Direct Detection of WIMP Dark Matter *

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The status of the recent efforts in the direct search for Weak Interacting Massive Particle (WIMP) Dark Matter is briefly reviewed and the main achievements illustrated by the contributions presented to TAUP 99. The strategies followed in the quest for WIMPs will be first revisited and then the new results and the future prospects reported.

1. Introduction

There is substantial evidence, reviewed at length in this Workshop, that most of the matter of the universe is dark and a compelling motivation to believe that it consists mainly of non-baryonic objects. From the cosmological point of view, two big categories of non-baryonic dark matter have been proposed: cold (WIMPs, axions) and hot (light neutrinos) dark matter according to whether they were slow or fast moving at the time of galaxy formation. Without entering into considerations about how much of each component is needed to fit better the observations, nor about how large the baryonic component of the galactic halo could be, we assume that there is enough room for WIMPs in the halo to try to detect them, either directly or through their by-products. Discovering this form of dark matter is one of the big challenges in Cosmology, Astrophysics and Particle Physics.

The indirect detection of WIMPs proceeds currently through two main experimental lines: either by looking in the space for positrons, antiprotons, or other antimatter produced by the WIMPs annihilation in the halo, or by searching in large underground detectors or underwater neutrino telescopes for upward-going muons produced by the energetic neutrinos emerging as final products of the WIMPs annihilation in celestial bodies (Sun, Earth...).

The direct detection of WIMPs relies in the measurement of the WIMP elastic scattering off the target nuclei of a suitable detector. Pervading the galactic halos, slow moving (~ 300 km/s), and heavy (10 ~ 10^3 GeV) WIMPs could make a nucleus recoil with a few keV (T ~ (1−100) keV), at a rate which depends of the type of WIMP and interaction. Only a fraction of the recoil QT is visible in the detector, depending on the type of detector and target and on the mechanism of energy deposition. The so-called Quenching Factor Q is essentially unit in thermal detectors whereas for the nuclei in conventional detectors range from about 0.1 to 0.6. Because of the low interaction rate [typically < 0.1 (0.001) c/kg day for spin independent (dependent) couplings] and the small energy deposition, the direct search for particle dark matter through their scattering by nuclear targets requires ultralow background detectors of a very low energy threshold. Moreover, the (almost) exponentially decreasing shape of the predicted nuclear recoil spectrum mimics that of the low energy background registered by the detector. All these features together make the WIMP detection a formidable experimental challenge.

Customarily, one compares the predicted event rate with the observed spectrum. If the former turns out to be larger than the measured one, the particle under consideration can be ruled out as a dark matter component. That is expressed as a contour line σ(m) in the plane of the WIMP-
nucleus elastic scattering cross section versus the WIMP mass which excludes, for each mass m, those particles with a cross-section above the contour line $\sigma(m)$. The level of background limits, then, the sensitivity to exclusion.

This mere comparison of the expected signal with the observed background spectrum is not supposed to detect the tiny imprint left by the dark matter particle, but only to exclude or constrain it. A convincing proof of the detection of WIMPs would need to find unique signatures in the data characteristic of them, like temporal (or other) asymmetries, which cannot be faked by the background or by instrumental artifacts. The only distinctive signature investigated up to now is the predicted annual modulation of the WIMP signal rate.

The detectors used so far (most of whose results have been presented to this Workshop) are Ge (IGEX, COSME, H/M) and Si (UCSB) diodes, NaI (ZARAGOZA, DAMA, UKDMC, SACLAY, ELEGANTS), Xe (DAMA, UCLA, UKDMC) and CaF$_2$ (MILAN, OSAKA, ROMA) scintillators, Al$_2$O$_3$ (CRESST, ROSEBUD) and TeO$_2$ (MIBETA, CUORICINO) bolometers and Si (CDMS) and Ge (CDMS, EDELWEISS) thermal hybrid detectors, which also measure the ionization. But new detectors and techniques are entering the stage. Examples of such new devices, presented at TAUP are: a liquid-gas Xenon chamber (UCLA); a gas chamber sensitive to the direction of the nuclear recoil (DRIFT); a device which uses superheated droplets (SIMPLE), and a colloid of superconducting superheated grains (ORPHEUS). There is also some new projects featuring a large amount of target nuclei, both with ionization Ge detectors (GENIUS, GEDEON) and cryogenic thermal devices (CUORE).

