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Results from the first science run of ZEPLIN-III

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Abstract. ZEPLIN-III is a two-phase (liquid/gas) xenon time projection chamber designed to search for dark matter in the form of weakly interacting massive particles (WIMPs). Its active volume contains 12 kg of liquid above an array of 31 2-inch photomultipliers. The detector uses both scintillation and ionization produced in the liquid in order to discriminate between electron recoil background interactions and the nuclear recoils expected from the elastic scattering of WIMPs off the xenon nuclei. The first science run of ZEPLIN-III acquired 847 kg.days of raw data. An analysis of those data has excluded a WIMP-nucleon elastic scattering spin-independent cross section above 8.1×10^{-8} pb at 60 GeV/c^2 WIMP mass and a WIMP-neutron spin-dependent cross section above 1.9×10^{-2} pb at 55 GeV/c^2 both with a 90% confidence two-sided limit.

1. Introduction

ZEPLIN-III is a galactic dark matter experiment deployed 1100 m underground at the Palmer Underground Laboratory at Boulby, UK. It is based on a two-phase (liquid/gas) xenon detector intended to detect weakly interacting massive particles (WIMP) via their elastic scattering from xenon nuclei. The recoiling nuclei will produce vacuum ultraviolet primary scintillation light (S1) and ionization charge in the liquid. Under an applied electric field, the electrons escaping recombination drift towards the top of the liquid being extracted into the gas layer where they produce proportional electroluminescence (S2). Event by event discrimination between nuclear recoils (expected from WIMP and neutron interactions) and electron recoils (from γ-ray background) is obtained from S2/S1 as this ratio is very different for these two classes of events.

ZEPLIN-III has 31 2-inch diameter photomultiplier tubes (PMTs) immersed in the liquid to detect the prompt S1 light signal and the delayed S2 pulse with good light collection efficiency. Its design and performance were described in detail elsewhere [1,2].

2. ZEPLIN-III first science run

For the first science run (FSR) the ZEPLIN-III detector was completely surrounded by a shield of 30 cm thick polypropylene and 20 cm thick lead that provide ~ 10^5 attenuation factors for both γ–rays and neutrons from the cavern walls.

WIMP-search data were collected over 83 days of underground continuous operation with 84% live time during which some 847 kg.days of raw data were acquired from the 12 kg target volume. This exposure is reduced to 453.6 kg.days after applying the cuts that define the fiducial volume: drift time window to limit the height of liquid and a radial limit coming from the S2 position reconstruction in the horizontal plane.

Energy calibrations of the S1 and S2 responses, as well as the flat-fielding of the PMT array, were obtained with ^{57}Co γ-rays. The primary and the secondary light yields were measured: S1 light yield was found to be 1.8 p.e./keVee at the operating field of 3.9 kV/cm and 5 p.e./keVee without electric field; the S2 light yield at the instrument operation conditions was measured to be 6.5×10^2 p.e./keVee. The data collected daily with the ^{57}Co source were also used to assess several operational parameters, such as the liquid purity, detector tilt, liquid level and pressure effects, over the entire run.

Calibration measurements were performed with ^{137}Cs and Am-Be (α,n) sources at the start and at the end of the science run. The Compton scattering events from the 662 keV γ-rays from the ^{137}Cs allow establishing the electron recoil response at low energies (down to 2 keVee, where 'keVee' unit refers to the equivalent mean S1 signal produced by 122 gamma-rays). The neutron elastic scattering events from the Am-Be provide calibration of the response to nuclear recoils in the energy range of interest to WIMP signals.

The low-energy Compton-scattered events from the ^{137}Cs were also used to investigate the linearity of response of each light readout channel and to determine the mean single photoelectron response of each photomultiplier [4].

Details on the calibration, data processing and selection are provided elsewhere [3].

3. Results

Clear separation between nuclear and electron recoils was achieved as shown in Fig.1 where electron-recoil data from ^{137}Cs and elastic nuclear recoil data from Am-Be are plotted.

The WIMP-search box boundary was defined as $2 < E < 16$ keVee and $(\mu_n\text{-}2\sigma) < \log_{10}(S2/S1) < \mu_n)$ where μ_n is the energy-dependent mean of the nuclear recoils (acceptance of 47.7%). This region was defined before unblinding and was kept for the subsequent analysis. The effective total exposure within this box after taking account all the efficiencies is 127.8 kg.days.

The single-scatter neutron background in the data set is estimated at 1.2±0.6 in the WIMP-search box with 90% originated in the PMTs. This estimate is obtained with a full GEANT4 simulation [1]. The electron-recoil background below hundreds keV was measured and was found to be in good agreement with the GEANT4 simulation [1], according to which the dominant contribution is 10.5 dru (1 dru= 1 evt/kg/day/keVee) from the photomultipliers.

