

Looking for WIMPs – A Review

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There is currently a race to find out what dark matter actually is. Weakly Interacting Massive Particles (WIMPs) are a strong candidate for dark matter. Direct and indirect methods for detecting WIMPs exist. A brief summary of direct methods for WIMP detection is presented, along with a detailed description of one of the experiments, CDMSII.

Introduction

The existence of dark matter is supported by a range of relatively simple observations and has been known for about half a century. Supersymmetry theories offer a framework for introducing candidates that have the observed characteristics of dark matter. The Lightest Supersymmetric Particle (LSP), such as the neutralino, is the best of such candidates. Inferences about the neutralino's important cosmological role suggest that the particle interacts with ordinary matter in the electro-weak scale. Also, supersymmetric particles are believed to be heavy. Hence, there is an active effort to find these Weakly Interactive Massive Particles, or WIMPs.

Dark matter is inferred to exist based on the rotational velocity curves of galaxies, including the Milky Way. A good assumption about the distribution of dark matter in our galaxy is that of an isothermal spherical halo with a mean velocity of about 230 km/s. The particles in this halo could interact with detectors on Earth as we move through the halo. They could also get trapped by the Sun as it passes through the halo. The particles could then meet an antiparticle, producing neutrinos, gamma rays, antiprotons and positrons. It is important to note here that neutralinos, the WIMPs getting the most attention, are their own antiparticles.

Indirect detection of WIMPs is based on the idea of detecting and identifying WIMP annihilation products. The detection rate of these products depends on the density of WIMPs and the model used to calculate the expected cross section. Neutrinos product of WIMP annihilation are expected to be in the few GeV energy range, which is accessible through current neutrino detection experiments. The first results of such an experiment

and its implications on the dark matter search were presented in 1987. Detection of antiproton and positron products of neutralino annihilation would require space missions, and it is not clear that the signal will be above the background noise, in order to distinguish the WIMP annihilation products.

Direct detection of WIMPs interacting with large detectors on Earth is also being considered by the scientific community. For example, the Cryogenic Dark Matter Search (CDMS) collaboration, which will be explained in detail later, detects the ionization signal and the phonon signal of an interaction within Ge and Si detectors. Another way the interaction of a WIMP could be detected is by using scintillating materials. The DArk Matter (DAMA) experiment in Italy uses this type of detectors to search for annual modulation, a predicted consequence of the existence of the dark matter halo. A third detection system for WIMPs is based on a bubble chamber, and is used by the Chicagoland Observatory for Underground Particle Physics (COUPP) experiment.

Direct detection experiments

Different experiments that are looking for WIMPs in general, or neutralinos in particular, are presented next:

- Cryogenic Dark Matter Search (CDMS) collaboration.

The experiment is currently set up in Soudan Underground Lab operated by the University of Minnesota. The CDMS experiments use Ge and Si crystals to detect nuclear recoils due to interactions with particles. The simultaneous measurement of the ionization and the phonons due to these recoils allows for discrimination of events due to background signals. Details about this experiment will be presented later in this paper. <http://cdms.berkeley.edu/>

- Chicagoland Observatory for Underground Particle Physics (COUPP) from the University of Chicago, located at Fermilab.

The basic idea of this detector is that a particle that interacts with a superheated liquid will induce the creation of a bubble, causing the liquid to boil. The liquids proposed are: CF₃Br, CF₃I, C₃F₈ and liquid xenon. A 2-kg prototype is being tested, and has shown that the liquid used is not affected by gamma rays, a significant source of background in other setups. The superheated liquid is contained in a small quartz pressure vessel. The pressure in the chamber is controlled by a piston, which is operated by compressed air. Gas is introduced with the piston fully compressed. When the desired amount of liquid has been condensed into the chamber, the compressed air in the piston is slowly discharged to reduce the internal pressure of the quartz chamber and cause superheating. When bubble nucleation occurs, it causes violent boiling, and a rise in pressure. Two CCD cameras take pictures of the bubbles; a single bubble would indicate a WIMP event.

<http://collargroup.uchicago.edu/projects/wimp/index.html>

- Cryogenic Rare Event Search with Superconducting Thermometers (CRESST) hosted at the Laboratori Nazionali del Gran Sasso, Italy

Most common backgrounds will produce some light in a scintillating material while on the other hand the sought-for WIMP induced recoils will produce little or no light. Detectors were developed based on scintillating crystals as absorbers. A particle interaction produces mainly phonons or heat, but in addition a small amount of the deposited energy is emitted as scintillation light. A second, smaller calorimeter is added to detect this light, and most common backgrounds can be eliminated through their light signal. The CRESST II setup will consist of up to 33 modules with both light and heat detection, reaching up to 10 kg of active target mass, read out by a 66-channel SQUID system, two readout channels for each module.

<http://www.cresst.de/>

- DArk MAter (DAMA) also in Gran Sasso, Italy
DAMA has had several experiments, some for development of detectors for bigger experiments.

