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Mini-review direct dark matter detection and recent XENON100 results

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Direct dark matter searches, in particular the detection of WIMPs (Weakly Interacting Massive Particles) is a rapidly evolving field which has led to interesting but also highly controversial results during the last years. This article shortly reviews the state of the field as of summer 2011 and describes in some detail the recent results from the XENON100 experiment.

XENON100 is a detector with 62 kg active volume located at the Gran Sasso underground laboratory in Italy. It is a two-phase liquid xenon TPC (Time Projection Chamber) where the light and charge produced are detected by photomultipliers. Xenon as detection medium has the advantage of combining a high WIMP sensitivity with an excellent self-shielding capability for background reduction. This year the collaboration has released science results from 100 days of data taken during 2010. No evidence for dark matter has been found and the experiment has set the world's best limit on the WIMP-nucleon cross section. This limit probes already significant regions of the cross section and WIMP mass parameter space, as predicted by theories beyond the standard model of particle physics. The XENON100 result is in tension with the signal excesses reported by the DAMA, CoGeNT and CRESST experiments.

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1. Direct dark matter search

Indirect evidence for cold dark matter is well established from astronomical observations but the nature of this matter is still unknown. The Weakly Interacting Massive Particle (WIMP) is a very popular candidate as several theories beyond the standard model independently predict such a particle [1]. The detection of WIMPs would constitute a very important discovery and therefore three different strategies are followed: its production at colliders (for example at the Large Hadron Collider (LHC), Geneva, Switzerland), the indirect detection (signal from the products of WIMP self-annihilation) and the direct detection.

Direct detection experiments aim to register a recoiling target nucleus after an elastic collision of a WIMP. Such a measurement would provide information on the interaction probability of WIMPs with ordinary matter and on the WIMP mass. The recoiling nucleus would, however, deposit only few keV energy making the detection challenging. In addition, the predicted rate is quite low, less than an interaction per kg and day. Therefore, the required detectors need to have a low energy threshold, a large mass and a very low background. As the aimed sensitivity in cross section increases, the requirements on the allowed backgrounds become stronger. The detector has to be well shielded from ambient neutrons and gammas which constitute the main source of background. Furthermore, the construction materials have to be selected carefully, in order to minimize their contribution to the radioactivity.

Most direct detection experiments combine two types of signals (out of ionization charge, scintillation light or phonons) to discriminate nuclear recoils from electronic recoils. In this way, the main background which is mainly due to electronic recoils can be separated from nuclear recoils possibly originating from dark matter collisions. Other signal signatures are the annual modulation of the flux resulting from the rotation of the Earth around the Sun (and through the WIMP wind), the direction of the WIMPs or the exponential shape of the spectrum at low nuclear recoil energies.

2. Current experimental status

The direct detection of dark matter is currently a very exciting field with many competing projects. While few experiments have an indication for excess events of unknown nature, others have set strong constraints on the WIMP nucleon cross-section and the WIMP mass. This section summarizes some of the most important recent results.

In addition to the annual modulation of the background observed by the DAMA experiment [2][3], two further experiments have recently claimed a possible indication for a dark matter signal. The CoGeNT experiment [4], which consists of a very low energy threshold germanium detector, has observed an excess of events close to the threshold. This detector measures only charge from ionization processes and therefore does not distinguish electron recoil from nuclear recoil signals. As in the case of DAMA, the total background rate is measured. Very recently, the CRESST collaboration has published [5] new results showing an excess of events that cannot be explained by the known background sources. In contrary to the experiments mentioned before, CRESST measures the scintillation and phonon signal of each interaction. Using the ratio of these two quantities electronic recoils can be distinguished from nuclear recoils. In all these three cases, the WIMP mass compatible with the data would be around 5-15 GeV/c^2. The signal regions favored by the

DAMA and the CoGeNT data can be seen in figure 2. The CRESST signal excess corresponds to a region which extends over a large range of WIMP masses, from about (9 - 50) GeV/c^2 and over a WIMP-nucleon cross section ranging from (10^{-43}-10^{-40}) cm^2.

