Neutron Background Studies for the CRESST Dark Matter Experiment

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Abstract

The new detection concept applied for the direct WIMP search experiment CRESST II, which enables a clear discrimination between electron recoils and nuclear recoils, will leave neutrons as the main background. This background will soon limit the sensitivity of the experiment and therefore become an important issue for the next phase of CRESST. We have performed a study based on Monte Carlo simulations to investigate how neutrons from different origins affect CRESST and which measures have to be taken to reach the projected sensitivity.

Key words: Dark Matter; Neutron Background; Muon-induced Neutrons

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1 Introduction

CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) is a direct WIMP (Weakly Interacting Massive Particles) search experiment using low temperature detectors [1]. The experiment is performed at the Gran Sasso laboratory in Italy, at a depth of 3600 m w.e. underground. In such a rare event search, where one expects an event rate of the order of less than 0.01 count/keV/kg/day, background must be suppressed as much as possible. In spite of the employment of passive background reduction techniques for CRESST, i.e. deep underground site, efficient shielding against radioactivity of surrounding rock, and the use of radiopure materials inside the shielding, there is remaining background dominated by \( \beta \) and \( \gamma \) emission from nearby radioactive contaminants that leads to electron recoils in the detector. On the

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other hand WIMPs, and also neutrons, produce nuclear recoils. Therefore, the sensitivity of detection can be improved dramatically if, in addition to the passive shielding, the detector itself is able to discriminate electron recoils from nuclear recoils and actively reject them. Such an active rejection technique is made possible in CRESST II by simultaneous measurement of phonons and scintillation light [2].

While a very efficient suppression of the electromagnetic background can be achieved by the aforementioned methods, neutron-induced nuclear recoils can not be discriminated from the WIMP-induced nuclear recoils. They remain as a background and will limit the sensitivity of the experiment. It is obvious that CRESST II and other current and future direct dark matter search experiments have to cope with neutron background to reach high sensitivity. Understanding this background and the way to overcome it, is hence crucial for these experiments.

The neutron flux present in the CRESST setup at Gran Saso comes from different origins:

1. Low energy neutrons induced by fission and \((\alpha,n)\) reactions due to uranium and thorium activities in the surrounding rock and concrete. They give the bulk to the total flux in the laboratory.
2. Low energy neutrons induced by fission in the shielding material and the setup.
3. High energy neutrons induced by muons in the rock. These neutrons could do spallation reactions in the experimental shield and produce additional neutrons.
4. High energy neutrons induced by muons in the shielding material (especially lead).

Based on Monte Carlo simulations we have studied the contribution of each neutron source to the expected background rate in CRESST II. We will first discuss the background induced by low energy neutrons (section 2). Section 3 starts with the investigation of the muon flux and spectrum at the Gran Sasso laboratory. Following are the muon-induced neutron production underground (subsection 3.2), the resulting neutron spectrum in the laboratory and inside the experimental setup (subsection 3.3) and finally the recoil spectrum in the CRESST detectors expected from this background source. Section 4 compares the background contribution from the different sources and discusses further possible improvement.
2 Background induced by low energy neutrons

2.1 Contribution of \((\alpha,n)\) and fission neutrons from the rock/concrete

In a previous paper [3] we have reported a detailed study of the neutron flux at the Gran Sasso laboratory, especially in hall A, where the CRESST setup is now located. From this study we have obtained a more detailed neutron energy spectrum in hall A than was available in literature before. We have also shown that the neutron flux in the hall is actually dependent on the humidity of the concrete layer in the laboratory: the flux is higher when the concrete is dry than when it is wet. We have used the dry-concrete spectrum to determine the background count rate expected in the CRESST CaWO\(_4\) detectors, because it would give a conservative estimate. Besides, we also found that our calculation of the integral flux in hall A is consistent with the measurement performed by Belli et al. [4] if we assume that the concrete in the hall is dry.