2. Strategies for WIMP detection

The rarity and smallness of the WIMP signal dictate the experimental strategies for its detection:

Reduce first the background, controlling the radiopurity of the detector, components, shielding and environment. The best radiopurity has been obtained in the Ge experiments (IGEX, H/M, COSME). In the case of the NaI scintillators, the backgrounds are still one or two orders of magnitude worse than in Ge (ELEGANTS, UKDMC, DAMA, SACLAY). The next step is to use discrimination mechanisms to distinguish electron recoils (tracers of the background) from nuclear recoils (originated by WIMPs or neutrons). Various techniques have been applied for such purpose: a statistical pulse shape analysis (PSD) based on the different timing behaviour of both types of pulses (DAMA, UKDMC, SACLAY); an identification on an event-by-event basis of the nuclear recoils by measuring at the same time two different mechanisms of energy deposition, like the ionization and heat capitalizing the fact that for a given deposited energy (measured as phonons) the recoiling nucleus ionizes less than the electrons (CDMS, EDELWEISS).

A promising discriminating technique is that used in the liquid-gas Xenon detector with ionization plus scintillation presented to this Workshop (see D. Cline’s contribution to these Proceedings). An electric field prevents recombination, the charge being drifted to create a second pulse in the addition to the primary pulse. The amplitudes of both pulses are different for nuclear recoils and gammas allowing their discrimination.

Another technique is to discriminate gamma background from neutrons (and so WIMPs) using threshold detectors—like neutron dosimeters—which are blind to most of the low Linear Energy Transfer (LET) radiation ($e, \mu, \gamma$). A new type of detector (SIMPLE) which uses superheated droplets which vaporize into bubbles by the WIMP (or other high LET particles) energy deposition has been presented to this Workshop (see J. Collar’s contribution to these Proceedings).

The other obvious strategy is to make detectors of very low energy threshold and high efficiency to see most of the signal spectrum, not just the tail. That is the case of bolometer experiments (MIBETA, CRESST, ROSEBUD, CUORICINO, CDMS, EDELWEISS).

Finally, one should search for distinctive signatures of the WIMP, to prove that you are seeing a WIMP. Suggested identifying labels are: an annual modulation of the signal rate and energy.
spectrum (of a few percent) due to the seasonal June-December variation in the relative velocity Earth-halo and a forward-backward asymmetry in the direction of the nuclear recoil due to the Earth motion through the halo. The annual modulation signature has been already explored. Pioneering searches for WIMP annual modulation signals were carried out in Canfranc, Kamioka and Gran Sasso. At TAUP 97, the DAMA experiment at Gran Sasso, using a set of NaI scintillators reported an annual modulation effect interpreted (after a second run) as due to a WIMP of 60 GeV of mass and scalar cross-section on protons of $\sigma_p = 7 \times 10^{-6}$ picobarns.

The implementation of these strategies will be illustrated by a selection of the experiments presented at TAUP 99. The characteristic features and main results of these experiments are overviewed in the following paragraphs.

3. Germanium Experiments with conventional detectors

The high radiopurity and low background achieved in Germanium detectors, their fair low energy threshold, their reasonable Quenching Factor (25%) and other nuclear merits make Germanium a good option to search for WIMPs with detectors and techniques fully mastered. The first detectors applied to WIMP direct searches (as early as in 1987) were, in fact, Ge diodes, as by-products of $2\beta$-decay dedicated experiments. The exclusion plots $\sigma(m)$ obtained by former Ge experiments [PNNL/USC/Zaragoza (TWIN and COSME-1), UCSB, CALT/NEU/PSI, H/M] are still remarkable and have not been surpassed till recently.

There are three germanium experiments currently running for WIMP searches (COSME-2, IGEX and H/M).

COSME-2 (Zaragoza/PNNL/USC) is a small (240 g) natural abundance germanium detector of low energy threshold (1.8–2 keV) and energy resolution of 400 eV at 10 keV. It has been underground for more than ten years and so is rather clean of the cosmogenic induced activity in the 8–12 keV region. It is currently taking data in Canfranc (at 2450 m.w.e.) for WIMPs and solar axion searches (see I.G. Irastorza’s contribution to these Proceedings). The background is 0.6 (0.3) c/(keV kg day) averaged between the 2–15 keV (15–30 keV) energy region.