In contradiction to the experiments mentioned above, there is a number of experiments which have set strong exclusion limits on the cross-section and mass of the WIMPs. These limits are in tension with the positive signal indications discussed. The results of some of these experiments are also shown in figure 2. The CDMS experiment uses germanium and silicon crystals as target material. The measurement of an ionization and a phonon signal gives a very good discrimination power between electronic and nuclear recoils. The latest results from 612 kg d exposure showed no significant excess of events in the signal region [6]. Two events were found; but based on their background estimate, the probability of observing two or more background events is 23%. Further low threshold analyses [7][8] using also the silicon crystals of the experiment have set strong limits at low WIMP masses. Also the Edelweiss experiment uses germanium detectors and the phonon to ionization ratio for particle discrimination. In the most recent analysis, data from 384 kg d taken during 2010 and 2011 [9] are used. The five events found are not statistically significant over the 3 events predicted as background. CDMS and Edelweiss have furthermore combined their data, performed a common analysis [10] and produced a new exclusion limit.

Looking to the noble liquid detectors, new results from XENON10 [11] and XENON100 appeared this year. A new analysis of the XENON10 data [12] using only the ionization signal has lowered the threshold down to 1.4 keV nuclear recoil energy. The data was used for a dedicated low WIMP mass search ($\lesssim$ 10 GeV) and severely constrained recent light elastic dark matter interpretations of the excess events at low energies as observed by CoGeNT and CRESST-II, as well as the interpretations of the DAMA modulation signal. The recent XENON100 result [13] of 100 days of data yields the most stringent limits above 15 GeV WIMP masses. Section 3 describes this experiment and the corresponding results in more detail.

Reference [14] discusses the compatibility of the CRESST, DAMA and CoGeNT claims with the limits of XENON100 and CDMS. The authors conclude that there is currently no known way of explaining all the positive signals simultaneously with all the null results.

3. The XENON100 experiment

This section focuses on XENON100 and summarizes the detector concept, the analysis of recent data and the latest science results. The future plans are also described.

3.1 The detector

The XENON100 detector is a liquid xenon two-phase time projection chamber (TPC). An energy deposition in the medium produces ionization and excites the xenon atoms. In a two-phase TPC, signal and background discrimination are possible based on the simultaneous detection of the scintillation light (S1) and the charge signal from electrons released in the interaction. These electrons are drifted in an electric field and extracted into the gas phase above the liquid, where the charge is converted via proportional scintillation in the gas to an amplified secondary light signal (S2). Two arrays of photomultipliers (PMTs) placed on top and bottom of the TPC record both signals. The interactions can be reconstructed with few mm precision based on the drift time (time difference between S1 and S2) and the PMT hit pattern of the S2 signal [15].

The detector is located at the Laboratori Nazionale del Gran Sasso in Italy. The total mass of liquid xenon is 161 kg of which 62 kg are contained inside the TPC. The rest of the xenon is located in an active veto around, above and below the TPC and is also instrumented with PMTs. The whole system is placed inside a shield consisting of an inner copper layer, lead, polyethylene and an outer neutron shielding made of water canisters around the lead shield. A careful screening and selection of radio-pure detector materials was performed [16], especially for those very close to the sensitive volume. The design of the experiment resulted in an electronic recoil background of less than 10^{-2} events$\cdot$ kg$^{-1}\cdot$ keV^{-1} [17] in the WIMP-search energy range and inside 30 kg fiducial mass.

3.2 Recent results

This section describes the data analysis and results of 100 days of data taken during 2010 and published in [13].

Data selection and corrections

The data used for this analysis was acquired between January and June 2010. A total of 100.9 live days remained after selecting stable detector operation periods, with low noise and stable high voltage. A fiducial volume of 48 kg of liquid xenon with the shape of a super-ellipse was used in the analysis. Regular calibration runs with ^{137}Cs, ^{60}Co (both gamma) and AmBe (neutron) sources were taken to monitor the detector response and to characterize its performance. Both charge (S2) and scintillation (S1) signals are corrected for spatial non-uniformity. The correction maps are made using cesium data and gamma lines which appear during the neutron calibration: the 40 keV line from neutrons scattering inelastically on ^{129}Xe and a line at 164 keV from the metastable state ^{131m}Xe. All maps agree within 3%. Due to the constant purification of the liquid xenon, the charge signal (very sensitive to electronegative impurities) has a varying size over the drift-length. This was monitored with the calibration sources and is corrected in the analysis.