To get a spectrum of neutron-induced recoils in the target we have performed Monte Carlo simulations using MCNP4B [5]. No neutron moderator is installed in the present setup of CRESST [1] and a simplified geometry, which consist of Pb/Cu shield, was used in the simulations. The outer dimension of the lead shield is 130 cm x 130 cm x 136 cm and the thickness is 20 cm. Inside the lead is a 15 cm thick copper layer housing the experimental cavity, in which a single cube detector crystal of 4 cm x 4 cm x 4 cm is placed. Using this geometry, our simulation with the dry-concrete spectrum gives 69 cts/kg/y in the energy range of 15-25 keV, while the spectrum from [4] gives 47 cts/kg/y. The lower limit (15 keV) here is determined by the threshold of the detector system of CRESST II.

In CRESST II, 60 GeV WIMPs with a cross section as claimed by the DAMA collaboration in [6] would give 55 cts/kg/y between 15 and 25 keV. With the aforementioned contribution of neutron background, it is therefore difficult for CRESST II to check the DAMA evidence without a neutron moderator shield.

If a neutron moderator of 50 cm polyethylene is placed outside the lead shield, \(6 \times 10^{-3}\) cts/kg/y are expected in the energy range of 15-25 keV for the dry-concrete spectrum, while the simulation with the spectrum from [4] gives \(3.6 \times 10^{-2}\) cts/kg/y, which is six times higher. This is due to the fact that in spite of the agreement between our result and [4] for the total flux, the detailed spectra are different. In addition, the results in [4] are given as integral fluxes over quite large energy bins. In sampling the energy in each bin we have assumed an equal probability in the whole bin. This makes the spectrum harder than it should be. On the other hand, we have given our results as integral fluxes over smaller bins [3], and therefore more detailed. The higher
number of neutrons with energies above 7 MeV in the spectrum from [4], which can partly penetrate the moderator, give more counts in the detector. This fact indicates the importance of detailed knowledge of the neutron spectrum at the experimental site.

2.2 Neutrons produced by fission in the lead shield

The use of radio pure material for the setup and shield in rare event search experiments is mandatory. However, it is still necessary to check, whether the low remaining activity is really harmless.

We have performed a simulation to study the effect caused by neutrons from the radio impurity in the lead shield of CRESST. Only neutrons induced by spontaneous fission of $^{238}$U were considered in our simulation, because the contribution of $(\alpha,n)$ reactions in lead is not significant. We found that neutrons from this origin would give 2 cts/kg/y in the energy range of 15-25 keV for a $^{238}$U concentration of one ppb, which is a factor of about 30 lower than the rate expected from low energy neutrons from the rock for the simple setup without neutron moderator. Hence, for the present CRESST setup a contamination of a few ppb $^{238}$U is still acceptable. This situation changes however, when a 50 cm polyethylene shield is put in place so that the contribution of low energy neutrons from the rock is significantly reduced. Only a few ppt $^{238}$U is already a limiting neutron source in this case. It is clear, that even a very low contamination in the lead shield can still be dangerous for the experiment, especially because it is very close to the detector.

The typical amount of radio impurity in lead commonly used in rare event search experiments is obtained from the measurements performed by several groups. Allesandrello et al. [7] reported a $^{238}$U contamination of < 2 ppb in roman lead and < 12 ppb in low activity lead. Assuming an equilibrium of $^{238}$U with its daughter products, the EDELWEISS collaboration has found an upper contamination limit of 0.7 ppb $^{238}$U in the most recent measurements of its lead. Previous measurements made on a different lead sample gave 0.1 ppb [8].