IGEX is a set of enriched Ge-76 detectors looking for $2\beta$ decay (see D. Gonzalez’s contribution to these Proceedings) which have been recently upgraded for WIMP searches with energy thresholds of $\leq 4$ keV, and energy resolution of 2 keV (at 10 keV). Data from one of these detectors (RG2, 2.1 kg $\times$ 30 d) show backgrounds of 0.1 c/(keV kg day) in the 10-20 keV region and 0.04 c/(keV kg day) between 20 and 40 keV. It is remarkable that below 10 keV, down to the threshold of 4 keV the background is $\sim 0.1$ c/(keV kg day) mainly from noise which is being removed. The spectrum is shown in Fig. 1. IGEX is also operating two other Ge detectors in Baksan [one natural—TWIN—and other enriched in Ge-76 (RV)] of about 1 kg each, and thresholds of 2 and 6 keV respectively. After a subtraction procedure a background of $\sim 0.1$ c/(keV kg day) between 10 and 30 keV was obtained.

The Heidelberg/Moscow Ge experiment on $2\beta$ decay in Gran Sasso is also using data of one of their enriched Ge-76 detectors (2.7 kg, and threshold of 9–10 keV) in a search for WIMPs. The background is similar to that of IGEX (0.16 c/(keV kg day) from 10-15 keV and 0.05 c/(keV day).
kg day) from 15-30 keV), although its threshold is more than a factor two higher. The low-energy spectrum is also shown comparatively to that of IGEX in Fig. 1.

The exclusion plots obtained from the spectra of Germanium detectors are shown in Fig. 2. The Ge-combined limit is the contour obtained from the envelope of all of them—including the last H/M data and is compared with that derived from the last COSME, IGEX and CDMS data presented at this Workshop. Also the most stringent NaI exclusion plot is shown together with the $(\sigma, m)$ region where a seasonal modulation effect in the recorded rate has been reported by the DAMA Collaboration and attributed to a WIMP signal. The exclusions depicted in this paper refer to spin-independent interactions. The sensitivity of the present detectors does not yet reach the rates needed to explore spin-dependent couplings. For comparison among different experiments, the coherent spin independent WIMP-nucleus cross-section is normalized to that of WIMP on nucleons. All the Ge and NaI exclusion plots shown have been recalculated from the original spectra by the author and his collaborators I.G. Irastorza and S. Scopel, with the same set of parameters. The values used for the halo model are $\rho = 0.3$ GeV cm$^{-3}$, $v_{\text{rms}} = 270$ Kms$^{-1}$ and $v_{\text{esc}} = 650$ Kms$^{-1}$.

There exist some projects with Ge detectors in different degree of development: HDMS (Heidelberg DM Search) is a small (200 g) Ge detector placed in a well-type large (2 kg) Ge crystal. The goal is to reach a background of $10^{-2}$ c/(keV kg day). GEDEON (Germanium Diodes in One Cryostat, Zaragoza / USC / PNNL) will use a single cryostat of IGEX technology hosting a set of natural Ge crystals of total mass of 28 kg. The threshold of each small detector is < 2 keV and the background goal—expected from the measured radioimpurities—is $10^{-2}-10^{-3}$ c/(keV kg day). A set of three cryostats (~ 80 kg of Germanium) is the planned final configuration which, embedded in Roman lead and graphite, will be installed in Canfranc. GENIUS (Germanium Detectors in Liquid Nitrogen in an Underground Setup) plans to operate 40 natural abundance, naked germanium crystals (of 2.5 kg each) submerged directly in a tank of liquid nitrogen.

4. Sodium Iodine experiments

The full isotopic content on A-odd isotopes (Na-23, I-127) makes sodium iodine detectors sensitive also to spin-dependent WIMP interactions. The main recent interest in scintillators is due to the fact that large masses of NaI crystals for exploring the annual modulation are affordable. There exist four NaI experiments running (UKDMC, DAMA, SACLAY and ELEGANTS V) and two in preparation (ANAIS and NAIAD).

