg [10]. Argon nuclei have no spin, so that spin-independent only interactions are allowed. The relatively low atomic mass of argon results in a lower integrated cross-section for elastic scattering off nuclei, which is proportional to $A^2$ due to the coherence effect, when compared to other materials like xenon and germanium. On the other hand the recoil spectrum is more energetic because of the nuclear form factor, so that at a recoil energy threshold of about 30 keV, the integrated rates in argon, xenon and germanium are almost the same but with recoil energies in argon that extend well above the ones from the other targets.

After the pioneering works done in CERN, the R&D activities were also carried on in the laboratories of the Collaboration groups: in Pavia, Padova, Naples, LNGS and later in Princeton. Various technical issues have been investigated in details: electrons extraction from liquid to gas, secondary light production and its proportionality to the extracted charge, light wave-shifting, methods for light collection and their optimization, photomultipliers (PMTs) behavior at cryogenic temperatures, materials behavior and their radioactivity, effects of argon pollutants, procurement of low activity argon either by isotopic separation of commercial argon or by extraction of “aged” argon from underground sources [11]. A key role has been played by a 2.3 liters prototype built at the beginning of years 2000. This device has been widely used (and it is continuously used) mainly to qualify the technical solutions to be implemented in the 100 liters detector. In 2004 it was taken to LNGS to extend the R&D activity. It has been run underground in several conditions. With full passive shields it was able to provide a very convincing limit on spin-independent WIMP-nucleon cross-section [12], even though the internal backgrounds were intentionally not kept at optimal levels, thus proving the goodness of the reached technological advances.

Design and construction of the 100 liters started in 2004 soon after the approval of the experiment proposal by INFN. In 2006 also NSF decided to approve the WArP proposal and provided the funds necessary to complete the detector instrumentation.
2. Design and construction of the 100 liters detector

The basic scheme of the 100 liters detector is shown in figure 1. Starting from the center, the detector consists in:

a) the inner detector: a double phase chamber with 100 liters of liquid volume surmounted by a gas volume where the readout PMTs are placed;

b) the active shield completely surrounding the inner detector, with a minimum thickness of 60 cm, for a total liquid argon volume of about 5600 liters, and readout by a set of PMTs placed on the external surface;

c) an internal passive shield made of polyethylene with 10 cm thickness, to filter neutrons coming from the main cryostat walls;

d) the main cryostat, made of stainless steel, with double walls, super-insulated under vacuum, with an internal volume of 30 m$^3$ of which 23 m$^3$ are to be filled with LAr;

e) an external passive shield made of 10 cm thick lead, encapsulated in stainless steel boxes, plus a 70 cm thick layer of polyethylene;

f) an external, anti-seismic, sustaining structure made of carbon steel;

g) circuits for the cryostat cooling and for the purification and recirculation of the liquid argon.

All the internal surfaces of the inner detector and the active shield are covered with a reflector / wave-shifting layer made of a highly reflective plastic foil onto which a highly efficient wavelength shifter (TetraPhenylButadiene – TPB) is deposited. For optimal uniformity and efficiency, the
wavelength shifter deposition is made by thermal evaporation under vacuum, with a specially designed evaporation system. The inner detector and the active shield are optically separated, but the argon volume is the same so that no independent filling and purification systems are required.

