The CRESST Dark Matter Search

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Abstract

We discuss the short and long term perspectives of the CRESST (Cryogenic Rare Event Search using Superconducting Thermometers) project and present the current status of the experiment and new results concerning detector development. In the search for elementary particle dark matter, CRESST is presently the most advanced deep underground, low background, cryogenic facility. The basic technique involved is to search for WIMPS (Weakly Interacting Massive Particles) by the measurement of non-thermal phonons, as created by WIMP-induced nuclear recoils. Combined with our newly developed method for the simultaneous measurement of scintillation light, strong background discrimination is possible, resulting in a substantial increase in WIMP detection sensitivity. This will allow a test of the reported positive evidence for a WIMP signal by the DAMA collaboration in the near future. In the long term, the present CRESST set-up permits the installation of a detector mass up to 100 kg.

In contrast to other projects, CRESST technology allows the employment of a large variety of detection materials. This offers a powerful tool in establishing a WIMP signal and in investigating WIMP properties in the event of a positive signal.

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1 CRESST and the Dark Matter Problem

After a long period of development, cryogenic detectors are now coming on line and in the next years will deliver significant results in particle-astrophysics and weak interactions. The stable operation of a kilogram of detecting material in the millikelvin range over long time periods by CRESST, as well as similar work by other collaborations, has confirmed the hopes that large mass cryogenic detectors are feasible. CRESST is presently the most advanced deep underground, low background, cryogenic facility. Other major projects are the CDMS project in Stanford, the EDELWEISS project at Frejus, the Milano $\beta\beta$ project in Gran Sasso, the ROSEBUD experiment at Canfranc, the Tokyo Cryogenic Dark Matter Search and the ORPHEUS project at Bern [1].

The goal of the CRESST project is the direct detection of elementary particle dark matter and the elucidation of its nature. The search for Dark Matter and the understanding of its nature remains one of the central and most fascinating problems of our time in physics, astronomy and cosmology. There is strong evidence for it on all scales, ranging from dwarf galaxies, through spiral galaxies like our own, to large scale structures. The history of the universe is difficult to reconstruct without it, be it big bang nucleosynthesis [2] or the formation of structure [3].

The importance of the search for dark matter in the form of elementary particles, created in the early stages of the universe, is underlined by the recent weakening of the case for other forms such as MACHOS, faint stars and black holes [4]. Particle physics provides a well motivated candidate through the assumption that the lightest supersymmetric (SUSY) particle, the ‘neutralino, is some combination of neutral particles arising in the theory and it is possible to find many candidates obeying cosmological and particle physics constraints. Indeed, SUSY models contain many parameters and many assumptions, and by relaxing various simplifying assumptions one can find candidates in a wide mass range [5]. Generically, such particles are called WIMPS (Weakly Interacting Massive Particles), and are to be distinguished from proposals involving very light quanta such as axions. WIMPS are expected to interact with ordinary matter by elastic scattering on nuclei and all direct detection schemes have focused on this possibility.

Conventional methods for direct detection rely on the ionisation or scintillation caused by the recoiling nucleus. This leads to certain limitations connected with the relatively high energy involved in producing electron-ion or electron-hole pairs and with the sharply decreasing efficiency of ionisation by slow nuclei. Cryogenic detectors use the much lower energy excitations, such as phonons, and while conventional methods are probably close to their limits, cryogenic technology can still make great improvements. Since the principal physical effect of a WIMP nuclear recoil is the generation of phonons, cryogenic calorimeters are well suited for WIMP detection and, indeed, the first proposals to search for dark matter particles were inspired by early work on cryogenic detectors [6]. Further, as we shall discuss below, when this technology is combined with charge or light detection the resulting background suppression leads to a powerful technique to search for the rare nuclear recoils due to WIMP scatterings.