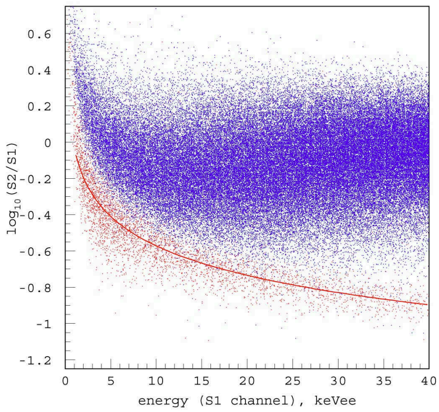

Figure 1. ^{137}Cs (blue) and Am-Be (red) calibration data.

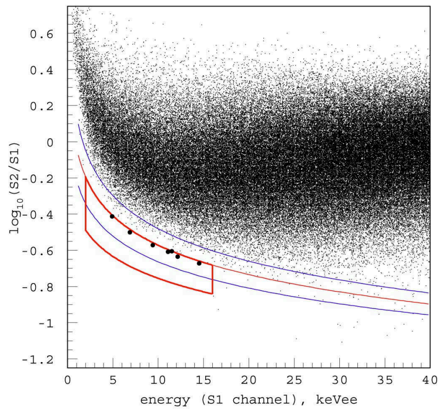

Figure 2. First science run data. The thick red box delimits the WIMP-search region.

The science data contain 7 events within the WIMP-search box, as shown in Fig. 2. To compute the WIMP-nucleon cross-section limits, the energy scale has to be converted from keVee into kVnr and the energy-dependent detector efficiency for nuclear recoils must be determined. The latter was found by comparing Am-Be data sets with very different trigger thresholds in both hardware and software [3]. The energy scale conversion is then obtained by comparing the experimental nuclear recoil differential spectrum with that obtained by simulation. In so doing, we find evidence for a significant non-linearity in the conversion between S1 keVee and S1 keVnr [3]. Recently, such non-linearity was also observed, though less pronounced, by other authors in beam measurements [5].

Following the procedure detailed in [3], it was found that the data is consistent with no WIMP signal and the 90% confidence upper limit was set as 3.05 events. This limit was then converted into an upper limit on the WIMP-nucleon spin-independent elastic scattering cross section as a function of the WIMP mass using the standard spherical isothermal galactic halo model [3]. The upper limit on WIMP-nucleon spin-independent cross-section from ZEPLIN-III is shown in Fig. 3 together with the results from the other presently leading experiments. The analysis of the data for obtaining the upper limit of the WIMP-neutron/proton spin-dependent cross-sections is presented elsewhere [6].

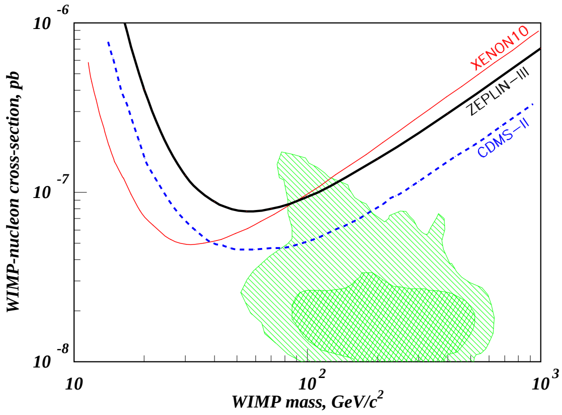

Figure 3. Limits on WIMP-nucleon spin-independent cross-sections from the first science run of ZEPLIN-III. The results published by XENON10 [7] and CDMS-II [8] are also shown. Note that the XENON10 curve is a one-sided limit while CDMS-II and our result are both 90% two-sided limits. For comparison, the XENON-10 two-sided limit is 1×10^{-7}pb at a WIMP mass of 30 GeV/c^2 [9]. Moreover the XENON10 result did not take into consideration the non-linearity between keVee and keVnr.

4. Second science run

ZEPLIN-III has been upgraded in view of a second science run. Since the photomultipliers were the dominant source of background in the first science run they were replaced by pin-by-pin compatible ones manufactured with materials of higher radiopurity. It is expected that the γ-ray and neutron backgrounds will be improved by a factor of ~30.

An active scintillator veto, surrounding the detector inside the lead castle, replaced the previously used passive neutron shielding. It consists of 52 plastic scintillator modules placed around and above the detector. Each module has a 3” photomultiplier at one end, a mirror at the other end and it is wrapped with PTFE along length followed by a black outer wrap. A 15 cm thick 1% gadolinium loaded polypropylene was placed between the scintillator and the target working as neutron moderator.

The second science run is expected to start by the end of the year.

5. Acknowldgements

We wish to pay tribute to our colleague and friend V.N. Lebedenko (1939-2008), who had a key role in designing and building the instrument. LIP-Coimbra acknowledges funding from Fundação para a Ciência e Tecnologia (FCT) through the project-grant CERN/FP/83501/2008.

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