The inner detector can be subdivided into three regions: the drift region, in liquid phase; the extraction and multiplication region, in gas phase; the light detection region, where the PMTs are placed, in the gas phase. The drift region is delimited by a cathode (an Oxygen Free copper disk with about 50 cm diameter) to be supplied to -75 kV, a stainless steel grid with inner diameter of about 50 cm, placed 60 cm above the cathode, to be put at -15 kV, and a set of circular stripes (copper stripes printed on a Kapton™ substrate) placed every 2 cm between the cathode and the grid, acting as field shaping electrodes (race-tracks) and ensuring in the drift region a uniform field that drives ionization electrons through the grid to the liquid surface. Race-tracks are arranged in a truncated conical shape to prevent ionization electrons from being trapped between the race tracks themselves. Supply voltage is distributed from the cathode to each race-track and to the grid, by means of a resistive divider chain. Above the first grid a second and a third grids are placed, in the gas phase. The field between the first and the second grid is arranged in such a way to provide complete extraction from the liquid of the ionization electrons and to accelerate them in the gas phase in order to produce a suitable secondary, proportional, light signal. Electrons are then decelerated above the second grid and collected on the third one. Voltage is supplied to the second and third grid by means of dedicated high voltage channels. A set of 31, 3” PMTs plus 6, 2” PMTs is placed 3 cm above the third grid. All the PMTs, including the ones of the active shield, are specifically designed to work at LAr temperature, they have glass windows and peak sensitivity (in the range of 20%) at 430 nm wavelength, well matched with the peak emission of the wavelength shifter. The photocathode coverage of the inner detector is about 10%. All PMTs have their divider chains mounted directly on them; divider chains are made of circuits printed on a Kapton™ substrate with discrete components (resistors and capacitors) selected for operation at LAr temperature. All PMTs are negatively biased; the anode signals are readout at ground. PMTs of the inner detector are coated with TPB in a polystyrene matrix to ensure good localization of the secondary signal in the horizontal plane. The upper part of the inner detector is contained into a vacuum super-insulated dewar placed upside down. This dewar is acting as a diving bell with a set of 12 small holes placed in correspondence of the desired liquid level (5 mm above the first grid). A set of heating resistances is placed just below the liquid surface; they continuously boil off the liquid and the produced gas in excess is evacuated through the holes, thus ensuring that the liquid level is precisely positioned. A copper sheet completely surrounds the inner detector. This sheet is grounded, ensuring that the drift fields are confined in the central volume.

The active shield volume is approximately of the shape of a rotational ellipsoid with a vertical axis of 220 cm and an horizontal axis of 180 cm for a total volume (excluding the volume occupied by the inner detector) of 5600 liters (corresponding to 7800 kg of LAr). The active shield mechanical structure is made of Oxygen Free copper pipes and plates and sustains the photomultipliers and the wave-shifting / reflector layers. Both the active shield and the inner detector are suspended to the main cryostat upper flange with adjustable mechanics that allow positioning and alignments to 0.5 mm precision. A total of 300 PMTs (264 of 3” diameter plus 36 of 2” diameter) are placed on the external surface of the active shield for a total photocathode coverage of about 7% of the active shield surface. Two different types of electronics are used to readout the PMTs. The one for the active shield was manufactured by CAEN on a custom design made by the Princeton group and is essentially based on signal digitization and multiplexing after charge integration. The one for the inner detector is based on fast digitization (1 GHz) of the non-integrated signals by means of high performance digitizers manufactured by Aquiris.

Construction of the 100 liters device started in 2005. All construction materials have been subject to strict selection for low radioactive contamination. Samples of all the employed materials have been measured in the LNGS Low Activity Facilities prior to their acceptance for the final construction. After the selection, the main source of unvetoed background for the WArP experiment, resulting from...
materials measurements and from Montecarlo data, is coming from the photomultipliers and is accounted for less than 1 event/ year of exposure.

The detector mechanical components were first delivered in Pavia where they have been completely assembled in order to control and qualify the assembly procedures and the mechanical tolerances. The detector was then dismounted and the components were sent to a specialized industry for cleaning before the final delivery to LNGS. PMTs were subject to very severe testing procedure: each PMT have been tested by the manufacturer in liquid nitrogen for stability and at room temperature for compliance to the specifications (quantum efficiency, dark counts, gain). The phototubes were then sent to Napoli where they underwent an additional set of tests (operational stability and intrinsic noise) in liquid nitrogen. The PMTs were then sent to LNGS for pre-assembly operations installation.