The detectors developed by the CRESST collaboration consist of a dielectric crystal (target or absorber) with a small superconducting film (thermometer) evaporated onto the surface. When this film is held at a temperature in the middle of its superconducting to normal conducting phase transition, it functions as a highly sensitive thermometer. The detectors presently employed in Gran Sasso use tungsten (W) films and sapphire (Al_2O_3) absorbers, running near 15 mK. It is important for the following, however, to realise that the technique can also be applied to a variety of other materials. The small change in temperature of the superconducting film resulting from an energy deposit in the absorber leads to a relatively large change in the film's resistance. This change in resistance is measured with a SQUID. To a good approximation, the high frequency phonons created by an event do not thermalise in the crystal before being directly absorbed in the superconducting film [7]. Thus the energy resolution is only moderately dependent on the size of the crystal, and scaling up to large detectors of some hundred gramms or even kilogramms is feasible. The high sensitivity of this system also allows us to use a small separate detector of the same type to see the light emitted when the absorber is a scintillating crystal.

2 Present Status of CRESST

The task set for the first stage of CRESST was to show the operation of 1 kg of sapphire in the millikelvin range, with a threshold of 500 eV under low background conditions [8]. Meeting this goal involved two major tasks:

- The setting up of a low background, large volume, cryogenic installation and
- the development of massive, low background detectors with low energy thresholds.

2.1 CRESST Installation in the Gran Sasso Laboratory (LNGS)

The central part of the CRESST low background facility at the LNGS is the cryostat. The design of this cryostat had to combine the requirements of low temperatures with those of a low background. The first generation cryostats in this field were conventional dilution refrigerators where some of the materials were screened for radioactivity. However, due to cryogenic requirements some non-radiopure materials, for example stainless steel, cannot be completely avoided. Thus for a second generation low background cryostat, a design was chosen in which a well separated ‘cold box houses the experimental volume at some distance from the cryostat. The cold box is constructed entirely of low background materials, without any compromise. It is surrounded by shielding consisting of 20 cm of lead and 14 cm of copper. The cooling power of the dilution refrigerator is transferred to the cold box by a 1.5 meter long cold finger protected by thermal radiation shields, all of low background copper. The experimental volume can house up to 100 kg of target mass. The cold box and shielding are installed in a clean room area with a measured clean room class of 100. For servicing, the top of the cryostat can be accessed from the first floor outside the clean room. This situation of a second generation cryostat in a high quality clean room, deep underground in the LNGS, presently makes this instrument unique in the world.