The DAMA/LIBRA (Large Sodium Iodide Bulk for RARE processes), a 250-kg, highly radio-pure NaI(Tl) setup in operation since March 2003, is foreseen to release results in 2008. The DAMA/NaI experiment, with a 100-kg detector of highly radiopure NaI(Tl), was aimed at investigating in a model independent way the presence of dark matter particles in the galactic halo by measuring the distinctive annual modulation signature. The annual cycle starts from autumn/winter toward summer. The DAMA/LXe experiment has as a detector a pure liquid xenon scintillator of about 6.5 kg with Kr-free xenon enriched in either 129 or 136 xenon isotopes.

<http://people.roma2.infn.it/~dama/web/home.html>

- Experience pour Detecter Les WIMPs en Site Souterrain (EDELWEISS) in Laboratoire Souterrain de Modane, France

Installed since 1994, the first stage operated 3 detectors of 320 g at a base temperature of 18 mK. In 2002 spin-independent limit obtained by EDELWEISS was published. EDELWEISS-I stopped in 2004. EDELWEISS-II operates 21 germanium detectors since the end of 2005. The expected event rate is about 0.01 per kg per day. The detectors are at low temperatures (20 mK). Each is made of a massive (320 g) crystal of high purity germanium. The recoil energy of a Ge nucleus is converted into heat and measured by a temperature rise within one millionth of a degree. Ionization is also measured; energies as low as 10 keV can be detected.

http://edelweiss.in2p3.fr/index_newwe.html

- Heidelberg Dark Matter Search (HDMS) from Russia and Germany

Two ionization Ge detectors are used: a small, p-type Ge crystal is surrounded by a well-type Ge crystal, both being mounted into a common cryostat system. A 1-mm thin insulator made from vespel is placed between them. The main radioactive background of Ge detectors comes from materials situated in the immediate vicinity of the crystals, like from copper parts of the cryostats. HDMS has the goal to achieve the absolute background counting rate of 0.07 events per kg per day per keV in the region between 2 keV and 30 keV in order to test the evidence region presented by the DAMA experiment. The HDMS started in 1998 with a prototype, while the full scale experiment was installed in 2000.

http://www.mpi-hd.mpg.de/non_acc/dm.html

- WIMP ARgon Programme (WARP) also in Gran Sasso, Italy

WARP uses a cryogenic noble liquid detector, like argon or xenon. This permits the detection of both ionization and scintillation. Electron mediated background can be eliminated, since there is a unique signature for the energy due to a recoiling nucleus. The setup consists of argon in liquid and gas states. A primary scintillation signal due to de-excitation of argon is detected by photomultipliers. Then, ionization electrons are accelerated to the gaseous phase by an electric field to produce secondary scintillation. <http://warp.pv.infn.it/>

- ZonEd Proportional scintillation in Liquid Noble gases (ZEPLIN) in the UK

The ZEPLIN program uses scintillating xenon, and was scheduled to operate during 2000. It has a lead shielding castle that takes care of most of the background from radioactivity and cosmic rays. It also has a veto system: xenon pulses that are almost simultaneous with the pulses in the veto are ignored. <http://hepwww.rl.ac.uk/ukdmc/project/project.html>

The CDMSII experiment

The CDMSII experiment is located deep inside a mountain in Soudan National Park, Minnesota, and the lab is run by the University of Minnesota.

The sensors are located inside a cryostat or ‘icebox’, composed of six nested cylindrical cans of low radioactivity copper kept at a temperature of 50 mK. Each icebox can hold 7 stacks or ‘towers’ of ZIP detectors, which will be explained in detail later. Each detector has its own electronics card, with two FETs for the readout of the ionization channels and four SQUIDs for readout of phonon detection. Several layers of shielding cover the icebox. From the outside in: forty scintillating, overlapping panels act as a muon veto system; 40-cm thick polyethylene layer for moderation of low-energy neutrons; 22.5-cm thick lead, the 4.5-cm thick inner layer made of ancient lead; 10-cm polyethylene layer for further neutron moderation. The icebox provides 3 cm of copper shielding directly surrounding the detector.

The basic operation of the Ge and Si sensors is explained next, followed by a list detailing the criteria behind selecting the positive hits for WIMP detection.

The physics behind the sensors

ZIP (Z-dependent Ionization and Phonon mediated) detector is a cylindrical high purity Ge or Si crystal that is 1 cm thick and 7.6 cm in diameter. A single Ge (Si) ZIP has a mass of 250 g (100 g). Two concentric ionization electrodes and four independent phonon sensors are photolithographically patterned onto each crystal.



Figure 1. Picture of a ZIP detector from CDMSII webpage.

An external particle scattering in a ZIP detector can interact with an electron or electrons in the crystal (‘electron recoil’) or with a nucleus (‘nuclear recoil’). The interaction deposits energy into the crystal through charge excitations (electron-hole pairs) and lattice vibrations (phonons). A ZIP detector measures both the ionization and the phonon energy for every event. The simultaneous ionization and phonon measurement not only allows an accurate measurement of the recoil energy independent of recoil type, but also distinguishes between these two types of recoils. Nuclear recoils produce fewer charge pairs, and hence less ionization energy, than do electron recoils of the same recoil energy.

