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Munich Cryogenic Detector Development 1995

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At the Technical University of Munich and the Max Planck Institute of Physics we are developing cryogenic detectors for the detection of small deposited energies, for example from the elastic scattering of WIMP dark matter particles, or the absorption of X-rays. Together with the University of Oxford and the Laboratori Nazionali del Gran Sasso we are preparing the CRESST experiment which uses our detectors to search for WIMP dark matter. This preprint contains reports of our work which we have presented at the Sixth International Workshop on Low Temperature Detectors (LTD-6) in Beatenburg/Interlaken, Switzerland, 28 Aug. - 1 Sept. 1995. This work has been supported in part by the "Sonderforschungsbereich 375 für Astroteilchenphysik" and the EU ERBCHRXCT930341 Network on Cryogenic Detectors.

Contents:

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Status and Low Background Considerations for the CRESST Dark Matter Search

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Abstract

We are preparing the CRESST experiment to search for dark matter WIMPs using cryogenic detectors with superconducting phase transition thermometers. In the first stage we plan to use four 250 g sapphire detectors with thresholds of 0.5 keV and resolutions of 0.2 keV at 1 keV. This will provide sensitivity to WIMP masses below 10 GeV, and is thus complementary to other dark matter searches.

1 Introduction

The lower range of WIMP masses an experiment can cover is mainly determined by the energy threshold of the detector. Our development [1] of cryogenic detectors with superconducting phase transition thermometers has progressed so that we expect to be able to make a detector of 1 kg of sapphire in 4 pieces with a threshold of 0.5 keV and a resolution of 0.2 keV at 1 keV. We are preparing the CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiment to run such a detector in a low-background environment in the Gran Sasso Underground Laboratory.

In a previous paper [2] we have presented a rough estimate of the expected sensitivity of this experiment. In this paper we briefly discuss the design and status of the experimental apparatus for the experiment. More detail is given on the steps we are taking to achieve a low background in our apparatus, on measured upper limits on contaminants, and on preliminary calculations of possible backgrounds.

2 Experimental Apparatus

For a Dark Matter experiment it is of extreme importance to achieve the lowest possible radioactive background levels. To avoid background events induced by cosmic rays the experiment will be located in the Gran Sasso Underground Laboratory. In addition it will be carefully shielded against the natural radioactivity of the surrounding rocks. All materials in the shielding and the vicinity of the detector have been specially selected for their radiopurity.

Fig. 1 shows our experimental setup. Because not all materials necessary for building a dilution refrigerator are radiopure, we divided the experimental setup into two parts: one containing the dilution refrigerator and the other one containing the detector surrounded by very low background materials and shielding. The cooling power of the refrigerator is transferred into this cold box by a cold finger protected by thermal radiation shields. The space for experiments in the cold box is about 30 liters. The line of sight into the cold box is blocked by a careful arrangement of the shielding materials, including two cold inner Pb shields. The materials of the cold box are the most critical. For first cryostat and detector tests we have made a prototype cold box, which will be replaced in 1996 by a new one made of radiopure copper. We have developed radiopure Pb seals for the cold box to replace the usual indium seals. In the vicinity of the detector there will be only radiopure copper (no cryogenic liquids, no stainless steel, etc.).

The experiment will be protected from electromagnetic interference by a Faraday cage, which has two levels. The lower level contains the cold box and its shielding, as well as most of the dilution refrigerator. This lower level will be kept dust-free and has sufficient space to assemble the cold box in clean conditions. The top of the dilution refrigerator extends into the second level of the Faraday cage, so that the cryostat can be serviced without entering the lower

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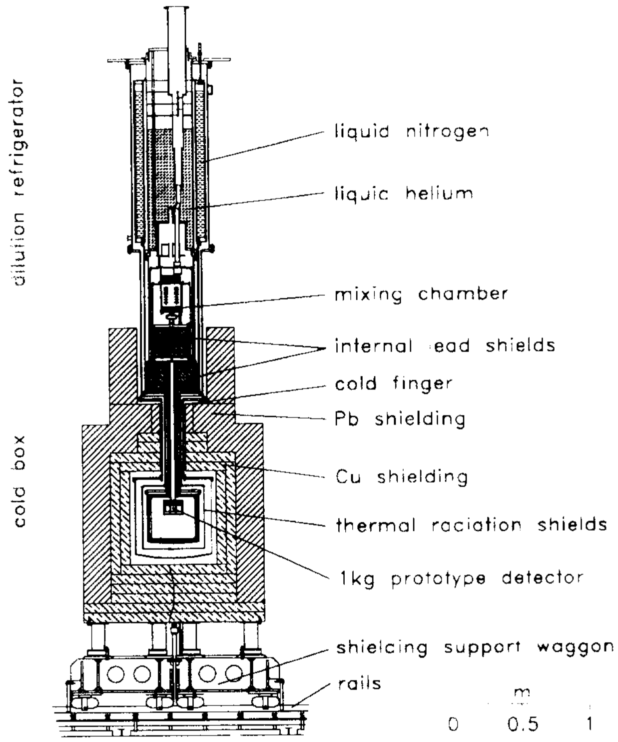

