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Background simulations for the ECHo experiment

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Abstract. ECHo-1K is an experiment designed to measure the electron neutrino mass from the spectrum of the electron capture on $^{163}$Ho using an array of 100 magnetic micro calorimeters each loaded with 10 Bq of $^{163}$Ho. In this article, we present the results of our activities in the investigation of possible backgrounds to the electron capture spectrum using GEANT4 based Monte-Carlo simulations of the sources $^{166m}$Ho, $^{40}$K, $^{210}$Pb and the $^{238}$U decay chain. For standard contaminations of the used materials, the contribution of the investigated sources is well below the background induced by the pile-up of $^{163}$Ho decays. Nonetheless, care has to be taken to avoid accidental contamination during the manufacturing and storage of the detectors, since a few mBq in total on the surface of all 100 detectors of either $^{40}$K ($\sim 12$ mBq) from residual potassium, or $^{210}$Pb ($\sim 4$ mBq) from radon emanation yield a background as large as the expected signal.

1. Introduction
ECHo-1K is an experiment with an novel approach to determine the neutrino mass from the measurement of the endpoint region of the $^{163}$Ho electron capture (EC)[1]. The goal is to collect a spectrum with $\sim 3.2 \times 10^{10}$ $^{163}$Ho decays by operating an array of 100 detectors each loaded with 10 Bq of $^{163}$Ho for one year. The endpoint $Q_{EC}$ of $^{163}$Ho has been determined by the measurement of the mass-difference $m_{^{163}Ho} - m_{^{163}Dy} = 2833 \pm 30 \pm 15$ eV with the Penning-trap mass spectrometer SHIPTRAP[2]. For this value, only $\sim 7 \times 10^{-10}$ of all decays are found within the last 10 eV before $Q_{EC}$, the region of interest (ROI). For ECHo-1K, about 30 signal events are expected in the ROI within one year of measuring time. An indiscriminable background of 5 events in the ROI arises due to the pile-up of $^{163}$Ho decays, for the ECHo-1K setup, other backgrounds have to be reduced below this level. In order to obtain the optimal sensitivity for the ECHo experiment, several sources of background have to be studied in simulations. GEANT4 is a Monte-Carlo simulation framework which is widely used in particle physics[3, 4]. It allows an easy implementation of detailed experimental setups and offers a large variety of physics lists for applications ranging from high energy accelerator physics to medical applications. These physics lists can be modified by the user if the application requires this. In the case of the background simulations for the ECHo experiment, several unusual demands are put to the simulation framework. The ROI in the ECHo experiment around the $Q_{EC} = 2.833$ keV is well below 10 keV which is a tiny energy for most particle physics scenarios. It must be ensured that the used physics lists do propagate particles in this energy region correctly. The physics of the atomic shell at these low energies are important, i.e., fluorescence and Auger electron emission must be included accurately in the used physics lists. After testing a variety of GEANT4
physics lists if they can satisfy these demands, we selected the LivermoreEm list for the low energy simulation of electromagnetic interactions. Due to the small size of the single ECHO detectors of only $200\,\mu m \times 200\,\mu m \times 10\,\mu m$, the minimum step size of the tracked particles in the GEANT4 simulation had to be lowered to 500 nm. The limiting factor is now given by the theoretical uncertainties of the energy loss function below 10 keV. Further complications arise from exotic processes in the ECHO setup, i.e. M- and N-shell $^{163}$Ho EC, decay of metastable isotopes in the case of $^{166m}$Ho and the correct treatment of Auger electron emission for atoms with $Z \approx 60$. In the case of the decay of metastable isotopes, a modification of the radioactive decay process in GEANT4.10.0.1 reestablished the correct process.

2. $^{166m}$Ho as coimplanted background source
Due to the limited life-time of $^{163}$Ho of only 4570 years, the $^{163}$Ho used in the ECHO experiment has to be produced via neutron irradiation of erbium. In this process, long-lived $^{166m}$Ho ($\tau_1/2 = 1200$ years) is also produced and cannot be separated by chemical methods. A reduction of the $^{166m}$Ho contamination to the level of $10^{-10}$ to $10^{-11}$ in the implantation material can be achieved via mass separation. $^{166m}$Ho decays via beta decay and has two low energy decay branches which provide a background to the measurement of the $^{163}$Ho EC.