Additional neutron flux can be expected from the copper and polyethylene shields. The contribution of the latter might be negligible, because neutrons will be moderated by polyethylene. To know the real contribution of neutrons from this origin, measurements of the contamination in the shielding materials used in CRESST are required.
3 Muon-induced neutron background

3.1 Muon flux and energy spectrum

To calculate differential and integral muon intensities at the depth of the Gran Sasso laboratory a special code called SIAM [9] was used. In this code the differential muon intensity underground was determined using the following equation:

\[ I_\mu(E_\mu, X, \cos \theta) = \int_0^\infty P(E_\mu, X, E_{\mu 0}) \frac{dI_{\mu 0}(E_{\mu 0}, \cos \theta^*)}{dE_{\mu 0}} dE_{\mu 0} \]  

(1)

where \( \frac{dI_{\mu 0}(E_{\mu 0}, \cos \theta^*)}{dE_{\mu 0}} \) is the muon intensity at sea level at the zenith angle \( \theta^* \):

\[ \frac{dI_{\mu 0}(E_{\mu 0}, \cos \theta^*)}{dE_{\mu 0}} = A \frac{0.14E_{\mu 0}^{-\gamma}}{\text{cm}^2\text{s sr GeV}} \times \left\{ \frac{1}{1 + \frac{1.1E_{\mu 0}\cos \theta^*}{115 \text{ GeV}}} + \frac{0.054}{1 + \frac{1.1E_{\mu 0}\cos \theta^*}{850 \text{ GeV}}} + R_c \right\} \]  

(2)

The relation between the zenith angle at the Earth’s surface, \( \theta^* \), and the zenith angle underground, \( \theta \), was determined taking into account the curvature of the Earth. \( R_c \) denotes the ratio of prompt muons to pions. The parameters in Eq. (2) were taken either according to Gaisser’s parameterization [10] (\( A = 1, \gamma = 2.70 \)) which is modified for large zenith angles and prompt muon flux [11], or following the best fit to the depth-vertical \( \mu \) intensity relation measured by the LVD experiment [11]. LVD reported the normalization constant \( A = 1.84 \pm 0.31, \gamma = 2.77 \pm 0.02 \) and the upper limit \( R_c \leq 2 \times 10^{-3} \) (95% C.L.) [12]. \( P(E_\mu, X, E_{\mu 0}) \) is the probability for a muon with energy \( E_{\mu 0} \) at the surface to have the energy \( E_\mu \) at depth \( X \) [9] and was obtained by propagating muons with various energies at the Earth’s surface using MUSIC (Muon Simulation Code) [13].

In this work we have taken \( 10^{-4} \) for the ratio of prompt muons to pions, well below the upper limit given by LVD [12]. To calculate the integral muon intensity, an integration of Eq. (1) over \( dE_\mu \) was carried out. A further integration over \( \cos \theta \) gives the global intensity for a spherical detector.

The absolute muon intensity underground depends in fact on the surface relief. Gran Sasso has a very complex mountain profile, that makes it difficult to predict the muon flux without precise information on the slant depth distribution. In this work a flat surface was assumed as approximation. In the near future, a further study is planned, taking the detailed mountain profile of Gran Sasso into account. There might not be a big difference in the neu-
tron production – the simulation results will after all be normalized to the muon flux measured in Gran Sasso (1\mu/h/m^2) – but it may be important for simulations of the muon veto.

3.2 Muon-induced neutron production at Gran Sasso

We have used FLUKA [14] to simulate neutron production by muons. The two muon energy spectra underground discussed in the previous subsection have been used in the simulations, i.e. the one obtained with the parameters according to Gaisser’s parameterization and the other following the LVD best fit. In addition, simulations have also been performed for mono energetic muons of 270 GeV, which is the mean muon energy at the depth of Gran Sasso [15].

The neutron production has been simulated for materials relevant for CRESST, i.e. Gran Sasso rock and concrete, lead, copper, and polyethylene. The compositions of Gran Sasso rock and concrete are taken from [16] and [3] respectively. Neutron production rates obtained from the simulations with the spectrum following the LVD best fit are shown in Table 1 for three different processes: muon spallation, hadronic shower and electromagnetic shower. The rates are in agreement with the results of simulations with the spectrum using Gaisser’s parameterization and also with the results from mono energetic 270 GeV muons. These data show that the neutron production rate at Gran Sasso is dominated by secondary processes, i.e. hadronic and electromagnetic showers. It can also be seen that neutron production increases with the average atomic weight $\langle A \rangle$ of the target. The production rates in rock and concrete are about the same due to their similar average atomic weights.

