THE EDELWEISS EXPERIMENT AND DARK MATTER DIRECT DETECTION

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This mini-review first introduces the motivations for Dark Matter Searches. The experimental aspect of the direct detection of Weakly Interactive Massive Particles (WIMPs) is described, detailing its principle and presenting some experiments with their recent results. The EDELWEISS experiment and its results are discussed in more details before concluding with the future direct detection experiments.

1 Introduction

1.1 Why Dark Matter?

One of the most important questions in physics today is the problem of the Universe mass. It is one of the topics that motivated the association of astrophysics and particle physics in a new field: astroparticle physics.

In 1933 F. Zwicky first proposed a dark component of Universe. By measuring the velocity dispersion of galaxies in the Coma cluster, he highlighted the fact that the Universe must contain something else in addition to visible matter: another form of matter which does not emit nor absorb radiation. In the seventies, this study was systematically extended to spiral galaxies by several teams. It was observed that the rotation velocity of galaxy arms remained constant as a function of distance from the center, even far beyond the luminous disc. This suggested that all galaxies are surrounded by a Dark Matter halo.

The hypothesis of Dark Matter has also gained momentum in the field of cosmology, as experiments are now determining with an increasing precision the cosmological parameters of the Universe.

Recently new interesting results reached us from the balloon-borne experiment Archeops and the WMAP satellite. These two experiments observe the CMB (Cosmic Microwave Background) fluctuations. Their results support a flat Universe with an energy density $\Omega = 1.00 \pm 0.03$ (normalized to the critical density). In addition, a gravitationaly self-repulsive "dark energy" accelerating the expansion of the Universe and accounting for $\sim 70\%$ of the total energy density, leaving only $30\%$ for the matter one, has been evidenced, in agreement with the results of experiments studying distant type Ia SuperNovae. Their data combined with other CMB results constrain the baryon contents of the Universe to a small
fraction of matter $\Omega_b = 0.044 \pm 0.003$, but compatible with the primordial nucleosynthesis scenario. Thus standard cosmology supports an important presence of non-baryonic Dark Matter, with a density $\Omega_{DM} \approx 0.3$. Therefore most of the matter in the Universe is dark and only a small part is baryonic.

1.2 Dark Matter candidates

Despite the growing acceptance for the existence of non-baryonic Dark Matter, its exact nature remains mysterious for a great part. It is worthwhile to go to particle physics to find well motivated candidates for Dark Matter.

Non-baryonic Dark Matter has two components: HDM (Hot Dark Matter) which was relativistic at the time when radiation decoupled from the matter and CDM (Cold Dark Matter), non-relativistic at that time. The neutrino is the main candidate for HDM, but the experiments dedicated to the CMB fluctuation observations strongly constrain the neutrino density $\Omega_\nu \approx 0.0076$ (95% C.L.), with $h = 0.71 \pm 0.04$. This paper will concentrate on CDM and in particular on the candidate with the best physics supports: the WIMP (Weakly Interactive Massive Particle)\(^a\). The WIMP has no electric charge and is a stable thermal relic from the Big Bang era, now trapped in the gravitational potential of galaxies and clusters of galaxies. On the other side, CMB experiments suggest a CDM density $\Omega_{CDM} \approx 0.22$; that confirms their importance in the galactic halo.

In the MSSM (Minimal Supersymmetric Standard Model) framework with the R-parity conservation, the LSP (Lightest Supersymmetric Particle) is a stable particle with a relic abundance. The most likely LSP is the neutralino, defined as a linear combination of the supersymmetric partners of the photon, Z and Higgs bosons. The neutralino mass ranges between 45 GeV/c\(^2\) (given by LEP\(^1\)) and a few TeV/c\(^2\)\(^2\). The neutralino is expected to be detected by an accelerator experiment like the LHC\(^11\) (Large Hadron Collider).

A great number of experiments all over the world are aiming at discovering Dark Matter in the form of WIMPs, and in particular as a neutralino or another particle with a similar behavior.

2 WIMP search

There are two different methods to observe WIMPs: direct and indirect detection. Indirect detection is the observation of the products of WIMP annihilation in cosmic rays. This technique is discussed elsewhere\(^12\). This paper is devoted to direct detection. We will describe its principles and present some of the leading experiments.

For the sake of comparing different experiments, it is usual to consider WIMPs distributed in a spherical halo around our galaxy with a local density $\rho = 0.3$ GeV/cm\(^3\), a Maxwellian velocity distribution with $v_{rms} \approx 270$ km/s, an escape velocity of 650 km/s and the velocity of the Sun in the halo of 230 km/s.

