Limits on WIMP-nucleon cross-sections from the ZEPLIN-II data

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Abstract. Results are presented from ZEPLIN-II, the world-first 31 kg two-phase xenon dark matter detector. Discrimination between nuclear recoils and background electron recoils is achieved by recording both the scintillation and ionisation signals generated within the liquid xenon, with the ratio of these signals being different for the two classes of events. This ratio is calibrated for different incident species using neutron and γ-ray sources. Background populations of gamma-induced events and radon progeny events were observed in the data. An acceptance window, defined by the neutron calibration data, of 50% nuclear recoil acceptance between 5 keV and 20 keV electron equivalent energy, had an observed count of 29 events, with a summed expectation of $28.6 \pm 4.3 \gamma$-ray and radon progeny induced background events. These figures provide a 90% CL upper limit to the number of nuclear recoils of 10.4 events in this acceptance window. This corresponds to a WIMP-nucleon spin-independent cross-section with a minimum of $6.6 \times 10^{-7}$ pb, and to a WIMP neutron spin-dependent cross-section of $7 \times 10^{-2}$ pb at a WIMP mass of around 65 GeV.

1. Introduction
Search for rare dark matter WIMP events requires a powerful discrimination between nuclear recoils (expected from WIMP and neutron interactions) and electron recoils (from γ-ray background). Event-by-event discrimination in liquid xenon target is based on the ratio of ionisation to scintillation known to be different for the two classes of events. This is implemented in two-phase liquid noble gas detectors where two signals are produced for each event, the 1st one being from the primary scintillation light (S1) and the 2nd one from the secondary scintillation (or electroluminescence) (S2). The latter is caused by electrons produced in the liquid phase, drifted in the electric field through the liquid, extracted into the gas phase and finally accelerated in the high electric field in the gas.

2. ZEPLIN-II experiment
ZEPLIN-II is a two-phase xenon detector with a target mass of 31 kg of liquid xenon, operated at the Boulby Underground Laboratory in the UK at a depth of 2805 m w.e. underground. The target volume is viewed from above by seven 13 cm diameter photomultiplier tubes (PMTs). To protect the target volume from radioactivity in rock (gammas and neutrons), the ZEPLIN-II detector is surrounded by hydrocarbon material and high-purity lead. Part of the hydrocarbon shielding is a liquid scintillator that also acts as an anticoincidence system (active veto) preventing the signals, detected simultaneously in the target and in the veto, being interpreted as WIMP interactions.
The trigger is provided by five-fold coincidences between different PMTs at a single photoelectron level. Either a primary, S1, or a secondary, S2, signal can trigger the data acquisition. The signals from all seven PMTs are recorded with 2 ns sampling time during ±100 µs around the trigger pulse, covering all possible arrival times for both primary and secondary signals. In an off-line data analysis three-fold coincidences between different PMTs at a single photoelectron level were used to identify and parameterise the primary signal S1.

A number of parameters have been measured for each waveform (Alner et al 2007a, 2007c), the most important being the total areas of the primary and secondary pulses (proportional to the number of photoelectrons), S1 and S2, respectively, the time delay between them and the width of the pulses (that determines whether the pulse is the primary or secondary signal).

Position sensitivity of the experiment in the vertical direction is achieved by considering the time delay of the secondary pulse which is proportional to the drift time of the electrons and thus determines the point of the interaction along the drift field direction. This allows us to exclude events originating on or close to the grid wires that provide the electric field and are contaminated mainly with radon progeny. In the horizontal plane the event position is reconstructed using the relative pulse areas from secondary signals on different PMTs. This method gives bigger uncertainty compared to the drift time due to the large PMT sizes and small photon statistics at low energies.

A daily energy calibration of the detector using a $^{57}$Co gamma-ray source allowed monitoring the stability of detector operation. The WIMP/gamma discrimination performance of ZEPLIN-II has been tested by calibrating the detector using high-energy gamma-ray ($^{60}$Co) and neutron (AmBe) sources. High-energy gamma-rays produce the main electron recoil background, whereas fast neutrons scatter elastically off nuclei producing nuclear recoils in the same way as expected from WIMP scatters. Using the S2/S1 versus S1 plot from neutron calibration run (Alner et al 2007a) the nuclear recoil acceptance box has been defined as retaining 50% of nuclear recoil events at any given energy chosen for analysis (5-20 keV electron equivalent energy). This acceptance box was expected to have a small number of electron recoils due to the tail of S2/S1 distribution observed in the gamma calibration run.

The detector, data acquisition system, analysis procedure and experimental data are described in detail by Alner et al (2007a, 2007b, 2007c).

3. Results
The first data run of the ZEPLIN-II detector had a live time of 31.2 days after time periods with unstable operation conditions were removed from the analysis. A number of software cuts have been applied to the parameterised pulses allowing the selection of single interactions within the fiducial volume of the detector to be made (Alner et al 2007a). For each cut an energy dependent efficiency has been evaluated either from the data or from a combination of data and simulations.

An important cut that reduces significantly the fiducial volume of xenon, is the radial cut. This rejects the events that are reconstructed as being close to the PTFE walls. In reality, due to imperfect position reconstruction of the interaction points in the horizontal plane, a long tail of events assumed to be originated at the walls is reconstructed towards the centre of the detector. The majority of these events is believed to be caused by the alpha decay of radon progeny accumulated on the charged surfaces. To remove most of the ‘wall’ events the radial cut has been applied reducing the fiducial mass of xenon down to 7.2 kg (Alner et al 2007a).

The analysis of data has revealed 29 events in the nuclear recoil ‘acceptance box’ defined using neutron calibration data. The expected background rate was estimated by extrapolating distributions of gamma-induced electron recoils and radon progeny events to the acceptance box and found to be 28.6 ± 4.3 (see Alner et al 2007a for full description of the procedure to evaluate the expected background). Applying the procedure described by Feldman and Cousins
we found that the WIMP signal in the ZEPLIN-II detector is consistent with zero and, hence, the 90% CL upper limit on the number of nuclear recoils was set as 10.4 using central confidence interval. This limit was then converted into an upper limit on the WIMP-nucleon spin-independent (Alner et al 2007a) and WIMP-neutron/proton spin-dependent (Alner et al 2007b) cross-sections. Limit on WIMP-nucleon spin-independent cross-section from ZEPLIN-II is shown in Figure 1 together with the results from some other experiments.

4. Summary
The world-first and largest (~31 kg) two-phase xenon detector ZEPLIN-II has been operated at the Boulby Underground Laboratory. Data collected during 31.2 days of running did not reveal the presence of WIMP-induced signals. The observed number of events in the nuclear recoil acceptance box, defined using neutron calibrations, was consistent with the expectations of background events based on the extrapolation of the gamma-induced electron recoils and radon progeny events accumulated on the walls, to the acceptance box. The upper limits were set on the WIMP-nucleon spin-independent and spin-dependent cross-sections.

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