Calibration of the nuclear recoil energy scale

The nuclear recoil scale E_{nr} is calculated from the light signal (S1) using the expression $E_{nr} = (S1/L_y)(1/L_{eff})(S_{ee}/S_{nr})$ where L_y is the light yield of a 122 keV gamma ray at zero applied drift field. L_{eff} accounts for all non linearities and quenching effects of the nuclear recoil scale and it is parametrized using all existing measurements from neutron scattering experiments. S_{ee} and S_{nr} are the electric field scintillation quenching factors for electronic recoils and nuclear recoils, $S_{ee} = 0.58$ and $S_{nr} = 0.95$ for a drift field of 533 V/cm. The latest measurement of L_{eff} and the comparison to previous ones can be found in [18]. Below the lowest measured point at 3 keV, L_{eff} is extrapolated logarithmically to zero at 1 keV$_{nr}$. The average light yield of XENON100 at 122 keV is (2.20 ± 0.09) photoelectrons/keV.

Signal region and background prediction

The signal and background regions are determined using data from calibration sources (^{60}Co, AmBe) and background data from outside the signal region. The science data in the signal region was blinded (not accessible) to avoid analysis biases. Two different methods were used to interpret the results: a Profile Likelihood analysis as described in [19] and a classical cut-based analysis using the optimal interval method. The first was defined as the main method before looking at the results. The signal region is defined by an energy cut ($4-30$ photoelectrons corresponding to $8.4-44.6\,\text{keV}_{nr}$) and the trigger threshold. The cut-based analysis uses, in addition, a constant discrimination line (separation of nuclear and electronic recoil bands) at 99.75% and the lower 3σ contour of the nuclear recoil distribution. The signal region boundaries are marked in blue (for both analyses) and green (only for cut-based analysis) in figure 1.

The expected background in the WIMP search region is the sum of the gaussian leakage from the electronic recoil band, the non-gaussian leakage and the neutron background ((α,n) reactions in the materials surrounding the detector and muon induced neutrons). Their contributions are (1.14 ± 0.48) events, $(0.56^{+0.21}_{-0.25})$ events and $(0.11^{+0.08}_{-0.04})$ for each background, respectively. These numbers and their uncertainties are calculated using data and Monte Carlo simulations. The total background prediction is (1.8 ± 0.6) events.

Figure 1 shows the distribution of the background events as function of energy. The discrimination parameter $\log_{10}(\text{S2/S1})$ is flattened by subtracting the mean electronic recoil band. The grey points represent the signal region calibrated with a neutron source, the black points are the dark matter data and the red points in the signal region remain after unblinding for the cut based analysis [13]. All events satisfy the data quality cuts defined in the analysis and in addition noise rejection cuts developed after looking at the events in the signal region.

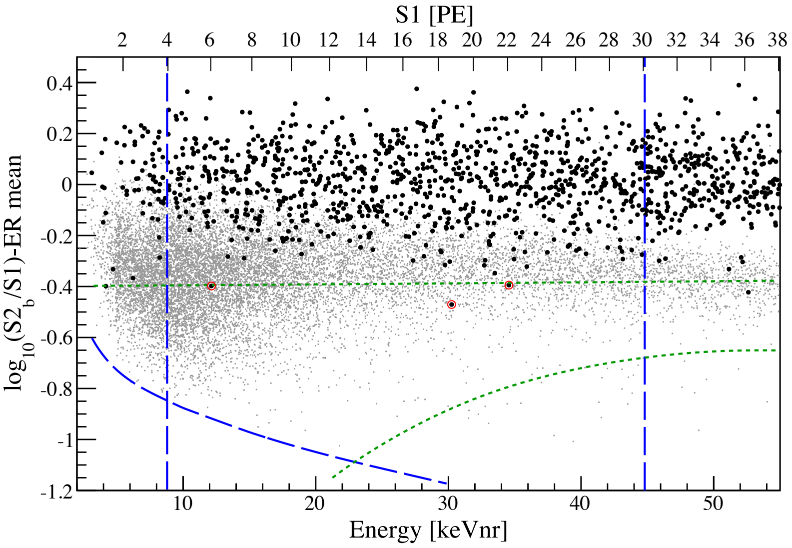

Figure 1: Histogram of the discrimination parameter versus energy. Grey points represent the nuclear recoil region calibrated with a neutron source and black points are the data from 100 days physics run. In red, the remaining data points in the signal region from the cut based analysis are shown. The lines indicate the definition of the signal region (see text). Figure from [13].