Final detector assembly started in July 2007, when the underground installation area, in LNGS Hall B, became available. The external shield basement, the main cryostat and the anti-seismic supporting structure were first put in place. The assembly clean and dehumidified room was then built and put in operation. Assembly of the internal passive shield followed. In parallel several pre-assembly operations took place in the external laboratories above ground, they consisted in: pre-assembly of the PMTs with Kapton™ bases, cutting and pre-assembly of the reflector foils, thermal evaporation of the wavelength shifter on the reflector foils and quality control of evaporated samples. All the pre-assembled components were taken in the clean room underground for the final installation. The final detector assembly started in June 2008 from the inner detector and was completed in December of the same year. All the PMTs were tested in dark conditions before that the detector was finally moved in the main cryostat around the mid of December. Vacuum pumping started soon after. The detector plant was completed in January 2009 with the installation of the external cooling and purification systems. In parallel, the external shield lead walls were installed together with a first part of the lateral polyethylene external shield.

Figure 2
3. Detector Commissioning

The first phase of the Detector Commissioning was started on Dec. 22nd, 2008 with the vacuum pumping of the cryostat internal volume, combined with a number of cycles of inert gas flushing ($N_2$ at room temperature) for the reduction of the residual $H_2O$ content of the internal materials. This phase lasted about five months (from Dec. 23rd, 2008 to May 5th, 2009).

Initially, leak search, localization and repairs required about one month and successively vacuum pumping lasted up until the design residual pressure was reached as measured by the pressure probes located in various points of the cryostat. During this period external cabling of the PMT’s and of the slow-control sensors (LAr levels, Temperature, Pressure) has been completed. A full test of the PMT signals and HV mapping has also been then performed and validated.

In this phase of the commissioning the composition of the residual gas has been continuously monitored by mass spectrometry. Air components (from residual leaks) and water (from material outgassing) have been identified and monitored during their progressive decrease (e.g. $H_2O$ outgassing rate was, in the last period of the vacuum pumping, $\approx 6 \times 10^{-5}$ mbar lt/sec). The vacuum pumping period was assumed as completed when the residual pressure reached the design value in the range $2 - 6 \times 10^{-6}$ mbar (end of March, 2009).

The second phase of the commissioning procedure (detector Cooling and LAr Filling) was started on May 5th, the first day of resuming into normal operation at LNGS underground – after the suspension of the activities due to the earthquake (during the month of April, vacuum pumping indeed continued without interruptions).

The Cooling phase lasted less than 3 days – via low-quality LAr forced recirculation in the piping system inserted in the vacuum jacket of the cryostat, in thermal contact with the internal wall. This produced a smooth cooling down of the materials inside the cryostat to less than 200 K (in the innermost element of the detector), thus stopping the water outgassing (as seen by the drop of the $H_2O$ partial pressure). The ultimate residual pressure just below 1 x 10$^{-6}$ mbar was then reached.

The following step with the “LAr filling” lasted four more days. Good-quality LAr (equivalent to 5.5 grade) at a speed of about 300 lt/hr was conveyed inside the cryostat through a dedicated vacuum insulated filling line from a movable LAr storage. The line included a large two-stages filter (Oxygen reactant for $O_2$ removal and molecular sieves for $H_2O$ trapping).

During the first day of the filling phase all the inner components (internal Polyetilene shield and detector) were cooled down to LAr temperature and successively the LAr level inside the cryostat increased to the detector operation design level (full immersion of the active veto detector).

On May 13th, the WArP-100 detector Technical Commissioning was successfully completed.

A technical run of the WArP 100lt detector started with the activation of the various components of the detector and of the cryogenic system (May-July, 2009):

- GAr recirculation (liquefaction and purification) activated, allowing direct measurement of the actual total heat load of the system (estimated at a level of $\leq 1$ kW, in agreement with design value).
- GAr/LAr precise level configuration for the two-phase 100lt inner detector successfully established (gas Argon pocket generated and maintained by resistive heaters inside the “bell-shaped” immersed cryostat).
- PMT activation with voltage bias at nominal value with slow HV ramp and individual test.
- DAQ & Trigger for 100lt detector, after initial debugging phase, in run with progressive tuning and optimization of the performance.
- Off-line event reconstruction successfully tested and used for first data analysis.
- HV system for the Inner Detector (connection from external power supply to inner detector cathode): while ramping up the HV a major discharge occurred inside the cryostat along the connection line. This unforeseen event prevented to establish the EF in the LAr volume of the 100 lt detector, necessary for operation in two-phase configuration.

The technical run was then continued in the summer to complete the analysis of the detector response.
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