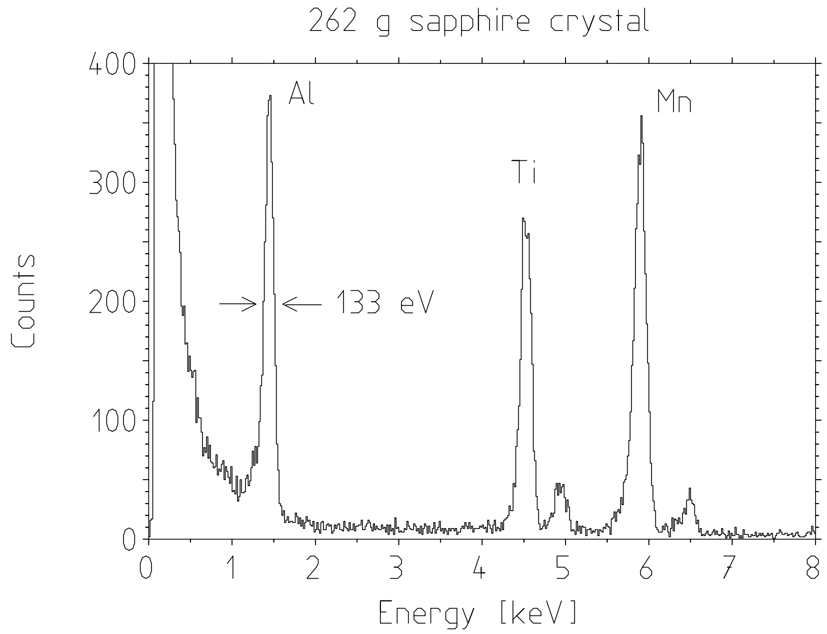

Figure 1: Pulse height spectrum of a 262 g detector operated with thermal feedback and an X-ray fluorescence source [9] installed inside the cryostat to provide the X-ray lines of Al, Ti, and Mn. The large background towards lower energies, which was not present in our earlier spectra [10], is attributed to damage later noticed to the thin Al sheet meant to absorb Auger electrons from the source.

The installation is now complete and entering into full operation. The system demonstrated its high reliability by running for more than a year with a prototype cold box made of normal copper. Runs with a new low background cold box in the fall of 1998 showed stable operation for a period of months. At present four 262 g detectors are in the experimental volume, performing first measurements under low background conditions. First results of this run have shown that at energies above 30 keV, the counting rate is on the order of a few counts/ (kg keV day) and above 100 keV below 1 count/(kg keV day) There are strong indications that the low energy part of the spectrum was dominated by external disturbances such as mechanical vibrations or electromagnetic interference. We are working to correct this in future runs.

2.2 Detector Development

The CRESST collaboration is among the pioneers of cryogenic detector development. Present CRESST detectors have by far the highest sensitivity per unit mass of any cryogenic device now in use. Figure 1 shows the spectrum of an X-ray fluorescence source measured with a 262 g CRESST sapphire detector, as presently being used, showing an energy resolution of 133 eV at 1.5 keV.

These 262 g detectors were developed by scaling up a 32 g sapphire detector [9]. Due to optimised design, and because of the non-thermalization of the phonons as explained in the introduction, this scaling-up could be achieved without loss in sensitivity. Further developments for the next detector generation are in progress.

- In order to improve linearity, dynamic range and time response, a mode of operation with thermal feedback was developed and successfully operated with the present CRESST detectors.

- For another thermometer type, the iridium-gold proximity sandwich, fabrication improvements now allow the application of these thermometers with a wide choice of absorber materials, even for low melting point materials such as germanium. A germanium detector with a mass of 342 g is in preparation.

- To further increase the energy sensitivity of the detectors we have also developed phonon collectors. The collectors provide a large collection area for phonons while retaining a small thermometer. This allows a more rapid collection of the phonons and so an increase in sensitivity. This concept can be applied to all detector types and is especially of interest with regard to scaling up the size of the detectors.

- Passive techniques of background reduction – radiopure materials and a low background environment – are of course imperative in work of this type. However, there is a remaining background dominated by β and γ emissions from nearby radioactive contaminants. These produce exclusively electron recoils in the detector. In contrast WIMPs, and of course also neutrons, lead to nuclear recoils. Therefore, dramatic improvements in sensitivity are to be expected if, in addition to the usual passive shielding, the detector itself is capable of distinguishing electrons from nuclear recoils and rejecting them.

2.3 Simultaneous Phonon and Light Measurement

We have recently developed a system, presently using $CaWO_4$ crystals as the absorber, where a measurement of scintillation light is carried out in parallel to the phonon detection. We find that these devices clearly discriminate nuclear recoils from electron recoils.

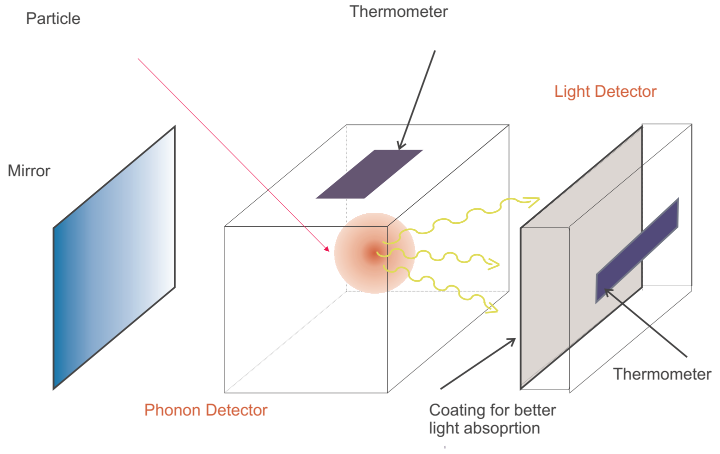

Figure 2: Schematic view of the arrangement used for the simultaneous light and phonon detection