The NaI experiments serve to illustrate one of the strategies for background discrimination mentioned above. The time shape differences between electron recoils and nuclear recoils pulses in NaI scintillators can be used to discriminate gamma background from WIMPs (and neutrons) because of the shorter time constants of nuclear versus electron recoils. Templates of reference pulses produced by neutron, gamma
(and X, β...) sources are compared with the data population pulses (in each energy band) by means of various parameters [time constants (UKDMC), momenta of the time distribution (DAMA, SACLAY), integrated time profile differences (SACLAY)]. From this comparison, the fraction of data which could be due to nuclear recoils turns out to be only a few percent, depending on energy, of the measured background [1 to 3 c/(keV kg day) in DAMA and UKDMC, and of 2 to 10 c/(keV kg day) in SACLAY], with different degree of success, depending of the experiment and (slightly) on the method used. Due to the drastic background reduction, the exclusion plots obtained from the stripped spectra have surpassed (DAMA, UKDMC) that derived from the (non-manipulated) spectra of the Ge detectors—whose radiopurity is much better than that of NaI. Let us briefly mention the main performances of these experiments.

The United Kingdom Dark Matter Collaboration (UKDMC) uses radiopure NaI crystals of various masses (2 to 10 kg) in various shielding conditions (water, lead, copper) in Boulby. Typical thresholds of 4 keV and background (before PSD) of 2–4 c/(keV kg day) (at about threshold) have been obtained. Recent results from NaI crystals of 5 and 2 kg show a small population of pulses (Fig. 3) of an average time constant shorter than that of gamma events and near to that corresponding to neutron-induced recoils, which is not due to instrumental artifact. (For recent results, see I. Liubarsky’s contribution to these Proceedings). Plans of the UKDMC include NAIAID (NaI Advanced Detector) consisting of 50–100 kg in a set of unencapsulated crystals to avoid surface problems and improve light collection.

The SACLAY group is carrying out a thorough program of investigation about the virtues and limitations of the pulse shape analysis as far as the statistical background discrimination is concerned. They use, at LSM Frejus, a radiopure 9.7 kg NaI crystal with an energy threshold of 2 keV and backgrounds of (before PSD) 8–10 c/(keV kg day) (at 2–3 keV) and of 2 c/(keV kg day) (and flat) above 5 keV. The high background at threshold, not well understood, has spoiled the exclusion plots of this experiment, compared with other NaI searches. On the other hand, their data—as it happened in that of UKDMC—cannot be sharply split into Compton plus nuclear recoils showing a spurious population (Fig. 4), a fact that limits the sensitivity of the PSA they could perform. Including this peculiar situation, as systematic effects, their PSA background reduction is only 65% to 85%.

The DAMA experiment uses also NaI crystals of 9.7 kg with energy threshold of ~ 2 keV. No spurious population is found in DAMA which could spoil the PSA separation background/nuclear recoils. In fact, their background reduction reaches levels of 85% (4–6 keV) and 97% (12–20 keV), providing exclusion plots which have surpassed that of germanium.

In conclusion, besides the significant reduction of background provided by this statistical method, a most intriguing result, as stated above, is that UKDMC and SACLAY, applying these PSD techniques to their data, have found that they are not compatible with a contribution of only Compton nor with nuclear recoil events, and suggest the existence of an unknown population or systematic effects. It is also an intriguing coincidence that the energy spectrum of that residual

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**Figure 3.** Pulse shapes for gammas, alphas, neutrons and the anomalous events from a 2-kg NaI crystal (UKDMC)
populations are very similar in both experiments (Fig. 5). (See G. Gerbier’s contribution to these Proceedings).

5. WIMPs Annual Modulation as a distinctive signature

The Earth rotation around the sun combined with the sun velocity through the halo makes the velocity of the detector with respect to the WIMPs halo a yearly periodic function peaked in June (maximum) and December (minimum). Such seasonal variation should provide an annual modulation in the WIMP interaction rates and in the deposited energy as a clear signature of the WIMP. However, the predicted modulation is only a few percent of the unmodulated, average signal. To reveal this rate modulation, large detector masses/exposures are needed.

Such type of seasonal modulation in the spectra has been reported in the DAMA experiment and attributed by the Collaboration to a WIMP signal (see P.L. Belli’s contribution to these Proceedings).

