Neutrino physics with DARWIN

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Abstract. DARWIN (DARk matter WImp search with liquid xenoN) will be a multi-ton dark matter detector with the primary goal of exploring the entire experimentally accessible parameter space for weakly interacting massive particles (WIMPs) over a wide mass-range. With its 40 tonne active liquid xenon target, low-energy threshold and ultra-low background level, DARWIN can also search for other rare interactions. Here we present its sensitivity to low-energy solar neutrinos and to neutrinoless double beta decay. In a low-energy window of 2-30 keV a rate of $10^5$/year, from pp and $^{7}$Be neutrinos can be reached. Such a measurement, with 1% precision will allow testing neutrinos models. DARWIN could also reach a competitive half-life sensitivity of $8.5 \cdot 10^{27}$ y to the neutrinoless double beta decay ($0\nu\beta\beta$) of $^{136}$Xe after an exposure of 140 t×y of natural xenon. Nuclear recoils from coherent scattering of solar neutrinos will limit the sensitivity to WIMP masses below 5 GeV/c$^2$, and the event rate from $^8$B neutrinos would range from a few to a few tens of events per tonne and year, depending on the energy threshold of the detector. Deviations from the predicted but yet unmeasured neutrino flux would be an indication for physics beyond the Standard Model

1. Introduction

Although it is firmly established that neutrinos change flavour when traveling over macroscopic distances, and the oscillation parameters of solar neutrinos are measured with certain precisions, the pp-neutrino flux has never been observed in real time [1, 2, 3]. Using the existing data from solar and terrestrial neutrino experimental data, and relaxing the solar luminosity constraints, the pp-neutrino flux can be determined with 1-$\sigma$ uncertainty of about 10% in a solar model independent analysis [3]. These constraints on the neutrino-inferred luminosity, which agree with the measured value within the same 1-$\sigma$ uncertainty, could be improved if the pp-flux can be measured directly. Additionally, a direct measurement allow the possibility of probing the vacuum-dominated oscillation probability of sub-MeV neutrinos which yields a further tests of the MSW-LMA solution of the neutrino problem.

The observation of neutrinoless double beta decay, $0\nu\beta\beta$, would prove that neutrinos are Majorana particles and would provide information about their absolute mass scale and hierarchy. Current searches, using liquid xenon, obtain lower limits of the $0\nu\beta\beta$ decay half-life of 1.07-10^{27} \text{ yr} at 90% CL [4, 5].

From the experimental side, the era of ton-scale dark matter detectors started already[12]. Their aim is to detect the low-energy nuclear recoils of WIMPS, Weakly Interacting Massive Particles, with nuclei of an ultra-low background detector. These detectors, like Xenon1T [12], use nobel liquids as a target. An even larger detectors, multi-ton scale, are being proposed. The DARWIN, DARk matter WImp search with liquid xenoN, experiment is a 50 t Liquid Xenon, LXe, detector. Its low-energy threshold and ultra-low background allow the detector to be sensitive to
other physics channels than WIMP detection. Among these channels that are discussed in this proceedings are: the solar neutrino detection and the question of Majorana nature of neutrinos. For further details about the physics’ topics of DARWIN the reader can look at [13, 14].

2. The DARWIN Detector
DARWIN will be an experiment using a multi-ton Liquid Xenon, LXe, TPC [14]. It will be made out of 50 t total LXe for which 40 t will constitute its active mass. It will be contained in a low-background cryostat, surrounded by a concentric shielding structures as shown in Fig.1.

![Figure 1. Sketch of the DARWIN detector inside a tank, operated as a water-Cherenkov muon veto.](image)

The dual-phase time projection chamber, inside liquid-scintillator neutron veto is enclosed within a double-walled cryostat and contains 40t of liquid xenon (50t total in the cryostat). The need for an additional liquid-scintillator neutron veto inside the water shield, as shown in the figure "Inner Shield", is subject to further studies. In the baseline scenario, the prompt and delayed scintillation signals, induced by particle interactions in the sensitive volume, are recorded by two arrays of photosensors installed above and below the liquid xenon target [14].

The core of the detector is a dual-phase Time Projection Chamber, TPC, containing the active xenon mass. It will be made out of oxygen free high conductivity copper as a conductor and polytetrafluoroethylene as an insulator. The TPC will be housed in double-walled cryostat made out of stainless steel titanium or copper. In the baseline scenario, two arrays of photosensors installed above and below the target will read the prompt and proportional scintillation signals. Well tested and used by the XENON1T experiment, photomultiplier tubes (Hamamatsu R11410-21) can be employed in DARWIN [15]. Other possible non-traditional light and charge read out are under studies, for details see [14].

