DARWIN: direct dark matter search with the ultimate detector

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Abstract. DARk matter WImp search with liquid xenoN (DARWIN) is a future experiment for the direct detection of dark matter based on a multi-ton liquid xenon time projection chamber. The main goal of DARWIN is to reach an unprecedented sensitivity to WIMP (Weakly Interacting Massive Particle)-nuclear recoil cross sections for a large WIMP mass range, down to the level where the irreducible background from neutrino interactions with the target is dominant. This ultra-low background experiment will also have competitive sensitivity to test other dark matter hypotheses such as dark photons and superWIMPs and to detect other rare events like solar neutrinos, neutrinoless double-beta decay of $^{136}$Xe, solar axions and neutrinos from galactic supernovae. In this paper we present the design of the DARWIN detector and the estimated WIMP sensitivity based on the expected backgrounds. Other rare event searches are also discussed.

1. Introduction

Many pieces of evidence of the existence of non-luminous dark matter have been observed on very different length scales, from cosmological to Milky Way sized galaxies, through its gravitational interaction with ordinary baryonic matter [1]. Understanding the nature of this unknown component is one of the most relevant open questions that need to be answered to improve our knowledge of the Universe and of its evolution. Models beyond the Standard Model of particle physics suggest the existence of weakly interacting massive particles (WIMPs) that would be stable, neutral and with a mass ranging from below GeV/c$^2$ to several TeV/c$^2$. Several underground experiments have been developed in the past decades with the goal of directly detecting these particles through their scattering in a detector medium. The xenon based experiment XENON1T [2] recently set the most stringent limit on the spin-independent WIMP-nucleon cross-section as a function of the WIMP mass, corresponding to $4.1 \cdot 10^{-47}$ cm$^2$ at 30 GeV. The primary goal of the DARk matter WImp search with liquid xenoN (DARWIN) experiment is to reach an extremely low sensitivity to cover entirely the parameter space for a wide mass range of WIMPs. This can be achieved with an exposure of 200 ton $\times$ yr and extremely low levels of background. In section 2 we present the main design of the DARWIN detector and the main challenges associated to the realization of this very large time projection chamber. In section 3 the sensitivity on the WIMP search and on other physics channels are discussed.
2. The DARWIN detector concept
The design concept of DARWIN is based on a large volume double-phase xenon time projection chamber (TPC) inside a water Cherenkov veto. The detector will contain 50 tons of liquid xenon for a TPC chamber of about 1.5 heigh and 1.5 m large. The fiducial target mass of xenon will be fixed based on the background and physics case. The electric field required to drift electrons from the interaction vertex across the liquid is of the order of 0.5 kV/cm, i.e. the cathode located at the bottom of the TPC must be biased with voltages larger than -100 kV. The field homogeneity is ensured by oxygen-free high conductivity (OFHC) copper field shaping rings. Drifted electrons are then extracted into the gas region by a stronger electric field generated by adding an additional electrode (the gate) at the liquid/gas interface between the cathode and the anode. Insulation is provided by polytetrafluoroethylene (PTFE) components, acting also as reflectors for vacuum ultra-violet (VUV) xenon scintillation light. Signals generated in both liquid and gas phases will be detected by two arrays of photosensors installed above and below the chamber. The low radioactivity 3" Hamamatsu photomultiplier tubes (PMTs) from XENON1T [3] are a good candidate for the DARWIN photosensors although alternative light detectors can be considered if they demonstrate to be less radioactive. An intensive R&D program is ongoing and alternative photosensors are under test. A pictorial view of the DARWIN detector is shown in figure 1 and a detailed image of the DARWIN detector components is shown in figure 2. In figure 1 the presence of an inner shield acting as neutron veto is also displayed. Future studies will establish whether this shield is required to further reduce the neutron background and what will be its final configuration. The cryostat containing the DARWIN TPC will be installed inside a water tank, acting as a Cherenkov veto for cosmic muons. Recent simulations established that the minimum required diameter for the Cherenkov tank is 12 m for which the expected muon-induced neutron background is ~0.4 neutrons/(200 t-yr).

3. WIMP search and other physics channels
The main background for the WIMP search with DARWIN originate from detector materials (γ-radiation, neutrons), β-decays of $^{85}$Kr (0.1 ppt of $^{nat}$Kr) and the progeny of $^{222}$Rn (assuming 0.1 $\mu$Bq/kg) in the xenon target, two-neutrino double beta decays ($2\nu\beta\beta$) of $^{136}$Xe, $pp$ and $^7$Be
The attainable bound on spin-independent WIMP nucleon cross-section as a function of the WIMP mass of 100 GeV/c^2 is shown in figure 3. The black curve indicates where the WIMP sensitivity will start to be limited by neutrino-nucleus coherent scattering. Figure adapted from [42].