On each ZIP detector, metal electrodes on the two faces of the crystal substrate serve as the sensors for the ionization measurement. The electrodes are used to apply an electric field of a few volts/cm across the crystal, which drifts electrons and holes produced by an interaction to the detector faces.

QETs (Quasiparticle assisted Electrothermal-feedback Transistor Edge sensors) photolithographically

patterned onto one of the crystal faces form the phonon sensors for a ZIP. Each QET consists of a 1-micrometer wide strip of tungsten (35 nm thick) connected to eight superconducting aluminum collection fins (300 nm thick), each roughly 380 micrometers x 55 micrometers. The narrow tungsten strips form the Transition Edge Sensors (TES), which are voltage biased, with the current through them monitored by a high-bandwidth SQUID. Energy deposited in the tungsten electron system raises the temperature of the film, increasing its resistance and reducing current.

An interaction in the crystal produces high-frequency phonons, which propagate quasi-diffusively through the crystal. In the first few hundred nanoseconds after an interaction, the freed electron-hole pairs drift across the entire crystal, shedding ballistic phonons and producing additional ballistic phonons upon relaxation at the electrodes. Since electron recoils produce more charges than nuclear recoils, these processes lead to a larger initial population of ballistic phonons for electron recoil. Ballistic phonons propagate at the speed of sound, while the energy flux of high frequency phonons moves at approximately one third the speed of sound. This difference in the speed of propagation leads to a faster phonon leading edge for electron recoils when compared to nuclear recoils because of the larger ballistic fraction.

Data cuts – discriminating useless data (very technical stuff)

Data-quality cuts: to exclude data sets with known problems, with increased noise, and events that were triggered by noise bursts.

Phonon pre-trigger cut: rejects events for which the pre-trigger part of a phonon trace is unusually noisy to eliminate pile-up events and noise-triggered events.

Ionization chi-squared cut: events with anomalous ionization pulse shapes are rejected by a cut on chi-squared of the optimum filter fit.

Fiducial-volume cut: the volume fraction covered by the inner electrode in the detector is 82%. The cut is set below this value, to be conservative.

Electron recoil and nuclear recoil bands: fit Gaussians to distributions of ionization yield for both electron recoil and nuclear recoil events (from calibration) in several recoil energy bins. The estimated means and standard deviations are then fitted versus recoil energy. The bands are taken to be plus/minus 2 sigma.

Ionization threshold cut: to select events that have measurable pulses in the charge channels, like an event with only noise in the inner ionization channel that could otherwise be mistaken for a low-energy nuclear recoil event.

Muon-veto cut: the time between the global trigger and the last hit in the muon veto was used. Events for which this time is long are unlikely to be caused by a muon interaction inside the veto; events occurring within 50 microseconds after veto activity are rejected.

Singles and Multiples cuts: to define single-scatter events use the distribution of phonon energy for noise events obtained by random triggering. Single-scatter events are events in which only one detector had a phonon signal larger than 6 sigma of this distribution.

Phonon timing cut: the peak delay and the peak rise time. First determine cuts in each of the two parameters for recoil energy bins. In each bin, determine a pair of cut values that would reject every event from a subset of calibrations that was in the 4 sigma nuclear recoil band.

Analysis Thresholds: effective discrimination of electromagnetic backgrounds is achieved for energies as low as 5 keV in most detectors. To be conservative, set analysis thresholds for most detectors at 10 keV. All detectors have an upper analysis bound on the recoil energy of 100 keV.

The run from October 2003 through January 2004 detected one possible WIMP event, though the signal was consistent with a surface event background as well. Figure 2 presents a graph of the parameter space for WIMP mass and cross-section, as presented by the CDMS collaboration.

References

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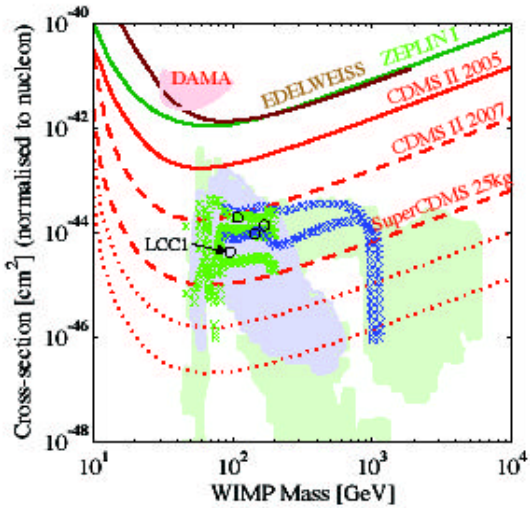


Figure 2. Measured and predicted exclusion regions of WIMP mass and cross-section for several experiments. This figure is copied from the CDMSII brochure.