Neutron background simulation for the CRESST–II experiment

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Abstract. The CRESST collaboration reported an excess signal in their latest physics run. After removal of expected electromagnetic background, low energy os and degraded lead recoils from the signal region, a mean value of 35.4 excess events remain. In this work, we investigate if neutron induced nuclear recoils can explain the reported excess. Three results are found: The total event rate in the simulation of $2.04^{+0.22}_{-0.13} \times 10^{-3}$ cts/kgd is much lower than the one inferred from the remaining excess events of $4.85 \times 10^{-2}$ cts/kgd in the experimental data. Additionally, the dominance of oxygen recoils ($\sim 90\%$) predicted by the simulation is in disagreement with the favored experimental lightyield distribution of the excess signal. Furthermore, the experimentally observed fraction of higher multiplicities is only half of the $\sim 20\%$ obtained by the simulation. Especially the experimental absence of double detector hits in the presence of higher multiplicities is in clear contradiction to the results of the simulation. In combination, these three discrepancies between the experimental and the simulated background allows the conclusion that the observed excess signal cannot be explained by neutron induced nuclear recoils alone.

1. Introduction
The latest result of the CRESST–II experiment reports an excess signal in the signal region of the experiment [1]. In order to determine if this excess signal is the result of neutron induced background, simulations of the various neutron sources have been conducted. The results of the simulation are checked against the experimental results considering the total expected background rate, the distribution of the multiplicity, i.e. the number of detector modules hit by particles simultaneously and the distribution of the lightyield (LY) of the detector hits.

2. Setup of the simulation
The simulation are conducted in GEANT4.9.4.p02 [2; 3]. Neutron–nuclear interaction is implemented via the data driven G4NeutronHP class using the G4NDL3.14 data base providing the cross-section data. The inelastic neutron scattering process is modified to correct the reaction kinematics and to ensure that the recoiling nucleus is always generated as reaction product. A description of the setup including a sketch can be found in Ref. [1], it has been accurately included into the simulation, especially the carousel holding the 18 detector modules. Holding the coldbox with the carousel, the cryostat is located along the central axis. The outmost shield

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Table 1. Simulated neutron sources, giving the required neutron flux per year, the starting volume and the production mechanism.

| Source       | Primary n required per a | Starting Volume | Production mechanism | Contamination in ppb |
|--------------|--------------------------|----------------|----------------------|----------------------|
| Ambient      | 1.27 × 10⁷               | outside        | s.f. + (α, n) in rock|                      |
| Lead         | 1790                     | Pb shield      | s.f.                 | U, Th: < 0.2         |
| Copper       | 76.09                    | Cu shield      | s.f. + (α, n) on Cu  | U, Th: 0.02          |
| PE           | 8570                     | PE shield      | s.f. + (α, n) on PE  | U: 0.5, Th: 1.3      |
| Cosmogenic   | 10087                    | outside        | cosmogenic           |                      |

The constraints used for analysis of the experimental data are also applied to the simulated data. 8 out of 18 installed modules are used for the analysis of the signal region and 9 modules are used as veto modules only. A standard detection threshold of 5 keV is applied to each detector module, the signal region extends from an individual separation threshold as given in Tab. 2 to 40 keV. The nuclear lightyields are the same as used in the experimental analysis (LY₀ = 0.102, LY_Ca = 0.0638 and LY_W = 0.0391). Only single hits in the signal region of one detector module are accepted. The muon veto rejects events if the sum of all energy depositions in the muon veto exceed 15 MeV, removing 35% of the events induced by cosmogenic neutrons. A successful test of the simulation has been done by comparing the spectral shape of the recoil spectrum and the detector hit multiplicities with calibration run data.

Table 2. The separation thresholds as applied to the detectors. These values have been taken from analysis of the experimental data given in Ref. [1].

| Channel | Separation threshold | Channel | Separation threshold | Channel | Separation threshold | Channel | Separation threshold |
|---------|----------------------|---------|----------------------|---------|----------------------|---------|----------------------|
| 05      | 12.3 keV             | 29      | 12.1 keV             | 43      | 15.5 keV             | 47      | 19.0 keV             |
| 20      | 12.9 keV             | 33      | 15.0 keV             | 45      | 16.2 keV             | 51      | 10.2 keV             |
3. Comparison between experiment and simulation

The 67 total events in the signal region are reduced to $36.9^{+10.6}_{-10.9}$ events for the M1 solution and $33.9^{+10.1}_{-8.8}$ for the M2 solution by the likelihood fit as γ leakage, degraded os and Pb recoils are subtracted [1]. For the mean value of 35.4 excess events and an exposure of 730 kgd, the background is $4.85 \times 10^{-2}$ cts/kgd. On top of those 35.4 single events, no double hit events but two triple hit events and one five-fold coincidence have been observed. The mean lightyield (LY) of the observed excess events for the M1 solution is 0.05 and 0.09 for the M2 solution.

The observed rate of the excess signal of $4.85 \times 10^{-2}$ cts/kgd exceeds the flux of the neutron sources considered in Tab. 3 by a factor of 24.

Tab. 4 presents the distribution of events in the nuclear recoil bands in the signal region, which is incompatible with the observed mean LY $\sim 0.05$ of the M1 solution. The distribution of the M2 solution with a mean LY of $\sim 0.09$ cannot be distinguished from the predictions of the simulation, however.

Using the distribution for the weighted sources for 35.4 single, 7.5 double, 1.78 triple events and 0.10 five-fold coincident events are expected. Tab. 5 shows the resulting multiplicity distributions from the simulation, the absence of any double detector hit events is incompatible with the combined simulation result at a C.L. of 99.95 %.