Table 1. Expected background components for the WIMP search with DARWIN. Background sources produce either nuclear (NR) or electron recoil (ER) scattering with xenon nuclei.

| Source                        | Rate [cts/(t-keV-yr)] | Interaction type |
|-------------------------------|------------------------|-----------------|
| γ-rays from materials         | 0.054                  | ER              |
| neutrons                      | 3.8 × 10^{-5}          | NR              |
| intrinsic 85Kr                | 1.44                   | ER              |
| intrinsic 222Rn               | 0.35                   | ER              |
| 2νββ of 136Xe                 | 0.73                   | ER              |
| pp and 7Be neutrinos          | 3.25                   | ER              |
| CNNS neutrinos                | 0.0022                 | NR              |

Figure 3. Sensitivity of DARWIN to the spin-independent WIMP nucleon cross-section as a function of the WIMP mass. Upper limits and sensitivity projections from other experiments are also shown. Picture from [4].

Figure 4. 1σ and 2σ credible regions of the marginal posterior probabilities for simulations of WIMP signals for some example value of mass and spin-independent cross-section. Picture from [4].

Solar neutrinos interactions and higher energy atmospheric neutrinos interactions via coherent neutrino-nucleus scattering (CNNS). The expected rates from these background components are listed in table 1. According to these values the expected sensitivity on the spin independent WIMP-nucleon cross-section with 200 t×yr exposure is shown in figure 3. At a WIMP mass \( m_W = 40 \text{ GeV}/c^2 \), the limit on the spin-independent WIMP-nucleon cross-section is \( 2.5 \times 10^{-49} \text{ cm}^2 \), assuming an electron recoil rejection level at 99.98% with 30% acceptance of nuclear recoil events. DARWIN can also detect spin-dependent scatterings of WIMPs with the two non-zero total angular momentum isotopes of xenon, \(^{129}\text{Xe}\) and \(^{131}\text{Xe}\). The projected sensitivity in this case appears complementary to the LHC searches [5] at 14 GeV center of mass energy. For both spin-dependent and spin-independent searches, from the measured recoil spectrum both mass and cross-section of the WIMPs can be inferred with very good precision for most of the explorable parameter space. In figure 4 the expected reconstructed masses are shown for a cross-section of \( 2 \times 10^{-47} \text{ cm}^2 \) and an exposure of 200 t×yr. The masses correspond to 154, 224 and 60 events for 20 GeV/c^2, 100 GeV/c^2 and 500 GeV/c^2, respectively. The uncertainties of the dark matter halo parameters have been marginalised over the mass and cross-section parameter space [4]. Other fundamental physics channels can be explored with the DARWIN detector. DARWIN has an excellent sensitivity for galactic and solar axions that can be identified by searching for monoenergetic peaks in the energy range between 0 and few hundreds of keV. The
projected sensitivity on the coupling for the axion-like particles as a function of the galactic axion mass is shown in figure 5. The dominant background for these searches is due to the $2\nu\beta\beta$ decays of $^{136}$Xe and the solar neutrinos interactions. As for solar neutrinos, detected via elastic neutrino-electron scattering, they represent the main and irreducible background for the WIMP search but, on the other hand, they can be detected by DARWIN with large statistics. In particular pp and $^7$Be neutrinos account for more than 98% of the total neutrino flux predicted by the Standard Model, therefore their detection can provide important pieces of information on the energy production mechanism in the Sun. The expected number of events above the threshold of 2 keV$\text{e}_e$ (electron recoil equivalent) and below 30 keV$\text{e}_e$ is $n_{pp} = 7.2$ events/day and $n_{^7\text{Be}} = 0.9$ events/day. A precision below 1% on the pp neutrino flux will be reached after 5 years of data taking, thus the solar model and neutrino properties can be tested. The sensitivity of DARWIN to the survival probability of solar electron neutrinos is shown in figure 6. Other fundamental physics channels that will be explored by DARWIN are the search for $0\nu\beta\beta$ decay of $^{136}$Xe with an excellent energy resolution (less than 1%), the detection of atmospheric neutrinos via the CNNS scattering and neutrinos emitted by core-collapse supernovae. For the latter case $\sim 100$ events are expected from a supernova distant 10 kpc therefore detailed studies of the time evolution of the event rate are possible [4].

4. Conclusions
DARWIN is multi-purpose experiment that will be able to cover the entire parameter space for the search for low-medium WIMP masses down to the neutrino background from solar and atmospheric neutrinos. Several additional fundamental channels can be explored: solar axions, axion-like particles, solar neutrinos, $0\nu\beta\beta$ decay of $^{136}$Xe and neutrinos from core-collapse supernovae.

5. References
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