Figure 1: Layout of dilution refrigerator and cold box

level. This second level provides space for the helium dewars needed to re-fill the cryostat and for the sensitive electronics. The gas-handling and pumping systems are placed next to the Faraday cage. On the top floor, above the Faraday cage, there is a room containing working space and the data-acquisition electronics.

The dilution refrigerator and gas handling system have been assembled and successfully tested in Munich. The cold box is now being attached. After it has been successfully cooled down, the apparatus will be disassembled and moved to Gran Sasso.

3 Radiopurity of Shielding Materials

The cold box will be shielded with 14 cm of radiopure copper and with 20 cm Pb, as shown in Fig. 1. In this section we discuss the radiopurity of these materials.

The radioimpurity with the highest abundance in lead is ^{210}Pb. Most of the outer lead shielding is made of Boliden lead with a ^{210}Pb content of 35 Bq/kg. Some of inner parts of the lead shields, where the inner 14 cm of copper is lacking for geometrical reasons, are made of Plombum lead with a ^{210}Pb content of 3.6 Bq/kg. Since the distance of these parts to the detectors is at least 0.5 m, with at least 4 cm of copper of the cold box in between, the ^{210}Pb should not be a serious source of background in the first stage of the experiment. Should it be a problem in later stages, we could replace it by lead with lower ^{210}Pb content, which is available at a much higher price.

For the shielding and for the cold box we use OFHC (Oxygen Free High Conductivity) copper freshly made by electrolysis and cast by Norddeutsche Affinerie. Copper of this type was measured by G. Heusser (Max-Planck-Institute for Nuclear Physics, Heidelberg) in order to determine its radioimpurities. The measured upper limits (90% CL) in mBq/kg were 0.4 for ^{226}Ra, 0.6 for ^{228}Th, 1.8 for ^{40}K, 0.2 for ^{137}Cs, and 0.1 for ^{60}Co. Within the detection limits this type of copper was as good as the usual low-level copper, and it is better for cryogenic purposes.

If the copper is not activated by cosmic rays for extended periods, it is certainly one of the best shielding materials. To minimize the cosmic ray exposure we arranged that the freshly electrolyzed copper was cast and rolled within 1 month, and then moved into underground storage in an old brewery cellar with a shielding of about 10 meters of water equivalent. This shielding reduces the nucleonic component of cosmic radiation by a factor of about 500 [3]. Including the time required for machining, the total cosmic exposure of the copper will be kept below 8 weeks.

An estimation of the cosmogenic activation is difficult because the production rate of radioisotopes depends on the size of the copper pieces (development of a meson-nucleon cascade). We based our calculation on the production rates measured by G. Heusser [4]. With an above-ground exposure time of less than 8 weeks before being put in the Gran Sasso tunnel and allowing for decays, by the end of 1996 the cosmogenic activity of the copper should be less than the following values in μBq/kg: 7 for ^{54}Mn, 1 for ^{56}Co, 20 for ^{57}Co, 1 for ^{58}Co, and 12 for ^{60}Co. This gives a total of less than 40 μBq/kg, a value which is comparable to the inner copper components of the Heidelberg-Moscow $\beta\beta$ experiment [4].