There are some measurements on the neutron production rate by muons in lead that can be used as a comparison for the result of this work. Gorshkov measured neutron production by muons at several depths underground for several elements including lead (see [17] and reference therein). At 800 m w.e. he found an average neutron production per nucleon in lead $m\sigma/A = 300 \times 10^{-29} \text{cm}^2/\text{Pb nucleus}$, where $m$, $\sigma$ and $A$ denote multiplicity, cross section and atomic weight respectively. This number multiplied by the Avogadro’s number gives the neutron production of $1.81 \times 10^{-3}$ neutrons/\mu/(g/cm^2). The mean energy at this depth is approximately 110 GeV. Using the law that the neutron production rate goes like $E_\mu^{0.75}$ as measured for liquid scintillator [18,19,20] would give a neutron production rate at 270 GeV (Gran Sasso mean muon energy) of $3.55 \times 10^{-3}$ neutrons/\mu/(g/cm^2), which is in reasonable agreement with the simulation in this work.

Bergamisco et al. performed an experiment on neutron production by muons in lead at Mont Blanc (4300 m w.e, or 5200 m w.e according to the LSD
They reported a product of multiplicity and cross section, \(\overline{m}\sigma = (400 \pm 150) \times 10^{-26} \text{cm}^2/\text{Pb nucleus}\), that leads to a neutron production of \(1.16 \times 10^{-2}\) neutrons/\(\mu/(\text{g/cm}^2)\) at this depth. If the mean muon energy at Mont Blanc is assumed to be 385 GeV as reported by LSD [21], the \(E_{\mu}^{0.75}\) law applied to Gorshkov's result would give a neutron production rate in lead at Mont Blanc as \(4.63 \times 10^{-3}\) neutrons/(g/cm\(^2\)), which is almost three times lower than Bergamosco's result. The \(\overline{m}\sigma\) reported by Bergamosco is, in fact, about three times higher than the theoretical prediction and extrapolation from several other experiments [22]. That means, if his measurement was off by a factor of three, the neutron production would be in reasonable agreement with our and Gorshkov's results.

Recent measurements at CERN to determine the neutron production rate in lead, copper and carbon by a 190 GeV muon beam (experiment NA55) were performed with thin targets and the results are reported at certain scattering angles only [23]. Therefore this information can unfortunately not easily be used to check our results.

3.3 Energy spectrum of neutrons entering the experimental hall and the Detector Area

To determine the energy spectrum of neutrons from the rock entering the laboratory hall, the muon spectrum with parameters following the LVD best fit was used. It is clear that the number of neutrons entering the hall depends on the thickness of the rock used in the simulations. A very large thickness needs too much computing time, whereas a too small thickness will underestimate the particle yield. It was found in our simulation of neutron production in Gran Sasso rock, that cascades were well developed and that the equilibrium between neutron and muon flux was reached after muons had crossed about 6-7 meter of Gran Sasso rock.

Additional information comes from the results of Monte Carlo simulations performed by Dementyev [24]. He found that the typical depth of Gran Sasso rock for hadrons with energies above 200 MeV is 90 cm, which means that 96% of the neutron flux entering the hall is produced at a depth of up to about 3 meter behind the rock surface.

In this work, muons were generated at the surfaces of a cube of rock with a size of 20 m x 20 m x 20 m. Inside the rock cube, the experimental hall was taken to be of a size of 6 x 6 x 5 m\(^3\). The top of the hall was placed 10 m below the top of the rock cube. This should be the optimal depth to allow the cascades to develop and to let neutrons produced in the last 3-4 meters of rock overburden enter the hall. The size of the experimental hall used in these
simulations was chosen smaller than the real hall at the Gran Sasso laboratory to save computing time. But some test simulations have been done to ensure that the results do not change significantly if a larger size is used. To sample muon energy and angular distribution the code MUSUN (Muon Simulation Underground) [9] was used.