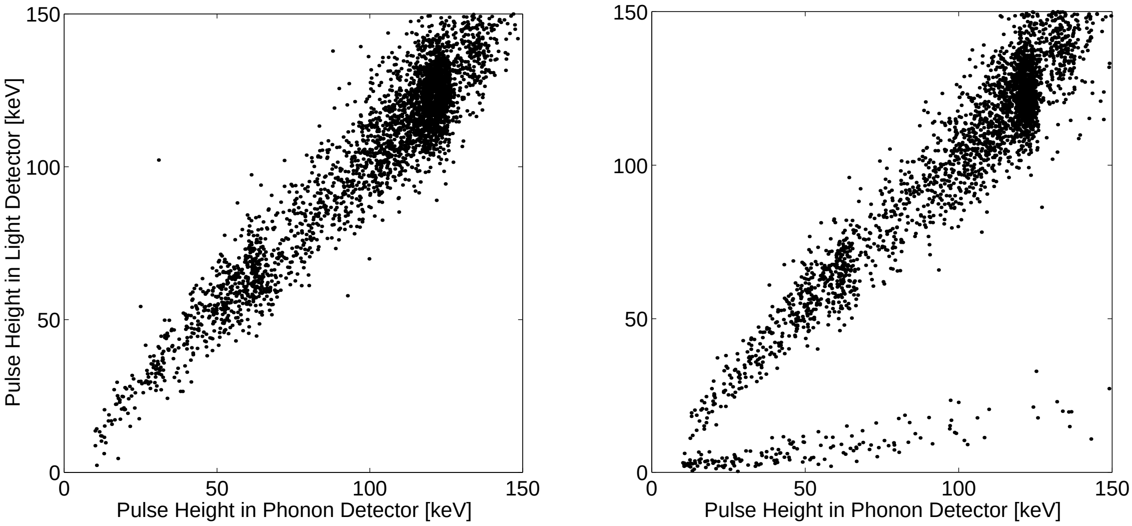

Figure 3: Pulse height in the light detector versus pulse height in the phonon detector. The scatter plot on the left side has been measured with an electron- and a photon source, while a neutron source was added on the right.

The system is shown schematically in fig. 2 . It consists of two independent detectors, each of the CRESST type: A scintillating absorber with a tungsten superconducting phase transition thermometer on it, and a similar but smaller detector placed next to it to detect the scintillation light from the first detector. A detailed description is given in [11]. Both detectors detectors were made by standard CRESST techniques and were operated at about 12mK. The $CaWO_4$ crystal was irradiated with photons and simultaneously with electrons.

The left plot in fig. 3 shows a scatter plot of the pulse heights observed in the light detector versus the pulse height observed in the phonon detector. A clear correlation between the light and phonon signals is observed. The right hand plot shows the result of an additional irradiation with neutrons from an Americium-Beryllium source. A second line can be seen due to neutron-induced nuclear recoils. It is to be observed that electron and nuclear recoils can be clearly distinguished down to a threshold of 10keV.

The leakage of some electron recoils into the nuclear recoil line gives the electron recoil rejection according to the quality factor of ref. [12]. A detailed evaluation yields a rejection factor of 98% in the energy range between 10 keV and 20 keV, 99.7% in the range between 15 keV and 25 keV and better than 99.9% above 20 keV.