Interpretation of the results

Three events were observed in the region of interest after all cuts including those defined after unblinding. Given the background prediction of (1.8 ± 0.6) events, the observation doesn't constitute an evidence for a dark matter signal. The Poisson probability of 1.8 events to oscillate to 3 or more is 28%. Also, the Profile Likelihood analysis doesn't give a significant signal excess: the p-value of the background only hypothesis is 31%. From the latter analysis, an exclusion limit on the WIMP-nucleon cross-section versus WIMP mass has been derived. Figure 2 shows this exclusion curve in blue. The expected sensitivity of the experiment is shown by the yellow (1σ) and green (2σ) bands. This limit is currently the most stringent one (for WIMP masses $\gtrsim 15\,\mathrm{GeV}$) and excludes spin-independent elastic WIMP-nucleon scattering cross-sections above $7.0 \times 10^{-45}\,\mathrm{cm}^2$ for a WIMP mass of $50\,\mathrm{GeV}/c^2$ at 90% confidence level. Results from other experiments are also displayed for comparison. The XENON100 result is in tension with the signal indications of CoGeNT, DAMA and CRESST.

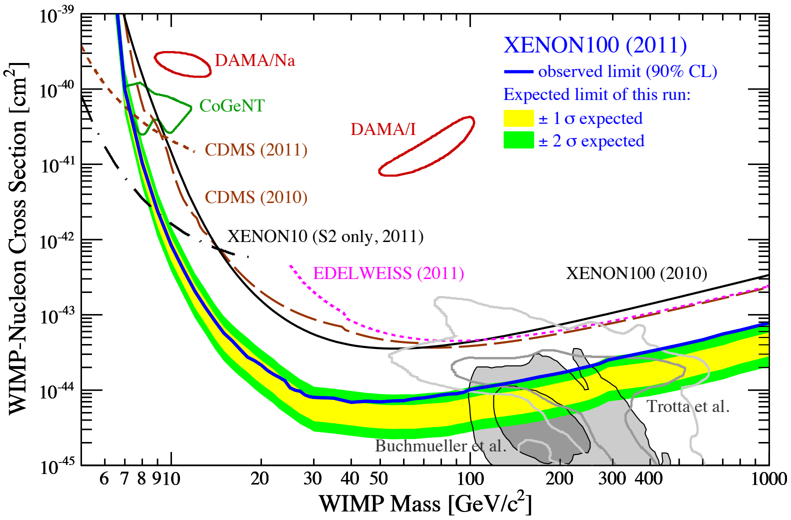

Figure 2: Spin-independent elastic WIMP-nucleon cross-section σ as a function of the WIMP mass. The claimed signal regions favored by DAMA and GoGeNT data are shown as well as the exclusion limits from XENON100, XENON10, CDMS and Edelweiss. Figure from [13].

The results have been interpreted as well as being due to inelastic dark matter [20]. In this scenario, the WIMP scatters off the nucleus and simultaneously transitions to an excited state at an energy δ above the ground state ($\chi N \to \chi^* N$). This model was introduced to avoid the tensions between the DAMA signal and the existing exclusion limits. In contrast to elastic WIMP scattering, this model predicts a spectrum in which the low energy component is suppressed. The current XENON100 data rules out this interpretation of the signal at 90% confidence level [21].

3.3 Future developments

Currently, the XENON100 detector continues to be operational and is taking dark matter data. The final goal is to acquire about 200 days of data to achieve a WIMP-nucleon cross-section sen-

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sitivity of $2 \times 10^{-45}\,\mathrm{cm}^2$ for a $100\,\mathrm{GeV}/c^2$ WIMP mass. To further investigate lower interaction cross-sections down to $10^{-47}\,\mathrm{cm}^2$, or to confirm a possible dark matter signal, the XENON1T [22] experiment is currently being designed. This detector will have a total liquid xenon mass of 2.4 ton with about 1 ton inside the fiducial volume. To reach the desired sensitivity the total background has to be reduced by a factor of 100 with respect to XENON100. Beyond the sensitivity of XENON1T, the European DARWIN facility [23] aims for multi-ton scale liquid argon and liquid xenon detectors. This project is in the design phase and has brought together scientists from experiments using both argon and xenon technologies (WARP, ArDM and XENON).

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