5 DARWIN: dark matter WIMP search with noble liquids

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Astrophysical observations show that 83% of gravitating matter in our universe is non-luminous and non-baryonic. The dark matter might be in the form of neutral, weakly interacting, stable or long-lived elementary particles, so-called WIMPs, which have eluded direct observation so far. Produced in the early universe, WIMPs would naturally lead to the observed dark matter abundance [1] and are predicted to exist in extensions to the Standard Model of particle physics [2]. Galactic WIMPs may be detected via scatters off atomic nuclei in deep underground experiments [3]. Since expected signal rates are below one interaction per kilogram of target material and year and momentum transfers are around 10 - 100 MeV [4, 5], large detector masses, low energy thresholds and ultra-low backgrounds are essential experimental requirements to directly observe these hypothetical particles.

Experiments using xenon [6–9] and argon [10] as a homogeneous detection medium in a time projection chamber have reached sensitivities of $\sim 10^{-44}\text{cm}^2$ for the spin-independent scattering cross section on nucleons. While a factor of five improvement is predicted with data already in hand [8], ton-scale experiments under commissioning [11] or construction [12] will likely probe the region down to $\sim 5\times 10^{-47}\text{cm}^2$. Notwithstanding this remarkable leap in sensitivity, and assuming local density and velocity distributions inferred from astronomical observations, significantly larger detectors are requisite to determine WIMP properties, such as its mass, scattering cross section and possibly spin [13]. To proof the dark matter interpretation of a signal, a measurement of the interaction rate with different target materials is compulsory.

Technologies

The DARWIN study [14–16] is focused on a multi-ton liquid argon and/or xenon experiment rooted in the noble liquid time projection chamber (TPC) technique. The TPCs will record the prompt scintillation light[3] created when a particle interacts in the active detector volume along with the few liberated electrons after drifting in a strong electric field[4] towards the vapor phase residing above the liquid. The prompt light signal will be observed by an array of photosensors immersed in the liquid, the electrons will be detected either directly, or indirectly via proportional scintillation in the gas phase with a second array of photosensors. The time difference between the prompt and delayed signals is determined by the z-position of the primary interaction, the spatial coordinates of the delayed signal reveal its $x-y$-position. The relative size of the charge and light signals, as well as their time structure will be used to distinguish nuclear recoils, as expected from WIMP scatters, from electronic recoils, which make the majority of the events. The spatial resolution allows to select an inner, low-background region and to reject fast neutrons, which – in contrast to WIMPs – tend to scatter more than once[5].

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[3] Photon emission from the decay of exited dimers to their dissociative ground state peaks around 128 nm and 178 nm in liquid argon and xenon, respectively [25].

[4] Typical drift fields are 0.5–1 kV/cm, with electron velocities around ~ 2 mm/μs [25].

[5] The mean free path of ~MeV neutrons is in the range of tens of cm.

DARWIN will immensely benefit from the research and development, and from the construction and operation experience gained with XENON10 [17], XENON100 [18], XENON1T [12], WARP [10], ArDM [11], DarkSide [19], and much of the ongoing work is carried out within the framework of these projects. Here we mention a few studies only, some of these are specific to DARWIN. Other work deals with the cryogenic, gas purification, circulation, storage and recovery systems; with the external water Cerenkov shield and its potential extension with a liquid scintillator (depending on the depth of the underground laboratory – the Gran Sasso Laboratory and the Modane extension are under consideration); with material screening, selection and radon emanation measurements; with high-voltage systems, electrodes and field uniformity simulations; with low-noise, low-power electronics, cables and connectors, trigger schemes, data acquisition and treatment; with Monte Carlo simulations of the expected background noise, of the light collection efficiency and position reconstruction capability; with the design of the time projection chamber, of the cryostat and of the calibration system.

- Light and charge response:
the light and charge yields of noble liquids when exposed to low-energy nuclear recoils (from neutron or potential dark matter interactions) or electronic recoils (from γ- and β-interactions) are studied by several groups participating in DARWIN. A new measurement of the relative scintillation efficiency $\mathcal{L}_{\rm eff}$ in liquid xenon [20] shows an $\mathcal{L}_{\rm eff}$ behavior which is slowly decreasing with energy, with a non-zero value at 3 keV nuclear recoil energy, the lowest measured point. A similar measurement is ongoing for liquid argon [21]. A measurement of the liquid xenon scintillation efficiency for electronic recoils down to 2.3 keV is in progress [22]. A preliminary data analysis indicates that the scintillation yield falls with decreasing energy, as predicted by models of scintillation mechanisms in noble liquids [23]. Nonetheless, the scintillation response at 2.3 keV is observed to be non-zero, confirming that liquid xenon experiments will have a finite sensitivity at such low interaction energies. Measurements of the charge yields of LAr and LXe within the same energy regime are being planned.

- Signal readout:
the prompt scintillation light is to be observed either with conventional photomultiplier tubes (PMTs) which are low in radioactivity [24] and built to withstand low temperatures and high pressures[6] or with a new, hybrid photodetector (QUPID [26]), which has an extremely low radioactivity content (<1 mBq/sensor for U/Th/K/Co) [24] and works both in liquid argon and xenon. The delayed signal can be observed directly, using detectors with single electron sensitivity and high spatial granularity (large electron multipliers [27]), or CMOS pixel detectors coupled to electron multipliers (GridPix [28]), or via proportional scintillation in the gas phase, using gaseous photomultipliers without dead zones (GPMs [29]), PMTs or QUPIDs.