Preceding the DAMA experiment, there have been various attempts to search for annual modulation of WIMP signals, starting as early as in 1991. COSME-1 and NaI-32 (Canfranc) (with 2 years statistics), DAMA-Xe (Gran Sasso), ELEGANTS-V (Kamioka), and more recently DEMOS (Sierra Grande) (with 3 years of statistics), are examples of seasonal modulation searches with null results. However, these experiments produced results which improved the $\sigma(m)$ exclusion plots and settled the conditions and parameters for new, more sensitive searches.

The DAMA experiment uses a set of 9 radiopure NaI crystals of 9.7 kg each, viewed by two low-background PMT at each side through light guides (10 cm long), coupled to the crystal. Special care has been taken in controlling the stability of the main experimental parameters. A noise removal is done by using the timing behaviour of noise and true NaI pulses (with 40% efficiency at low energy). The background after noise removal is, averaging over the detectors: B (2–3 keV) $\sim$ 1–0.5 c/keV kg day and B (3–20 keV) $\sim$ 2 c/keV kg day. Notice the drop in the first two channels, precisely where the expected signal is more significant and, consequently, essential for deriving the reported modulation effect. (The Pulse Shape Analysis is not used in the annual modulation search). The multidetector energy spectrum of single hit events (each detector has twelve de-
tectors as active veto) has been reported to this Workshop (Fig. 3) (see P.L. Belli’s contribution to these Proceedings).

At the time of TAUP 99, DAMA had issued the results of two runnings. Run 1 reported at TAUP 97, extended over 1 month in winter and 2 weeks in summer, i.e. a total of 4549 kg day. Run 2, which used a slightly different setup, extended from November to July, (one detector for 90 days and eight detectors for 180 days) i.e. a total of 14962 kg day. Both DAMA 1 and 2 results are compatible and consistent with each other. A likelihood method applied to the total statistics of 19511 kg day provides a minimum for: \( m = (59^{+17}_{-14}) \) GeV, \( \sigma_p = (7.0^{+17}_{-14} \times 10^{-6} \) pb as the most likely values of the mass and interaction cross-section on proton of an “annual oscillating” WIMP (at 99.6% C.L.). Other statistical approaches essentially agree with the likelihood result. Fig. 7 shows the so-called DAMA region of the positive modulation effect and the scattered plot of the MSSM prediction of \( \sigma_p \) in function of \( m \). The time evolution of the DAMA signal has been recently issued by the collaboration indicating an oscillating trend in spite of the small exposure time and the discontinuity of the two runnings (Fig. 8). The DAMA results have aroused great interest but also critical comments related to various aspects of the experiment. One of the most frequently heard has to do with the drop of background in the first energy bins or to the peculiar look of the residual background after subtracting the likelihood-emerging signal. Obviously the delivery of new data is eagerly awaited.

Independently of other considerations and beyond any controversies whatsoever, it is imperative to confirm the DAMA results by other independent experiments with NaI (like ANAIS or ELEGANTS) and with other nuclear target. The ZARAGOZA group is preparing ANAIS (Annual Modulation with NaIs), consisting of 10 NaI scintillators of 10.7 kg each, stored for more than ten years in Canfranc, and recently upgraded for DM searches. It will be placed in Canfranc within a shielding of electroformed copper and a large box in Roman lead, plus a neutron screen and an active veto. The tests of a smaller set are underway. Expected performances are an energy threshold of 2 keV and a background at threshold of \( \sim 2-3 \) c/(keV kg day).
The OSAKA group is performing a search with the ELEGANTS V NaI detector in the new underground facility of Otho, with a huge mass of NaI scintillators (760 kg) upgraded from previous experiments. A search for annual modulation with null result has been presented to this Workshop (see S. Yoshida’s contribution to these Proceedings).

The DAMA $\sigma(m)$ region should also be explored by the standard method of comparing theory with the total time-integrated experimental spectrum (without enquiring about possible variations in time). In fact, various experiments are reaching the DAMA region (below $\sim \sigma^p \sim 10^{-5} - 10^{-6}$ pb for WIMPs of 40–80 GeV) which is itself half-excluded by a previous DAMA-0 running data using PSA discrimination. For instance, CDMS has reached the upper left corner and exclude it (see Fig. 2 and R. Gaitskell’s contribution to these Proceedings), whereas the IGEX and H/M germanium experiments are very close to it (with direct, non-stripped data).