Two different cases have been considered: all neutrons were absorbed immediately after entering the hall (that is without back scattering) and neutrons were scattered by the rock surrounding the hall (with back scattering). Figure 1 shows the neutron energy spectra at the boundary of rock and hall for these two cases. The total flux of neutrons above 1 MeV entering the hall is $4.27 \times 10^{-10}$ n/cm²/s (135 n/m²/year) for the first and $8.53 \times 10^{-10}$ n/cm²/s (269 n/m²/year) for the second case. In Figure 2 our spectrum with back scattering is shown together with the spectrum reported by Dementyev [24]. The two spectra are in agreement at high energy, but for the energy range between 6 - 60 MeV Dementyev’s flux is higher.

The angular distributions of neutrons entering the hall with energies above 1 MeV are shown in Figure 3 separately for the roof, the floor, the walls and total for the cases with and without back scattering. Almost all neutrons entering the hall from the floor are back scattered neutrons. Energy spectra of neutrons with energies above 1 MeV entering the hall from the roof, the wall and the floor are shown in Figure 4 for the cases without and with back scattering. High energy neutrons come mainly from the roof. The number of lower energy neutrons increases due to scattering.

In Figure 5 the neutron flux at the boundary between the shield and the detector area inside the shield is shown. The neutrons here are produced by muons both in the rock and in the shielding materials used in CRESST. The flux below 1 MeV comes mainly from neutrons produced by muons in the lead shield.

3.4 Recoil spectrum and count rate of muon-induced neutron background

While the background induced by muons in the shield can efficiently be removed by a muon veto system, the neutrons produced by muons in the rock can not be suppressed easily. Therefore, we investigate these two contributions separately.

Because FLUKA does not treat individual nuclear recoils, MCNPX [25] and MCNP4B [5] were employed to study the contribution of muon-induced neutrons in the rock to the expected background rate in the CRESST CaWO₄ detector. The simple experimental setup as described in section 2.1 with 50 cm polyethylene shield was placed inside the hall and neutrons (the spectrum with
back scattering) were generated at the hall’s surface and transported further down to the detector level to eventually get the recoil spectrum. In the experimental setup these high energy neutrons produced additional neutrons. The surrounding rock was replaced with vacuum, to prevent neutrons from being scattered again by the rock. The count rate in the energy range of $(15 - 25)$ keV is $8.81 \times 10^{-4}$ cts/kg/day. This result is higher than the rates for low energy neutrons from activity of the surrounding rock and concrete with the same polyethylene thickness.

To determine the contribution of muon-induced neutrons in the experimental setup, muons following the LVD best fit were generated at the hall’s surface and the simple setup with 50 cm polyethylene shield was placed inside the hall. Muons were transported inside the hall and through the experimental setup with FLUKA. The rock surrounding the experimental hall was replaced by vacuum, to avoid muon-induced neutron production therein. Neutrons produced by muons in the experimental setup and entering the experimental cavity (passing through the boundary between the inner surface of the copper shield and the experimental cavity) were then transported further with MCNPX and MCNP4B to get the recoil spectrum in the detector crystal. The count rate in $(15 - 25)$ keV range is $2.78 \times 10^{-3}$ cts/kg/day. This rate is higher than that from low energy neutrons from the rock/concrete after being moderated by 50 cm polyethylene and even higher than that rate from high energy neutrons from the rock.