The intrinsic background in our $CaWO_4$ crystals is now being measured in the new Munich low background laboratory. No contamination was found as of this writing. The present limits are 45 counts/(kg keV day) for the thorium chain and 6 counts/(kg keV day) for the uranium chain in the energy region relevant for the WIMP dark matter search.

3 Next Steps for CRESST

All our detectors, including those measuring scintillation light, use superconducting phase transition thermometers with SQUID readout and can be run in the present set-up. The CRESST cold box is designed to house detectors of various types, up to a total mass of about 100 kg.

Due to the complementary detector concepts of low threshold calorimeters on the one hand and detectors with the simultaneous measurement of light and phonons on the other, CRESST can cover a very wide range of WIMP masses.

3.1 Low Mass WIMPs

The present sapphire detectors, with their extremely low energy thresholds and a low mass target nucleus with high spin (Al), cover the low WIMP mass range from 1 GeV to 10 GeV in the sense that they are presently the only detectors able to explore this mass range effectively for non-coherent interactions. The sensitivity for WIMPS with spin-dependent interactions, an expected threshold of 0.5 keV, a background of 1 count/(kg keV day) and an exposure of 0.1 and 1 kg year is shown in fig. 4. For comparison the present limits from the DAMA [14] and UKDMC [15] NaI experiments are also shown.

Data-taking with the present sapphire (Al_2O_3) detectors (262 g each) will continue during 1999. The goals for this period include the identification and removal of noise sources and radioactive contaminants as well as the presentation of first results. In parallel, a run with a Ge detector is also planned. Running two target materials in parallel is expected to help substantially in understanding backgrounds and the systematics, as well as preparing the way for the study of a possible positive signal (see below).

3.2 Medium and High Mass WIMPs

In the second half of 1999 we intend to start the installation of the next detector generation with background suppression using the simultaneous measurement of scintillation light and phonons. These detectors will have target nuclei of large atomic number, such as tungsten, making them particularly sensitive to WIMPs with coherent interactions. Here the WIMP cross section profits from a large coherence factor of the order A^2, (A = number of nucleons). Combined with the strong background rejection, this means these detectors can be sensitive to low WIMP cross sections. Figure 5 shows the anticipated sensitivity obtained with a $CaWO_4$ detector in the present CRESST set-up in Gran Sasso. The CRESST $CaWO_4$ curve is based on a background rate of 1 count/(kg keV day), an intrinsic background rejection of 99.7 % above a recoil threshold of 15 keV and an exposure of 1 kg year.

For comparison the recently updated limits of the Heidelberg-Moscow ^{76}Ge-diode experiment [16], and the DAMA NaI experiment [14] are also shown. A 60 GeV WIMP with the cross section claimed in [17] would give about 55 counts between 15 and 25 keV in 1 kg $CaWO_4$

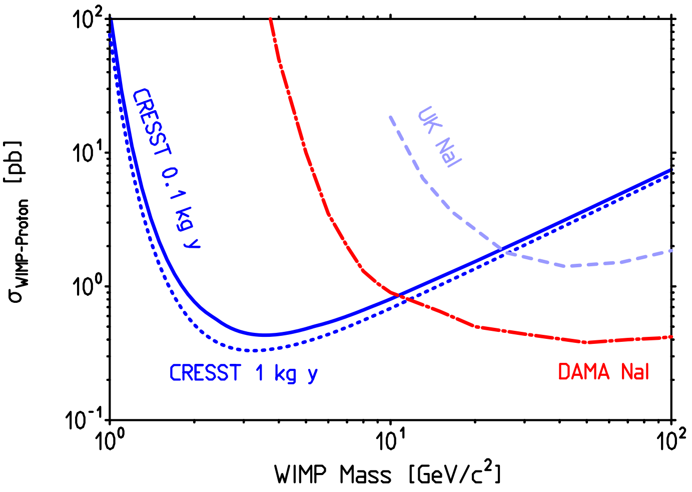

Figure 4: Equivalent WIMP-proton cross section limits (90% CL) for spin dependent interactions as a function of the WIMP-mass, as expected for the present CRESST sapphire detectors with a total mass of 1 kg. The expectation is based on a threshold of 0.5 keV, a background of 1 count/(kg keV day) and an exposure of 0.1 and 1 kg year. For comparison the present limits from the DAMA [14] and UKDMC [15] NaI experiments are also shown.