Due to what is at stake, it is important to know what the prospects of WIMP detection are through the annual modulation signature for planning the right experiments. In fact, to find an unambiguous, reproducible and statistically significant modulation effect is, by now, the best identifying label of a WIMP. Sensitivity plots for modulation searches (presented to this Workshop) give the MT exposure needed to explore $\sigma_m$ regions using the annual modulation signature or, equivalently, needed to detect an effect (should it exist) at a given C.L., due to a WIMP with a mass $m$ and cross-section $\sigma^p$. Examples of sensitivity plots for Ge, NaI and TeO$_2$—and the ensuing capability to explore $\sigma^p$, $m$ regions, are given to illustrate the modulation research potential of some detectors (see S. Scopel’s contribution to these Proceedings) running or in preparation.

6. Cryogenic Particle Detectors

In the WIMP scattering on matter, only a small fraction of the energy delivered by the WIMP goes to ionization, the main part being released as heat. Consequently, thermal detectors should be suitable devices for dark matter searches with quenching factors of about unity and low effective energy threshold ($E_{\text{vis}} \sim T$) as WIMPs searches require. Moreover, bolometers which also collect charge (or light) can simultaneously measure the phonon and ionization (or scintillation) components of the energy deposition providing a unique tool of background subtraction and particle identification.

There exist five experiments searching for direct interactions of WIMPs with nuclei based on thermal detection currently running (MIBETA, CDMS, EDELWEISS, CRESST, and ROSE-BUD) another one, CUORICINO, being mounted and a big project, CUORE, in preparation.

The CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) (MPI Munich / TUM Garching / Oxford, Gran Sasso) detectors are four sapphire crystals (Al$_2$O$_3$) of 262 g each with a tungsten superconducting transition edge sensor. The energy resolution and threshold obtained with an x-ray fluorescence source are respectively 133 eV (at 1.5 keV) and 500 eV. The background obtained in the Gran Sasso running is of about 10–15 counts/(keV kg day) above 30 keV, going down to 1 c/(keV kg day) above 100 keV, whereas below 30 keV the spectrum is largely dominated by noise and other spurious sources preventing to derive exclusion plots.

Recently the collaboration has performed simultaneous measurements of scintillation and...
heat, with a 6 g CaWO$_4$ crystal as absorber. The preliminary results indicate a rejection of electron recoil events with an efficiency greater than 99.7% for nuclear recoil energies above 15 keV. Short term prospects for CRESST are the implementation of the scintillation-phonon discrimination of nuclear recoils in a CaWO$_4$ detector of 1 kg (see J. Jochum’s contribution to these Proceedings).

ROSEBUD (Rare Objects Search with Bolometers Underground) [University of Zaragoza and IAS (Orsay)] is another sapphire bolometer experiment to explore the low energy (300 eV–10 keV) nuclear recoils produced by low mass WIMPs. It is currently running in Canfranc (at 2450 m.w.e.). It consists of two 25g and one 50g selected sapphire bolometers (with NTD (Ge) thermistors) operating inside a small dilution refrigerator at 20 mK. One of the 25g sapphire crystals is part of a composite bolometer (2 g of LiF enriched at 96% in $^6$Li glued to it) to monitor the neutron background of the laboratory. The inner (cold) shielding and the external one are made of archaeological lead of very low contamination. The experimental setup is installed within a Faraday cage and an acoustic isolation cabin, supported by an antivibration platform. Power supply inside the cabin is provided by batteries and data transmission from the cabin through convenient filters is based on optical fibers. Infrared (IR) pulses are periodically sent to the bolometers through optical fibers in order to monitor the stability of the experiment. Pumps have vibration-decoupled connections.