4 **Comparison of neutron background from different sources**

In Figure 6 the recoil spectra in the CaWO$_4$ detector induced by neutrons from different origins are shown. The recoil spectra induced by low energy neutrons from the rock/concrete have been obtained with the dry-concrete spectrum. The spectrum for neutrons from fission reactions in the lead shield here is obtained by taking a $^{238}$U contamination of 0.1 ppb. The remaining neutron flux with the neutron moderator installed is dominated by neutrons induced by muons in the lead shield. This background would limit the sensitivity of the experiment for the WIMP-nucleon cross section to about $10^{-7}$ pb. As aforementioned, it is possible to suppress this neutron background by a muon veto system. For CRESST II such a system is planned in addition to a neutron moderator. This will enable CRESST II to reach the projected sensitivity for the WIMP-nucleon cross section of below $10^{-7}$ pb. The muon veto will be placed inside the polyethylene shield and will have an efficiency of more than 90%. However, the muon veto will reduce the neutron background only by a factor of three, unless high energy neutrons from the rock can be overcome. Neutrons scattered in more than one detector can be
rejected as background, because WIMPs do not scatter multiply. Therefore the neutron background will be further reduced and multiple scattering can also be engaged to determine the remaining single scatter neutron background. This technique has already been successfully applied for the CDMS experiment [26]. Simulations with an array of detectors will be done in the near future to investigate, which sensitivity level can be reached by this technique.

5 Conclusions

We have discussed the contribution of different neutron background sources relevant for CRESST. The flux of low energy neutrons from the surrounding rock/concrete can be reduced efficiently by a hydrogen-rich material like polyethylene. For the CRESST II setup a polyethylene shield (35-50 cm thick) is advisable. This will reduce the background count rate in the CaWO$_4$ detector by more than three orders of magnitude. Then the background will be dominated by neutrons from other origins. To reach the projected sensitivity, a muon veto is planned for CRESST. Multiple scattering should be studied and the radio impurity of the shielding materials need to be measured to determine a more realistic contributions of muon-induced neutrons in the rock and fission-induced neutrons in the shielding materials.

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Table 1
Neutron production rate from muons with the LVD best fit spectrum in several materials.

| Material          | Average atomic weight $\langle A \rangle$ | Neutron production rate ($10^{-5}$ n$/\mu$/g/cm$^2$) | $\mu$-spallation | Hadronic shower | E.m. shower | Total  |
|-------------------|------------------------------------------|------------------------------------------------------|------------------|----------------|-------------|--------|
| Lead              | 207.20                                   | 10.13                                               | 239.45           | 178.68         |             | 428.26 |
| Copper            | 63.55                                    | 4.22                                                | 74.95            | 41.04          |             | 120.20 |
| LNGS rock         | 22.87                                    | 1.79                                                | 26.42            | 7.37           |             | 35.59  |
| LNGS concrete     | 20.50                                    | 1.86                                                | 25.40            | 5.70           |             | 32.96  |
| Polyethylene      | 10.40                                    | 1.23                                                | 16.32            | 6.27           |             | 23.82  |

Fig. 1. Flux of muon-induced neutrons entering the Gran Sasso hall obtained from simulations in this work, without (○) and with (●) back scattering.
Fig. 2. Comparison of the spectra of muon-induced neutrons entering the Gran Sasso hall: Dementyev [24] (solid line) and this work (with back scattering, triangles).

Fig. 3. Angular distribution of neutrons with energies above 1 MeV entering the hall from a) the roof, b) the walls, c) the floor and d) anywhere for the case without back scattering (solid lines) and with back scattering (dotted lines).
Fig. 4. Energy distribution of neutrons entering the hall from the roof (solid lines), the walls (dotted lines) and the floor (dashed lines) for the cases a) without back scattering and b) with back scattering.

Fig. 5. The flux at the boundary between the shield and the detector area inside the shield (O). As a comparison the flux of neutrons entering the hall (including back scattering) is shown (●).
Fig. 6. Recoil spectra in a CaWO₄ detector induced by neutrons from different origins: (a) low energy neutrons from the rock/concrete, no neutron moderator, (b) low energy neutrons from the rock/concrete after being moderated by 50 cm polyethylene, (c) low energy neutrons from fission reactions of 0.1 ppb ²³⁸U in the lead shield, (d) high energy neutrons induced by muons in the rock and (e) high energy neutrons induced by muons in the experimental setup.