2.1 Direct detection principle

In this technique, a WIMP is detected by measuring the nuclear recoil produced by its elastic interaction in an ordinary matter target.

In the MSSM model, the WIMP can couple to nuclei via 2 mechanisms\(^3\):

- spin-dependent, with $\sigma_{SD} \propto J(J+1)$, where J is the target nuclear spin
- spin-independent, with $\sigma_{SI} \propto A^2$, where A is the target atomic mass

In most MSSM models, $\sigma_{SI}$ dominates over $\sigma_{SD}$\(^3\) for $A>30$ (as it is for most of the used targets). The most striking signature of WIMP interaction is the fact that it induces a nuclear recoil, while the natural radioactive background (except neutrons) leads to electronic recoils. With sufficient statistics, other signatures can be used. The WIMP recoil energy spectrum should have the expected exponential behavior. In addition, the nuclear recoil directions should be correlated with the motion of the Sun in the galaxy. Although the measurement of recoil directions is difficult\(^13\), it could be possible to observe an annual modulation effect on the WIMP rate, as the Earth revolves around the Sun. To remove nuclear recoils due to neutron collisions, two following signatures can be used: because

\(^a\)A second candidate is the axion, a Goldstone boson which could permit to solve the CP violation problem in the strong interactions (for more details, see\(^7\)).
of the weak interaction probability in matter, a WIMP can’t produce multiple scattering (contrary to a neutron), and the spin-independent WIMP-nucleon cross section is proportionnal to $A^2$, while the dependence for neutron is approximately $A^{2/3}$. When a WIMP hits a nucleus, its recoil energy is given by:

$$E_R = \frac{\mu^2}{M} v^2 (1 - \cos \theta)$$

(1)

where $M$ is the nucleus mass, $\mu$ the reduced mass ($M, m$) with $m$ the WIMP mass, $v$ the WIMP velocity and $\theta$ the scattering angle of WIMP. Given the velocity of WIMPs in our halo ($\sim 10^{-3} c$) and the interesting mass range (GeV/c$^2$ to TeV/c$^2$), the energy deposited by the particle is very low (10-100 keV). In addition, supersymmetric calculations predict that the interaction rate should be very low (from 1 evt/day/kg of detector to 1 evt/decade/kg).

These two facts lead to some constraints for the detectors. The low interaction rate requires a large detector mass and a very low background while the low deposited energy requires a low detection threshold ($\sim 10$ keV recoil).

When a particle hits matter, according to the nature of the target, three different physical effects can be measured: ionization, scintillation and heat. Some experiments measure only one process and others measure two processes, in order to discriminate electronic and nuclear recoils (see Table 1). This discrimination is based on the fact that nuclear recoils produce proportionally less ionization and scintillation than electronic recoils. Because of these differences in responses, in this paper two kinds of energy are quoted: the recoil energy in keV and the ionization or scintillation energy in keV$\_ee$ (keV electron equivalent); for Ge $\frac{\text{keV} \_ee}{\text{keV}} \approx 0.33$ and for I $\frac{\text{keV} \_ee}{\text{keV}} \approx 0.09$.

Of these different techniques, we will present Germanium diodes, scintillating detectors and cryogenic detectors.

### Table 1: Running experiments

| Experiment  | Location               | Technique             | Detectors          |
|------------|------------------------|-----------------------|--------------------|
| EDELWEISS I| Laboratoire Souterrain de Modane | ionization-heat | 3 × 320 g of Ge |
| CDMS I     | Standford Underground Facility | ionization-heat | 4 × 165 g of Ge |
| ZEPLIN I   | Boulby mine            | scintillation         | 4 kg of LiqXe |
| CRESST I   | Gran Sasso             | scintillation-heat    | 6 g of CaWO$_4$ |
| IGEX       | Canfranc               | ionization            | 2 kg of Ge |
| HDMS       | Gran Sasso             | ionization            | 200 g of Ge |
| DAMA       | Gran Sasso             | scintillation         | 100 kg of NaI |

2.2 Classical Germanium detector

These detectors are Germanium diodes with two electrodes for collecting the charge induced by a particle interaction. The first search made with these detectors was that of neutrinoless double-beta decay ($0\nu 2\beta$). Their advantages are their energy resolutions and the lowest total background event rate of any Dark Matter search thanks to improvements in the Germanium purification techniques.

The most important experiments are HDMS$^{15}$ and IGEX$^{11}$.