3. Solar Neutrino Detection
Besides its main physics goal for dark matter searches, DARWIN can also detect neutrinos that comes from the sun. The detection of low-energy solar neutrino is through the elastic channel, $\nu + e^- \rightarrow \nu + e^-$ which proceeds through the Z and W$^-$ exchange for electron neutrinos and only through neutral current reactions for neutrinos of other flavors. Figure 2 (left) shows the recoil spectrum from the pp and $^7$Be neutrinos. The total expected number of events above the energy threshold of 2 keV$_{ee}$ (electronic recoil equivalent) and below an upper limit of 30 keV$_{ee}$ is $n_{pp} = 7.2$ events/day and $n_{7Be} = 0.9$ events/day. These numbers assume a fiducial target mass of 30 tons. Detailed calculations of the expected flux can be found in [13]. A pp-neutrino flux with a precision $\sim 1\%$ will be reached after 5 years of data taking.

Non-standard neutrino interactions [17, 18], can modify the survival probability of electron neutrino. The 1% precision that DARWIN would achieve in measuring the pp-flux will allow for testing neutrino and solar models as shown in Figure 2 (right). This probability, $P_{ee}$, can be modified in both energy region around 1 MeV and also at the pp-neutrino energies.
Figure 2. (left) Differential electron recoil spectra for pp- (blue) and $^7$Be neutrinos (red) in liquid xenon. The sum contribution (solid line) is split into the contributions from $\nu_e$ (dashed) and the other flavours (dotted). Figure adapted from[13]. (right) The survival probability of solar, electron-neutrinos. The expected sensitivity of DARWIN (red) is shown together with existing measurements from Borexino and the MSW neutrino oscillation prediction ($\pm 1\sigma$, green) for the large mixing angle scenario [16]. The precise measurement of the pp-flux with sub-percent precision with DARWIN will allow for testing neutrino and solar models. Figure adapted from[14].

4. Neutrinoless double-beta decay
The most practical investigation of the Majorana nature of neutrino, and lepton number violation, is through the search for neutrinoless beta decay, $0\nu\beta\beta$. $^{136}$Xe nucleus is one of the interesting $0\nu\beta\beta$-decay candidate, it has an 8.9% abundance in natural xenon. Its $Q_{\beta\beta}$ value is at 2.458 MeV, well above the energy range expected from the WIMP recoil signal, will allow DARWIN to perform a search for $0\nu\beta\beta$-decay in 3.5 t of $^{136}$Xe target. The main challenge for this measurement is the optimisations of detector sensors and electronics to perform at both O(1 keV) and O(1 MeV) energy scales. Fig.3 shows the reach for the Majorana neutrino mass [$m_{\beta\beta}$] versus the mass of the lightest neutrino [13, 14]. This sensitivity is obtained with an energy resolution $\sigma/E \sim 1-2\%$ at 2 MeV and strong background reduction by fiducialization or the selection of ultra-low radioactivity detector materials. The obtained sensitivities to the half-life time are $T_{0\nu1/2} > 5.6 \cdot 10^{26}$ y and $T_{0\nu1/2} > 8.5 \cdot 10^{27}$ y assuming a natural xenon exposures of 30 t×y and 140 t×y respectively.

Figure 3. Expected sensitivity for the effective Majorana neutrino mass. The sensitivity band widths reflect the uncertainties in the nuclear matrix element of the $^{136}$Xe $0\nu\beta\beta$-decay. The DARWIN sensitivity assumes a 30 t×y exposure of natural xenon and a background dominated by $\gamma$-rays from detector materials. The ultimate case with 140 t×y exposure assumes this background being absent. Also shown are the expected regions for the two neutrino mass hierarchy scenarios. Figure adapted from [14].

In conclusion, with its large target mass, low energy threshold and ultra-low background level, DARWIN will be able to address questions related to neutrino physics. In 5 years data taking,
DARWIN will be able to measure directly the pp-neutrino flux with \( \sim 1\% \) precision which will allow for the measurement of the survival probability of electron neutrino in the pp-neutrino energy region. With its 140 tt\( \times \)y exposure, DARWIN will be able to probe the neutrino mass hierarchy and distinguish between the scenarios, the inverted and normal mass hierarchy.

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