within one year. A background of 1 count/(kg keV day) suppressed with 99.7% would leave 11 background counts in the same energy range. A 1 kg $CaWO_4$ detector with 1 year of measuring time in the present set-up of CRESST should allow a comfortable test of the recently reported positive signal.

3.3 CRESST in the case of a positive signal

In addition to improving limits on dark matter, it is important to have means for the positive verification of a dark matter signal as well as for the elucidation of its nature. Once a dark matter signal is suspected, it can be verified by CRESST through the following effects.

- Varying the mass of the target nucleus leads to a definite shift in the recoil energy spectrum. For example, in the case where the WIMP is substantially lighter than the target nucleus, the recoil *momentum* spectrum has an unchanged shape from nucleus to nucleus. Hence there is a simple rescaling of the recoil energy spectrum. The observation of the correct behaviour will greatly increase our confidence in a positive signal. Here the significant advantage of the CRESST technology, that it can be applied to different target materials, comes into play. In this context, the wide variety of materials that may be used for simultaneous light and phonon measurement is extremely important. We have already measured the relative scintillation efficiencies of $CaWO_4$, $PbWO_4$, BaF and BGO crystals at low temperatures and found similarly encouraging results for all materials.
- Another verification of a dark matter signal is to be expected through an annual modulation of spectral shape and rate, which results from the motion of the earth around

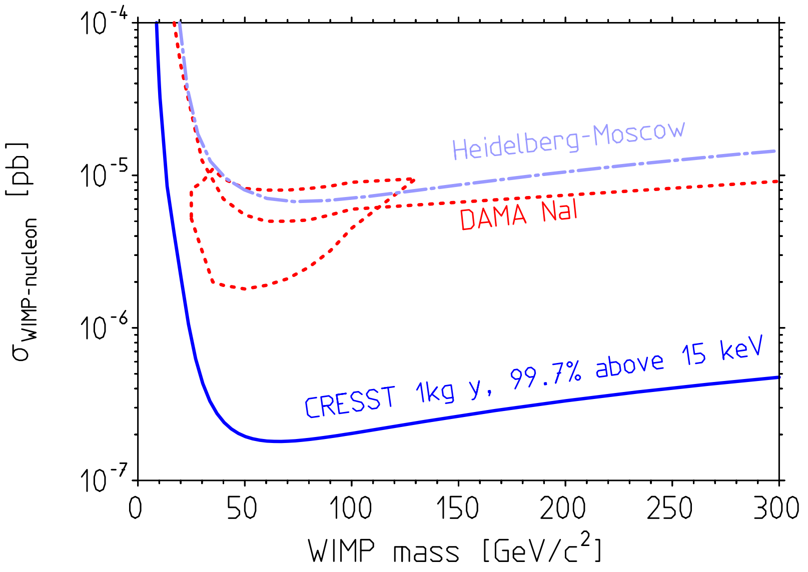

Figure 5: WIMP-nucleon cross section limits (90% CL) for scalar (coherent) interactions as a function of the WIMP mass, expected for a 1 kg $CaWO_4$ detector with a background rejection of 99.7% above a threshold of 15 keV detector and 1 year of measurement time in the CRESST set-up in Gran Sasso. For comparison the recently updated limit from the Heidelberg-Moscow ^{76}Ge experiment [16] and the DAMA NaI limits [14] (with the contour for positive evidence [17]) is also shown.

the sun. However, a 1 kg $CaWO_4$ detector is too small to reach a really significant statistical accuracy within one year of measurement. Here the large mass potential of the present CRESST installation, about 100 kg, will play an important role for establishing such an effect in the future.