The HDMS (Heidelberg Dark Matter Search) detector is devoted to WIMP detection. It is located at the Gran Sasso Underground Laboratory (LNGS) and comprises a 200 g natural Germanium detector surrounded by a 2.1 kg Germanium veto detector. With a resolution of 1.06 keV$\_ee$ at 0 keV$\_ee$ (determined by extrapolation) and an energy threshold of 2 keV$\_ee$ for the inner detector, they recorded a background of 0.2 evt/keV$\_ee$/kg/d$^{15}$ in the range 11–40 keV$\_ee$. The limit deduced from these data is not yet competitive with their previous limit$^{17}$: 0.042 evt/keV$\_ee$/kg/d in the range 15–40 keV$\_ee$ (with an energy threshold of 9 keV$\_ee$) obtained with a Germanium crystal enriched in $^{76}$Ge. Another stage was reached in 2002 with the first result in the final setup$^{16}$ where the inner detector was replaced by enriched $^{75}$Ge.

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$^b$We present here only the experiments which have published a limit and are sensitive to the spin-independent cross section.
have obtained 0.43 evt/keV\textsubscript{ee}/kg/d in the range 11-40 keV\textsubscript{ee} (with an energy threshold of 4 keV\textsubscript{ee} for the inner detector). The IGEX detector is a 2.2 kg Germanium crystal enriched in \textsuperscript{76}Ge for the 0\nu2\beta decay search, operated at the Canfranc Underground Laboratory. Their latest results correspond to an exposure of 80 kg day\textsuperscript{-1}. With an energy threshold of 4 keV\textsubscript{ee} and a resolution of 800 eV\textsubscript{ee} at 75 keV\textsubscript{ee}, they obtained a background of \sim 0.06 evt/keV\textsubscript{ee}/kg/day\textsuperscript{-1} between 10-40 keV\textsubscript{ee}. Their data exclude a WIMP with a mass of \sim 50 GeV/c\textsuperscript{2} and a WIMP-nucleon cross section $\sigma_{\chi-n} \approx 7 \times 10^{-6}$ pb. For experiments using Ge diodes, this is the highest Dark Matter sensitivity.

The disadvantage of this Germanium technique for Dark Matter direct detection is the impossibility to discriminate nuclear and electronic recoils.

2.3 Scintillating detectors

The second category of direct detection detectors includes liquid and solid scintillators. The running experiments use detectors with already large masses (5 to 100 kg).

The DAMA detector\textsuperscript{18} is made with 100 kg of NaI crystals placed at the Gran Sasso Underground Laboratory (LNGS). In four years, they accumulated an exposure of 58000 kg day\textsuperscript{-1}. Their statistical background rejection is based on annual modulation. In 2000 this team claimed to observe an annual modulation\textsuperscript{18} of their event rate, in the 2-6 keV\textsubscript{ee} range, corresponding to a WIMP with $m = 52$ GeV/c\textsuperscript{2} and $\sigma_{\chi-n} = 7.2 \times 10^{-6}$ pb using standard astrophysical assumptions. In combining this result with their previous exclusion curve of 1996\textsuperscript{19}, their most likely WIMP mass is 44 GeV/c\textsuperscript{2} with $\sigma_{\chi-n} = 5.4 \times 10^{-6}$ pb.

The ZEPLIN (ZonEd Proportionnal scintillation in LIquid Noble gases) collaboration uses another type of scintillator: the liquid Xenon. This detector is located at the Boulby mine. The first stage, ZEPLIN I, consists in a liquid Xe single phase with a fiducial mass of \sim 4 kg. For more details on its preliminary results, see\textsuperscript{13}. A second stage\textsuperscript{20} is in preparation with 2 phases (liquid-gas) allowing the simultaneous measurement of scintillation and ionization with a Xe target of \sim 30 kg.

2.4 Cryogenic detectors

When a particle hits a crystal (the absorber), its temperature increases by $\Delta T = \frac{\Delta E}{C}$, where C is the heat capacity of the crystal and $\Delta E$ is the deposited energy. To measure this tiny increase, the detector has to be placed at a cryogenic temperature of \sim 10 mK in order to minimize C. $\Delta T$ is measured by a sensor glued, or evaporated, on the absorber. By measuring the heat signal in coincidence with another signal such as ionization or scintillation, it is possible to discriminate nuclear and electronic recoils, and thus to remove a major part of the background.
The CRESST experiment

The CRESST detector is located at the Gran Sasso Underground Laboratory (LNGS). It measures at the same time the scintillation and the heat signals produced by the incident particle to perform a discrimination. Their detectors have three parts: a scintillating absorber made of Calcium Tungstate, a Sapphire light detector and a Tungsten thermometer placed on the absorber. The latest results of the collaboration were obtained with a 262 g Sapphire crystal with a Tungsten film as sensor, operating at 15 mK. At present, two detectors each with a mass of 300 g are running.