The first tests in Canfranc have shown that microphonic and electronic noise level is quite good, about 2nV/Hz$^{1/2}$ below 50Hz. The bolometers were tested previously in Paris (IAS) showing a threshold of 300 eV and energy resolution of 120 (at 1.5 keV) are in the range of 0.3–1 $\mu$V/keV. Overall resolutions of 3.2 and 6.5 keV FWHM were typically obtained in Canfranc with the 50 g and 25 g bolometers, respectively, at 122 keV. Low energy background pulses corresponding to energies below 5 keV are seen. In the test runnings, the background obtained was as large as 120 counts/keV/kg/day around 40–80 keV. After various modifications in the cryostat components, the background level of the 50 g bolometer stands about 15 counts/keV/kg/day from 20 to 80 keV. This progressive reduction is illustrated in Fig. [Fig. 9]. Measurements of the radiopurity of individual components continue with an ultralow background Ge at Canfranc and their removal done when needed with the purpose of lowering the background one more order of magnitude. The next step of the ROSEBUD program will deal with bolometers of sapphire and germanium, operating together to investigate the target dependence of the WIMP rate (see P. de Marcillac’s contribution to these Proceedings).

![Figure 9. ROSEBUD background spectrum](image-url)

The Cryogenic Dark Matter Search Collaboration (CDMS) (CIPA / UC Berkeley / LLNL / UCSB / Stanford / LBNL / Baksan / Santa Clara / Case Western / Fermilab / San Francisco State) has developed bolometers which collect also electron-holes carriers for discriminating nuclear recoils from electron recoils. The electron-hole pairs are efficiently collected in the bulk of the detector, but the trapping sites near the detector surface produce a layer (10 – 20$\mu$m) of poor charge collection, where surface electrons from outside suffer ionization losses and fake nuclear recoils.

Two types of phonon readout have been developed. In the BLIP (Berkeley Large Ionization and Phonon) detector, a NTD Ge thermistor reads the thermal phonons in milliseconds. In the
FLIP (Fast Large Ionization and Phonon) detectors, non-equilibrium, athermal phonons are detected (microsecond time scale) with superconducting transition edge thermometers in tungsten. Current prototypes are BLIPs of 165 g Germanium and FLIPs of 100 g Silicon. The FWHM energy resolutions are 900 eV and 450 eV respectively in the phonon and charge channels in BLIP detectors and about 1 keV in the FLIPs. The electron nuclear recoil rejection in both detectors is larger than 99% above 20 keV recoil energy. Backgrounds below 0.1 c/(keV kg day) in the 10–20 keV energy region have been obtained in recent runs.

Following new developments achieved in the detectors, the surface events have been successfully discriminated using their phonon rise time: the low-charge collection events (surface electrons) have been proved to have faster phonon rise time than the bulk events. A rise time cut is applied to get rid of them. Results from a recent run are depicted in Fig. 10. In spite of the small masses and short time runs, CDMS exclusion plots are competitive with much larger exposures of other detectors. In fact, CDMS is now probing the DAMA region, as reported to this Workshop (see Fig. 2 and R. Gaitskell’s contribution to these Proceedings). Projects of the CDMS Collaboration include the transfer of the FLIP technology to germanium crystals of 250 g. Planned exposure at Stanford (only 17 m of overburden) is of 100 kg day, with a background goal of B = 0.01 c/keV kg day. The experiment will be moved to Soudan along the year 2000 with twenty FLIP detectors of Germanium (250 g each) and the background goal of B = few x 10^{-4} c/keV kg day.

EDELWEISS (Orsay/Lyon/Saclay/LSM/IAP) has operated two 70 g HP Ge bolometer in the Frejus tunnel with heat-ionization discrimination getting similar results to that of the BLIP detectors of CDMS and so they will not be repeated here. The background obtained is B = 0.6 c/keV kg day in the 12 – 70 keV region of the recoil energy spectrum. The rejection is 98% for surface events and > 99.7% for internal events. (For more details, see G. Chardin contribution to these Proceedings).

The collaboration is preparing a small tower of three Ge bolometers of 70 g each, to be enlarged to other three of 320 g each. The background goal is to get B = 10^{-2} c/keV kg day which seems to be at hand. A second phase of EDELWEISS (2000–2001) will use a reverse dilution refrigerator of 100 liters now under construction to host 50 – 100 detectors. Twenty Ge detectors of 300 g will be placed in the next two years, expecting to improve the rejection up to 99.99% and get a background of 10^{-4} c/(keV kg day).