Backgrounds and physics reach

DARWIN will be an "ultimate" argon and/or xenon dark matter experiment, before the solar and atmospheric neutrinos become the main, possibly irreducible background. It will directly probe WIMP-nucleon cross sections down to $\sim10^{-48}$cm^2. These cross sections are compatible with recent LHC results, should the dark matter particle turn out to be the neutralino [30–32]. The external background from gammas, muons and neutrons and the background from detector construction materials will be diminished to negligible levels by external shields, the self-shielding of the noble liquids[7], and the choice of fiducial volumes[8]. More problematic are intrinsic backgrounds from ^{85}Kr and ^{222}Rn decays in xenon and from ^{39}Ar decays in argon. In xenon, the natural krypton concentration is to be reduced

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[6] One example is the Hamamatsu R11410/R11065 3"-tube for LXe/LAr, currently tested for its performance, long-term stability and radioactivity levels at several DARWIN institutions.

[7] The mean free path of 3 MeV gammas is ∼9 cm and ∼20 cm in liquid xenon and argon, respectively.

[8] The final choice of the size and target materials are part of the outcome of the study, a baseline scenario is 20 t (10 t) total (fiducial) LAr/LXe mass.

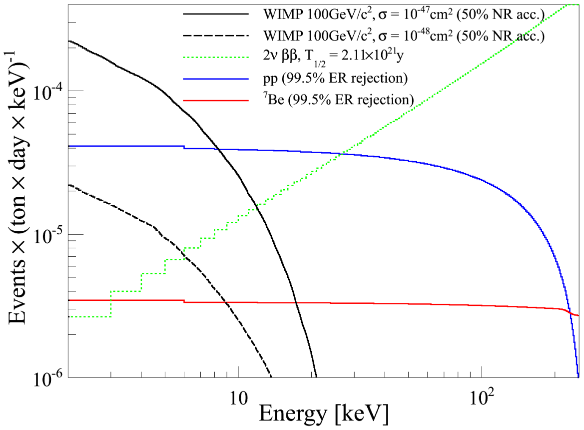

Fig. 5.1 – *Expected nuclear recoil spectrum from WIMP scatters in LXe for a spin-independent WIMP-nucleon cross section of 10^{-47} cm^2 (solid) and 10^{-48} cm^2 (dashed) and a WIMP mass of 100 GeV/c^2 (using the standard halo model as in [13]), along with the differential energy spectrum for pp (blue) and ^{7}Be (red) neutrinos, and the electron recoil spectrum from the double beta decay of ^{136}Xe (green), assuming the natural abundance of 8.9% and the recently measured half life of 2.1×10^{21} yr [34]. Other assumptions are: 99.5% discrimination of electronic recoils, 50% acceptance of nuclear recoils, 80% flat analysis cuts acceptance.*

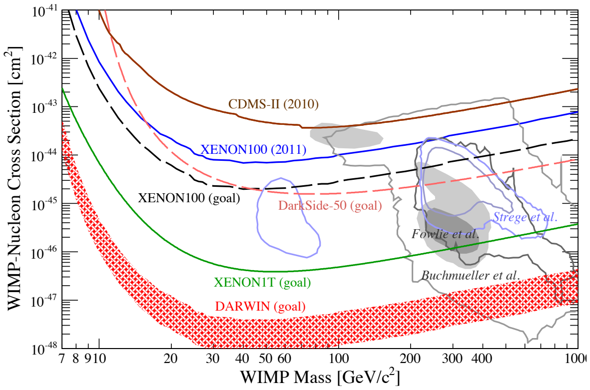

Fig. 5.2 – *DARWIN's sensitivity goal for spin-independent WIMP nucleon cross sections, existing limits from XENON100 [8] and CDMS-II [35], future goals and updated theoretical predictions from supersymmetry (closed contours and shaded regions) [30–32].*

by cryogenic distillation to <1 ppt and the radon level in the liquid is to be kept <1 μBq/kg. Argon gas that is extracted from deep underground wells is depleted in the radioactive ^{39}Ar [33]. Still, a background rejection by pulse-shape analysis of >10^8 is required in the case of a liquid argon detector [14, 15]. Figure 5.1 shows the expected nuclear recoil spectrum from WIMP scatters in xenon together with the background from neutrino-electron elastic scatters of solar neutrinos and from the double beta decay of ^{136}Xe.

In Fig. 5.2 we show the aimed sensitivity of DARWIN, along with existing best upper limits on the WIMP-nucleon cross section, projections for the future and theoretically predicted regions from supersymmetric models.

DARWIN, which was endorsed in recent updates to the European and Swiss roadmaps for astroparticle and particle physics [36, 37], has officially started in 2010. A rough time schedule is the following: a technical design study is to be ready in spring 2013, leading to a letter of intent and engineering studies towards the proposal of a concrete facility in spring 2014, and a technical design report for detector construction by the end of 2014. The shield and detector construction phase is to start in 2015, commissioning in late 2016 with the start of the first physics run by mid 2017.

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