The simulation was set up with $^{166m}$Ho placed in the middle of the gold absorber of the size $200\,\mu m \times 200\,\mu m \times 10\,\mu m$ where it would be coimplanted in the experiment. Additionally, the beta decay of the metastable isotope was reestablished in the simulation code and the cut off length was reduced to 500 nm to prevent the premature stopping of low energy gammas. According to the simulation, the background contribution of $^{166m}$Ho is several orders of magnitude below the pile-up level, for a separation of $^{166m}$Ho/$^{163}$Ho of $10^{-10}$, $3 \times 10^{-4}$ counts are expected for ECHO-1K.

3. $^{40}$K as surface contamination on the detector
$^{40}$K is a ubiquitous radioactive contamination found in natural occurring potassium. It can decay via EC which releases X-rays and Auger electrons around 2.5-3.2 keV and a 1460 keV gamma which rarely interacts in the tiny detectors. The most dangerous situation arises when potassium is deposited on the surface of the detector during the manufacturing or installation of the detectors. Two setup were simulated, in the first scenario, $^{40}$K was forced to decay on the surface of the detector, in the second simulated scenario a PCB board was put under the detector setup and $^{40}$K decayed within the first $\mu m$ of the board below the detector. Fig.1 shows the energy deposition of surface contamination, the pile-up level of 5 counts in the ECHO-1K run is achieved for a rather high surface contamination of $\sim 75$ mBq/cm$^2$ on the detectors. In the case of the bulk contamination of the board, the resulting background was negligible.

4. $^{210}$Pb and its subsequent decays as background sources
The next series of simulations investigated the decay of $^{210}$Pb, which is a long-lived low energy beta emitter ($\tau_1/2 = 22.2$ years, $Q_{\beta^-} = 63.5$ keV) which appears on surfaces exposed to air from the decay of radon. In the simulation, the $^{210}$Pb nuclei were placed inside the absorber volume, and the energy deposition in the absorber within 100 ms after the decay was collected. Since low energy electrons from the decay are fully stopped in the absorber and a surface contamination emits 50% of the secondaries into the surroundings of the detector, its background can be guessed from the bulk contamination. Due to the tiny overall mass of the detectors, a noticeable background contribution requires unrealistic bulk contamination of the gold of tens of Bq/kg.

For surface contaminations the situation is more critical. The simulation predicts that a surface contamination of $\sim 12$ mBq/cm$^2$ of $^{210}$Pb on all detectors combined induces a background on the level of the pile-up, i.e. 5 counts for ECHO-1K.
5. Uranium decay chain on copper surfaces in the detector setup

For this study, the detector pixel was surrounded by a copper tube. $^{238}$U nuclei were placed on the inside of tube and decayed in the simulation. The resulting daughter nucleus was also subject to the radioactive decay, thus the full decay chain was simulated. Fig. 2, shows the spectrum of the deposited energy of the secondary particles inside the detector. Assuming measured bulk contaminations in copper of 100 mBq/kg, the background due the uranium decay chain of $7.5 \times 10^{-4}$ events in the 10 eV around $Q_{EC}$ in the simulation of ECHO-1K is four orders of magnitude below the pile-up background.

6. Conclusion

We investigated the suitability of GEANT4 for the background simulations of the ECHO experiment and investigated the influence of several model contaminations of interesting background sources. For expected contamination levels in the experimental setup, these sources are well below the contribution of the $^{163}$Ho pile-up events. After successful mass separation in the implantation process, $^{166m}$Ho contamination of the implantation material is not relevant. Furthermore, standard contaminations of $^{238}$U and its daughter nuclei within copper do not contribute to the background in the endpoint region of the $^{163}$Ho EC. However, care has to be taken to avoid accidental contaminations during and the manufacturing process and storage, especially with $^{40}$K and $^{210}$Pb from radon exposure close to the detectors.

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References

[1] Gastaldo L et al. 2013 Nucl. Instr. Meth. Phys. Res. A 711 150
[2] Eliseev S et al. 2015 Phys. Rev. Lett. 115 062501
[3] Agostinelli S et al. 2003 Nucl. Instr. Meth. Phys. Res. A 506 250
[4] Allison J et al. 2006 IEEE Trans. Nucl. Sci. 53 270