- Given the detection of a dark matter particle, an important task will be to determine its nature, e. g. for SUSY the gaugino and higgsino content, which gives rise to different strengths of the spin-dependent interaction. Significant steps in this direction can be taken by using different target materials (see e.g. fig. 24 in ref. [5]).
- Finally we note calculations [18] concerning the possible existence of a WIMP population orbiting in the solar system rather than in the galaxy. These would have a much lower velocity (about 30 km/sec) as compared to galactic WIMPs (270 km/sec), so that even heavy WIMPs have low momenta. This underlines the need for low threshold recoil detection and CRESST is well suited for such an investigation.

4 Long Term Perspectives

The sensitivity reached by a system that simply relies passively on radiopure materials, but lacks active intrinsic background suppression, saturates at some point and cannot be improved with more mass (M) and measuring time (t). On the other hand, in a system with

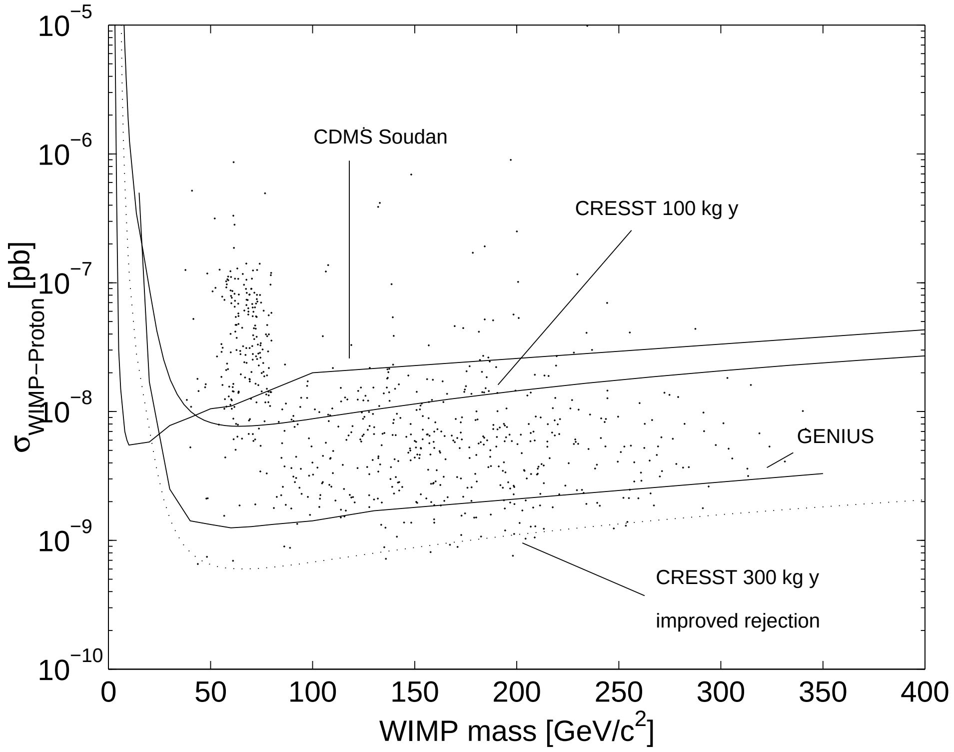

Figure 6: WIMP-nucleon cross section limits (90% CL) for scalar (coherent) interactions, as a function of the WIMP mass, expected for a $CaWO_4$ detector with a background of 1 count/(keV kg day) , a background suppression of 99.9% above a threshold of 15 keV, and an exposure of 100 kg-years in the CRESST set-up. With a suppression of 99.99% above 15 keV, a reduced background of 0.1 counts/(kg keV day), and an increased exposure of 300 kg years most of the MSSM parameter space would be covered. For comparison, the projected sensitivity of CDMS at Soudan [19], and the limits of the proposed GENIUS experiment [20] are also shown. For comparison, all sensitivities are scaled to a galactic WIMP density of 0.3 GeV/cm^3. The dots (scatter plot) represent expectations for WIMP-neutralinos calculated in the MSSM framework with non-universal scalar mass unification [21].