### Table 3. Background rates obtained for the neutron sources presented in Sec. 2. Oxygen events have $0.084 < \text{LY}_O < 0.162$, calcium events are defined by $0.052 < \text{LY}_\text{Ca} < 0.084$ and tungsten events show $\text{LY}_W$ of less than 0.052. The error interval denotes the 90 % C.L.

| Source          | Background rate in cts/kgd | Oxygen in cts/kgd | Calcium in cts/kgd | Tungsten in cts/kgd |
|-----------------|----------------------------|-------------------|--------------------|---------------------|
| Cosmogenic      | $1.25^{+0.06}_{-0.06} \times 10^{-3}$ | $1.14^{+0.06}_{-0.06} \times 10^{-3}$ | $9.22^{+1.78}_{-1.55} \times 10^{-5}$ | $2.07^{+0.94}_{-0.70} \times 10^{-5}$ |
| Lead shielding  | $4.28^{+0.10}_{-0.10} \times 10^{-4}$ | $3.93^{+0.10}_{-0.10} \times 10^{-4}$ | $3.05^{+0.28}_{-0.28} \times 10^{-5}$ | $4.94^{+1.10}_{-1.33} \times 10^{-6}$ |
| Ambient         | $2.50^{+2.20}_{-1.33} \times 10^{-4}$ | $2.50^{+2.20}_{-1.33} \times 10^{-4}$ | $0.00^{+8.23}_{-8.23} \times 10^{-5}$ | $0.00^{+8.23}_{-8.23} \times 10^{-5}$ |
| Cu shielding    | $8.56^{+0.35}_{-0.35} \times 10^{-5}$ | $7.58^{+0.35}_{-0.35} \times 10^{-5}$ | $8.17^{+1.24}_{-1.15} \times 10^{-6}$ | $1.71^{+0.47}_{-0.47} \times 10^{-6}$ |
| PE shielding    | $2.68^{+0.28}_{-0.23} \times 10^{-5}$ | $2.51^{+0.27}_{-0.22} \times 10^{-5}$ | $1.55^{+0.80}_{-0.80} \times 10^{-6}$ | $1.93^{+4.15}_{-1.55} \times 10^{-7}$ |
| Total           | $2.04^{+0.15}_{-0.14} \times 10^{-3}$ | $1.88^{+0.14}_{-0.14} \times 10^{-3}$ | $1.32^{+0.16}_{-0.16} \times 10^{-4}$ | $2.76^{+0.71}_{-0.71} \times 10^{-5}$ |

### Table 4. Lightyield distribution for perfect detector resolution given for signal region. The LY bands and the weights are as given in Tab. 3, the error interval contains the 90 % C.L.

| Source          | Mean lightyield  | Oxygen in % | Calcium in % | Tungsten in % |
|-----------------|------------------|-------------|--------------|---------------|
| Cosmogenic      | 0.094            | 90.96$^{+0.40}_{-0.42}$ | $7.37^{+1.30}_{-1.16}$ | $1.66^{+0.73}_{-0.55}$ |
| Pb shielding    | 0.094            | 91.72$^{+0.20}_{-0.20}$ | $7.13^{+0.66}_{-0.62}$ | $1.15^{+0.66}_{-0.25}$ |
| Ambient         | 0.097            | 100$^{+24.73}_{-24.73}$ | $0.00^{+24.73}_{-24.73}$ | $0.00^{+24.73}_{-24.73}$ |
| Cu shielding    | 0.093            | 88.47$^{+0.45}_{-0.47}$ | $9.54^{+1.14}_{-1.24}$ | $2.00^{+0.68}_{-0.54}$ |
| PE shielding    | 0.096            | 93.52$^{+0.59}_{-0.67}$ | $5.76^{+2.06}_{-2.37}$ | $0.79^{+1.51}_{-0.59}$ |
| Weighted sources| 0.094            | 92.16$^{+0.69}_{-0.67}$ | $6.49^{+2.06}_{-2.06}$ | $1.35^{+1.51}_{-0.59}$ |
Table 5. Multiplicity distribution of events in the signal region as detailed in Sec. 2. Events induced by cosmogenic neutrons reach much higher multiplicities than shown. The error interval denotes the 90 % C.L.

| Source             | Multiplicity in % of all events |
|--------------------|---------------------------------|
|                    | 1     | 2     | 3     | 4     | 5     |
| Cosmogenic         | 72.43±0.94 | 20.54±1.50 | 5.52±0.98 | 1.02±0.50 | 0.36±0.34 |
| Lead shielding     | 81.89±0.37 | 15.86±0.78 | 2.00±0.35 | 0.29±0.15 | 0.02±0.07 |
| Ambient            | 100.00±24.73 | 0.00±24.73 | 0.00±24.73 | 0.00±24.73 | 0.00±24.73 |
| Copper shielding   | 82.29±0.60 | 15.00±1.30 | 2.33±0.60 | 0.32±0.31 | 0.05±0.20 |
| PE shielding       | 82.99±1.36 | 14.02±3.20 | 2.69±1.91 | 0.30±1.10 | 0.00±0.68 |
| Weighted sources   | 78.35  | 16.71  | 3.94   | 0.70   | 0.22   |

4. Conclusion

The observed excess signal of the latest CRESST–II run 32 cannot be explained by neutron induced background since the simulated background falls short by a factor of 24. This discrepancy alone is not a decisive argument, as a point like neutron source close to the detectors could evade detection while rising the background to the observed level. The simple comparison of the mean light yield is in disagreement with the M1 solution presented in Ref. [1] while being compatible with the M2 solution. The most striking argument against a neutron induced excess signal is the observed absence of double detector hits while observing higher multiplicities which cannot be explained by any conceivable neutron source. In combination, these three results exclude neutrons as the origin of the observed excess signal.

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