Beside minimizing the exposure time to cosmic rays, we need to ensure that the surfaces are kept clean. During the rolling of the cast material, surface impurities might be rolled into the bulk material. Together with the technical manager of Carl Schreiber GmbH, Neunkirchen we optimized the rolling procedure to minimize the risk of contaminations (choice of heating oven, etching and cleaning procedures, etc.). During the further machining there is also a considerable risk to contaminate the surfaces. Contact with bare hands involves the risk of a contamination with ^{40}K, the smoke of cigarettes contains a lot of ^{210}Po, abrasion of tools contains ^{60}Co, etc. Therefore we left an allowance of a few mm for each dimension on the copper parts for the shielding. This allowance is being milled under clean conditions (no lubricants, contact only with cleaned copper surfaces and never with hands) at the J. Behr company in Munich. The final milling is done with a diamond cutter. According to an experience from fusion technology (Max-Planck-Institut für Plasmaphysik) this avoids a smearing of surface contaminations into sub-surface regions. Thin copper parts like sheets, which cannot be milled, will be etched using very pure chemicals.

Radon is a severe problem in all low level experiments, because it easily penetrates inside the shielding. We will enclose the entire shielding in a gas-tight box that will be flushed with N_2 and maintained at a small overpressure.

Even in an underground Laboratory there are neutrons

Table 1: Upper limits of the uranium, thorium and potassium (detection limits of the neutron activation analysis) and ^{26}Al content (accelerator mass spectroscopy limit) of sapphire crystals from Single Crystal Technology (SCT) and Crystal Systems (CS), and resulting expected continuum count rates in the range 0–25 keV (excluding the X-ray lines).

Upper limits on impurities in sapphire				
element	limit [ppb]		counts/(keV kg day)	
	SCT	CS	SCT	CS
U	0.04	0.02	< 0.8	< 0.4
Th	0.033	0.0023	< 2.9	< 0.2
K	900	1800	< 1.7	< 3.4
^{26}Al	10^{-6}	-	< 0.006	-

from α,n reactions and fission. Therefore a neutron shielding outside the lead shielding could be useful and could consist of about 10 cm of borated polyethylene. Since the flux of thermal, epithermal and fast neutrons in the Gran Sasso Laboratory is each well below $2 \cdot 10^{-6}$ cm^{-2}s^{-1} [5], the contribution to the background should be small. In the first stage of the experiment we will not install a neutron shield.

4 Radiopurity of detectors

The radiopurity of the absorber crystals is most critical for reaching a low background level. We have analyzed the radiopurity of sapphire crystals from several suppliers using neutron activation analysis. Samples of two different suppliers (SCT : Single Crystal Technology, Holland and CS : Crystal Systems, USA) had no contamination with uranium, thorium and potassium within the detection limits. The crystals were grown with the Czrochalski (SCT) and heat exchanger (CS) methods. Table 1 lists the detection limits on uranium, thorium and potassium. Conversion factors are : 1 mBq ^{238}U kg^{-1} $\equiv$ 81 ppt U, 1 mBq ^{232}Th kg^{-1} $\equiv$ 246 ppt Th, 1 mBq ^{40}K kg^{-1} $\equiv$ 32.3 ppb K. One ppm of natural K (10^{-6} g K per gram material) corresponds to 0.12 ppb of ^{40}K. The sensitivity to K in this method is poor because of the high activation of the sapphire matrix. A determination of the ^{26}Al content by accelerator mass spectrometry [6] gave an upper limit of 2×10^{-15} for the ^{26}Al/^{27}Al-ratio for the Al_2O_3 powder of SCT.

We have made Monte-Carlo simulations with the PRESTA version [7] of EGS4 [8] in order to calculate the background rate and the energy spectrum. The simulations take into account all γ-lines with relative intensity of more than 1% in the decay of the corresponding isotope. Angular correlations within a gamma cascade are neglected. The calculated absolute intensities agree very well with the values given in [9] except for those decays where many excited levels of the daughter are populated. In those few cases deviations of up to 15 % compared with [9] occur. Beta-decay spectra are generated with a non-relativistic formula with 2 parameters [10]. These parameters are obtained from a fit to the Fermi function of the particular isotope; we use the tabulated values in [11]. This approximation is very good in the non-relativistic region; deviations of a few percent occur at energies where relativistic effects start to be important. For unique forbidden transitions we use shape factors given by Wu [12]. For non-unique transitions we don't apply any shape correction, since there are no isotope-independent shape factors [13] available. Atomic effects (shake up, shake off) accompanying α or β decays are neglected, since their probability is well below one percent [14], but atomic electrons (conversion electrons, Auger electrons, Coster-Kronig transitions) as well as the emission of characteristic X-rays are taken into account, if the energy of electrons or X-rays exceeds a few keV or 500 eV, respectively. Conversion factors are taken from [15], electron-capture sub-shell ratios from [16], X-ray, Auger and Coster-Kronig transition probabilities from [17] and [9], atomic binding energies from [9], γ-ray energies from [9] and [18], and decay schemes and gamma intensities from [18].