Heat and ionization bolometers

The CDMS and EDELWEISS experiments use bolometers with simultaneous measurements of ionization and heat.

The interaction of a particle in the semiconducting absorber (Silicium or Germanium crystal) produces ionization collected by two electrodes. The rise in temperature is measured with a heat sensor (NTD (Neutron Transmutation Doped) or TES (Transition Edge Sensor)). These two simultaneous measurements provide an event-by-event discrimination between nuclear and electronic recoil.

The principle of this discrimination is as follows. The ratio of the ionization and heat signals depends on the recoiling particle, since a nucleus produces less ionization in crystal than an electron. On a plot of the ratio of the ionization energy to the recoil energy, versus the recoil energy, two populations can be distinguished (Fig. 2). The first population centered on $\sim 1$ (by construction) represents electron recoils from gamma interactions, while the second one centered on $\sim 0.3$ corresponds to nuclear recoils, in this case from neutron scattering. Fig. 2 shows an example where it is possible to reject more than $\sim 99.9\%$ of gammas down to 15 keV recoil energy.

The CDMS experiment

Until last year the CDMS experiment was located at the Stanford Underground Facility. Their setup includes two different crystal absorbers ($4 \times 165$ g Germanium and $1 \times 100$ g Silicium). In 1998 and 1999 CDMS performed some runs with these Germanium bolometers (Fig. 3) with an analysis threshold of 10 keV. They recorded 11.9 kg.day (in the inner volume) after subtracting neutron background on the basis of the relative rate in Si and Ge, and the coincident rate of nuclear recoils between Ge detectors. Their data exclude at more than 99 % C.L. the DAMA experiment candidate with $m = 52$ GeV/c$^2$ and $\sigma_{\chi-n} = 7.2 \times 10^{-6}$ pb, and moreover, exclude a large part of the DAMA region (Fig. 4).

In 2002 CDMS moved to the Soudan mine for a better protection against neutrons induced by cosmic rays. Data taking is in progress.
3 The EDELWEISS experiment

The EDELWEISS collaboration combines several laboratories from CEA (DAPNIA, DRECAM), CNRS (IN2P3, DSM, INSU) and Germany (FZKA, Karlsruhe). EDELWEISS means “Expérience pour DEtecter Les Wimps En SiTe Souterrain” and is located at the LSM (Laboratoire Souterrain de Modane) in the Frejus tunnel under the Franco-Italian Alps. Their latest results were published in 2002.

3.1 The experimental setup

The present stage of the EDELWEISS experiment consists of three 320 g Germanium cryogenic detectors placed in a dilution cryostat with a base temperature of ∼ 17 mK. To decrease the background in the experiment, all materials around the detectors were carefully selected for their low radioactivity. The front end electronic components are placed behind a roman lead shield above the three detectors. The Germanium bolometers are equipped with a NTD heat sensor. The ionization is collected by two Aluminium sputtered electrodes operated at voltages between 2 and 4 V. One of the three detectors has a Germanium amorphous layer under the electrodes.

A segmented electrode defines a central fiducial part and a guard ring. Most of the radioactivity due to the detector environment is collected on this latter part of the detector. In addition, the electrostatic field is more uniform in the central part. The fiducial inner volume, defined as ≥75 % of the charge collected on the central electrode, corresponds to 57% of the total detector volume.

3.2 Results

Calibrations with gamma-ray sources revealed that two of the three detectors had problems with the charge collection, that were related with the absence of amorphous layer. Therefore only the third detector data were used for the final results.

The low-background physics runs between February and May 2002 resulted in 8.6 kg.day effective exposure in the fiducial volume of the selected detector. The baseline resolutions for this detector are below 1.5 keVee and 1.3 keVee for ionization and heat respectively. The ionization threshold corresponding to an efficiency of 50% is measured to be 3.7 ± 0.2 keVee, implying a full efficiency at a recoil threshold of 20 keV.