CUORE (Cryogenic Underground Observatory for Rare Events) (Berkeley / Florence / LNGS / Leiden / Milan / Neuchatel/ South Carolina / Zaragoza) is a project to construct a large mass (775 kg) modular detector consisting of 1020 single bolometers of TeO2 of dimensions 5 × 5 ×5 cm³ and 760 g each, with glued NTD Ge thermistors, to be operated at 7 mK in the Gran Sasso Laboratory. A tower of 14 planes consisting of 56 of those crystals with a total mass of 42 kg, the so-called CUORICINO detector, will be a first step in the CUORE project.

Preliminary results of a 20 crystal array of telurite bolometers (340 g each) (MIBETA experi-
ment) optimized for $2\beta$ decay searches show energy thresholds ranging from 2 to 8 keV (depending on the detector) and background levels of a few counts per keV kg day in the 15–40 keV low energy region. CUORICINO is planned as an extension of the MIBETA setup featuring more and larger crystals. The sum of the 20 contemporary calibration spectra with a single $^{232}$Th source shows that the array is indeed acting as a single detector.

Four bolometers of the future CUORICINO array have been recently tested in Gran Sasso. The results on the energy resolution in the region of neutrinoless double beta decay of $^{130}$Te (2500 keV) are about 5–8 keV (see M. Pavan’s contribution to these Proceedings). Other values obtained are ~2 keV at 46 keV and 4.2 keV at 5400 keV. Energy resolutions of 1-2 keV and backgrounds of $10^{-2}$ c/(keV kg day) in the few keV region can be expected.

Fig. 11 shows the exclusion contour obtained from running experiments (Ge, NaI), and the projections for GEDEON, CUORICINO and CDMS assuming the parameter values expected in such experiments.

7. Where we stand and where we go

Unrevealing the nature of the dark matter is of uttermost importance in Cosmology, Astrophysics and Particle Physics. It has triggered a large experimental activity in searching for all its possible forms, either conventional or exotic. In particular, there exist various large microlensing surveys looking for dark baryons (EROS, MACHO, OGLE...) and a variety of observations searching for the baryonic component of dark matter. (See J. Usón’s contribution to these Proceedings).

As far as the exotic, non-baryonic objects are concerned, a few experiments are looking (or project to look) for axions (RBF/UF, LIVERMORE, KYOTO, CRYSTALS, CERN Solar Axion Telescope Antenna...), as reviewed in P. Sikivie’s contribution to these Proceedings.

In the WIMP sector (see L. Roszkowski’s contribution to these Proceedings) to which this experimental overview is dedicated, there are various large underground detector experiments (MACRO, BAKSAN, SOUDAN, SUPER-K...) and deep underwater (ice) neutrino telescopes (AMANDA, BAYKAL, ANTARES, NESTOR...) looking for (or planning to look for) neutrino signals originated by the annihilation of WIMPs, as well as some balloons and satellite experiments looking for antimatter of WIMP origin, most of them included in these Proceedings. About thirty experiments either running or being prepared are looking for WIMPs by the direct way (COSME, IGEX, HEIDELBERG/MOSCOW, ELEGANTS-V and VI, DAMA, SACLAYS, UKDMC, ANAIS, TWO-PHASE Xe, LqXe, CASPAR, SIMPLE, MICA, DRIFT, CRESST, ROSEBUD, MIBETA, CUORICINO, CDMS, EDELWEISS, ORPHEUS...), with conventional as well as with cryogenic techniques... and some large projects with 100 to 1000 detectors (CUORE, GEDEON, GENIUS...) are being initiated. Their current achievements and the projections of some of them have been shown in terms of exclusion plots $\sigma^p (m)$, which illustrate the poten-
tial to investigate the possible existence of WIMP dark matter in regions pretty close to where the supersymmetric candidates must appear.

After witnessing the large activity and progress reported to this Workshop, it is clear that the main strategies recommended to search for WIMPs have proved to be quite efficient to reduce the window of the possible particle dark matter and to approach the zone of the more appealing candidates and couplings. Examples of the achievements in radiopurity, background identification or rejection, in low (effective) threshold energy and efficiency, as well as in investigating the genuine signatures of WIMPs, like modulation and directionality, have been largely reported to TAUP 99 and reviewed selectively in this paper. The conclusion is that these strategies are well focused and should be further pursued. Finally, an annual modulation effect—supposedly produced by a WIMP—is there, alive since the last TAUP 97, waiting to be confirmed by independent experiments.

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