The geometry we used in the simulation was a setup of four 250 g crystals, arranged in a square with a distance of 1.5 cm between the surfaces. This arrangement will be used in the first stage of CRESST. Events were discarded if they deposited energy in more than one crystal (this gave a 5–10% reduction in the rate). The distribution of the radioimpurities inside the crystals is taken to be homogeneous.

Fig. 2 shows the calculated spectrum from ^{40}K in sapphire in the energy range up to 25 keV assuming infinite detector resolution. The spectrum is dominated by the β decay into ^{40}Ca and is nearly flat in this low energy range. The single lines correspond to the K and L shell binding energies of Ar, and occur when ^{40}K decays into ^{40}Ar by electron capture to the respective shell. If the natural potassium content in the crystal were to be as high as one ppm, the 3.2 keV line would contain about 180 counts/(kg day) and might be useful for a continuous calibration of the detector.

The spectrum expected from ^{26}Al is similar to that from K, with a flat continuum and X-ray lines at 1.3 keV and 89 eV. At the detection limit of 2×10^{-15} for ^{26}Al/^{27}Al the 1.3 keV peak would contain about 7 counts/(kg day).

Fig. 3 shows the calculated spectrum caused by the decay chain of ^{238}U. Secular equilibrium is assumed in this simulation. A clear contribution from ^{210}Pb arises at 46.5 keV with an additional β spectrum with an end point of 17 keV. The small step at 92.3 keV is due to ^{234}Th. The shape rises slightly towards lower energies. Comparing Fig. 3 with Fig. 2 shows that the effects on the low energy part of the spectrum have to be considered, and not only the concentrations of the various radioimpurities.

In Table 1 the limits on the U, Th and K content of the sapphire crystals are converted into continuum background rates in the 0–25 keV range. With these numbers we are quite optimistic that a total background rate of less than one count/(keV kg day) is achievable.

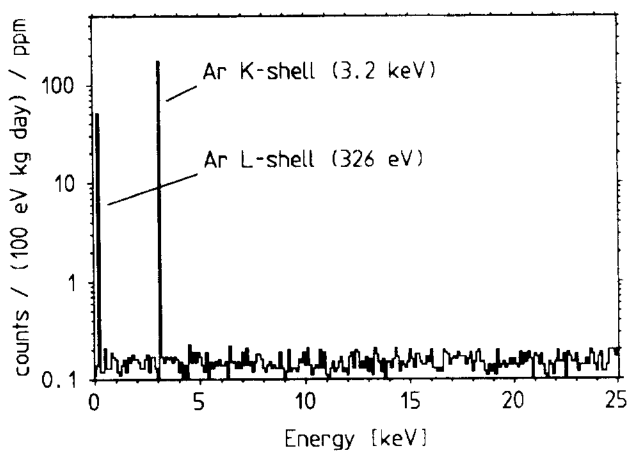

Figure 2: Calculated background from ^{40}K decays in 100 eV bins for 1 ppm of K in sapphire.

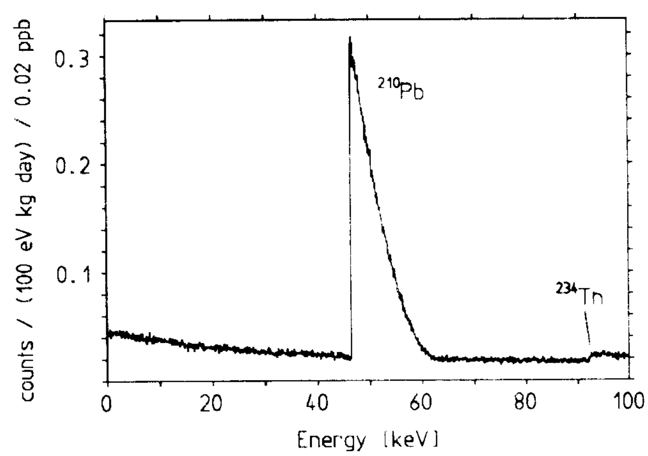

Figure 3: Calculated background in 100 eV bins induced by 0.02 ppb of ^{238}U and its daughters in sapphire.

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