No events have been observed in the band corresponding to 90% of all nuclear recoils (Fig. 3). One event lies on the edge of the nuclear recoil zone at recoil energy ∼ 120 keV but is incompatible at 95% C.L. with a WIMP with a mass below 10 TeV/c². These data exclude at more than 99.994 % the DAMA candidate with m = 52 GeV/c² and σχ−n = 7.2 × 10⁻⁶ pb.

3.3 Comparison with the CDMS results

EDELWEISS and CDMS using the same type of detectors, it is interesting to compare their results (Fig. 3). EDELWEISS observed no events in the nuclear recoil band, in the range 20-200 keV, in 8.6 kg.day, while CDMS observed 13 events, in the range 10-100 keV, in 11.9 kg.day. CDMS attributes these events to a neutron background based on their Silicium detectors data (compared to Ge, Si is relatively more sensitive to neutrons than to WIMPs) and the coincident rate between Germanium detectors. This background arises because of their shallow site. EDELWEISS is located under 1600 meters of rock, which reduces the prompt activation by cosmic rays by a factor one million.

3.4 Exclusion limit

Finally all experiments compare the observed rate to the predicted one and interpret the results as 90% C.L. exclusion limits on the WIMP-nucleon cross section as a function of the WIMP mass (Fig. 3). To be able to compare various experiments, all of them assume the same parameters for the halo model. The EDELWEISS experiment excludes at 99.8% the DAMA candidate with m = 44 GeV/c² and σχ−n = 5.4 × 10⁻⁶ pb. Its sensitivity for spin-independent WIMP-nucleon interaction is the best published result for masses above 35 GeV/c². Moreover, their curve start to covers some supersymmetric predictions. Experiments with event-by-event discrimination are today more sensitive than experiments with classical detectors.

Note that the ZEPLIN curve is still preliminary.
4 Outlook

4.1 Coming developments

All the described experiments are preparing for the near future new stages with increased masses and improved techniques (see Table 2).

For example, the EDELWEISS experiment is running in 2002-03 with three 320 g Germanium bolometers, all of them having an amorphous layer (either in Germanium or Silicium).

| Experiment  | Location          | Technique          | Detectors       |
|-------------|-------------------|--------------------|-----------------|
| EDELWEISS II| Laboratoire Souterrain de Modane | ionization-heat | $120 \times 320$ g of Ge |
| CDMS II     | Soudan mine       | ionization-heat    | $21 \times 250$ g of Ge $21 \times 100$ g of Si |
| ZEPLIN II   | Boulby mine       | scintillation-ionization | $30$ kg of LiqXe |
| CRESST II   | Gran Sasso        | scintillation-heat | $33 \times 300$ g of CaWO$_4$ |
| GENINO      | Gran Sasso        | ionization         | $100$ kg of Ge   |
| LIBRA       | Gran Sasso        | scintillation      | $250$ kg of NaI |

4.2 EDELWEISS II

EDELWEISS II will be an experiment with 120 (40 kg) Germanium cryogenic detectors placed in a new cryostat. The detectors will be placed in an innovative reversed cryostat with a volume of 100 $\ell$. Inside, the detectors are close packed in an hexagonal arrangement. The cryostat has been already tested at $\sim 10$ mK. At present, a first phase with 28 detectors is approved.

The goal of this experiment is to improve by two orders of magnitude the present sensitivity. In order to reduce the neutron background below $\sim 0.02$ evt/kg/day, the shielding will be improved by surrounding the experiment with muon vetos and by increasing the thickness of the Polyethylene shield.

4.3 Sensitivity goals

Dark Matter direct detection experiments are now reaching WIMP-nucleon cross sections of $10^{-6}$ pb and start to probe the most optimistic supersymmetric models. But testing a more significant fraction of the models requires to reach a WIMP-nucleon cross section of $10^{-8}$ pb at least (Fig. 5). This is the main
Figure 4: 90% C.L. exclusion limit for the experiments DAMA, IGEX, CDMS, EDELWEISS, and ZEPLIN (preliminary) and two regions spanned by some supersymmetric calculations are shown.

purpose of the second phases of the experiments. In this aim, they increase the target masses and work

to improve their sensitivity with new materials and new techniques.

5 Conclusion

At present, WIMP direct detection experiments start now to be sensitive to a small fraction of the most optimistic supersymmetric models. Next generation of experiments should allow a factor 100 improvement in sensitivity and begin to test a larger fraction of models. But testing the bulk of supersymmetric models requires experiments in the one-ton range and an extreme background rejection. All the experiments aim at discovering the nature of the main part of Dark Matter in the coming years, to possibly confirm a signal observed with the LHC after 2007.
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