a precisely determined background suppression factor, the sensitivity continues to improve as $\sigma \propto 1/\sqrt{Mt}$ [12], as is possible with the CRESST scintillation light method.

Beginning in the year 2000 we intend to upgrade the multi-channel SQUID read out and systematically increase the detector mass, which can go up to about 100 kg before reaching the full capacity of the present installation.

With a 100 kg $CaW0_4$ detector, the sensitivity shown in fig. 6 can be reached in one year of measuring time. If we wish to cover most of the MSSM parameter space of SUSY with neutralino dark matter, the exposure would have to be increased to about 300 kg years, the background suppression improved to about 99.99 % above 15 keV, and the background lowered to 0.1 count/(kg keV day). The recent tests in Munich with $CaWO_4$, which were limited by ambient neutrons, suggest that a suppression factor of this order should be within reach underground, with the neutrons well shielded and employing a muon veto.

The excellent background suppression of cryodetectors with active background rejection makes them much less susceptible to systematic uncertainties than conventional detectors, which must rely heavily on a subtraction of radioactive backgrounds. Since this kind of systematic uncertainty cannot be compensated by an increase of detector mass, even moderate sized cryogenic detectors can achieve much better sensitivity than large mass conventional detectors. Note that the excellent levels shown in fig. 6 can be achieved with the rather moderate assumptions of background at 1 count/(kg keV day) and 0.1 count/(kg keV day). To a large extent, even higher background levels can be compensated with increased exposure. On the other hand, dark matter searches with conventional detectors, require a scaling of the presently reached best background levels of 0.057 counts/(kg keV day) [22] by a factor of 2000 to reach the same sensitivity level.

If WIMPs are not found, at some point the neutron flux, which also gives nuclear recoils, will begin to limit further improvement. With careful shielding the neutron flux in Gran Sasso should not limit the sensitivity within the exposures assumed for the upper CRESST curve in fig. 6. With still larger exposures, the neutron background may still be discriminated against large mass WIMPS. This can be done by comparing different target materials, which is possible with the CRESST technology, since different variations with nuclear number for the recoil spectra are to be expected with different mass projectiles.

The phase of the project with large increased total detector mass will necessitate certain improvements and innovations in the technology, particularly involving background rejection, optimisation of the neutron shielding, and muon vetoing. As described above, if a positive dark matter signal exists, increased mass and improved background rejection will be important in verifying and elucidating the effect. A large target mass, such as 100 kg, is of importance to reach the high statistics needed to study the annual modulation effect.

5 Conclusions

The installation of the large volume, low background, cryogenic facility of CRESST at the Gran Sasso Laboratory is completed. The highly sensitive CRESST sapphire detectors are up to now the only technology available to reasonably explore the low mass WIMP range.

The new detectors with the simultaneous measurement of phonons and scintillation light allow to distinguish the nuclear recoils very effectively from the electron recoils caused by background radioactivity. For medium and high mass WIMPs this results in one of the highest sensitivities possible with today's technology.

This will allow a test of the reported positive evidence for a WIMP signal by the DAMA collaboration in the near future. In the long term, the present CRESST set-up permits the installation of a detector mass up to 100 kg. In contrast to other projects, CRESST detectors allow the employment of a large variety of target materials. This offers a powerful tool in establishing a WIMP signal and in investigating WIMP properties in the event of a positive signal.

By its combination of detection technologies CRESST is over the whole WIMP mass range one of the best options for direct particle Dark Matter detection.

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