Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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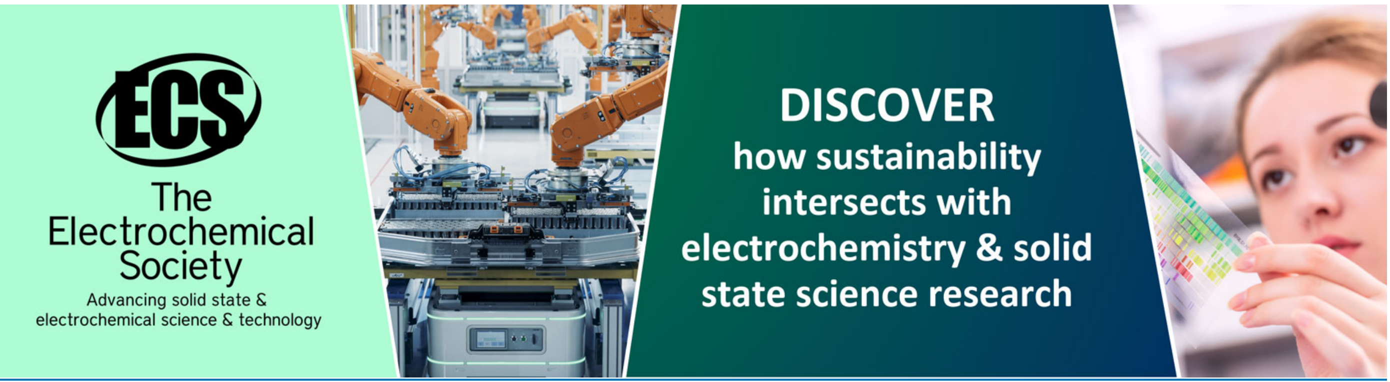
To cite this article: Stephan Scholl 2016 *J. Phys.: Conf. Ser.* **718** 062051



Background analysis and reduction for the ECHo experiment

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Abstract. ECHo-1k is a new experiment which is designed to investigate the electron neutrino mass from the calorimetric measurement of the electron capture spectrum of ^{163}Ho. In this presentation, we give an overview of our recent activities in the background analysis and reduction. Low background measurements of the radiopurity of the implanted Holmium in the ECHo detectors have been used to constrain the maximum activity of $^{166\text{m}}$Ho in the sample to be less than $\sim 0.4\,$mBq. On top of this, the background spectrum introduced by coimplanted ^{166}Ho in the absorber of the ECHo detectors has been obtained with a GEANT4 simulation showing that if the projected reduction of coimplanted $^{166\text{m}}$Ho to ^{163}Ho of 10^{-10} can be achieved, the background contribution of $^{166\text{m}}$Ho is negligible. Additional GEANT4 based Monte-Carlo simulations of test contaminations have been conducted. Simulations have been completed for internal ^{210}Pb contamination in the absorber and ^{55}Fe contaminations on the surface of the absorber.

1. Introduction

To achieve the optimal sensitivity for the ECHo experiment, several sources of background have to be analyzed and reduced. In the ECHo–1k phase, a total of 3.2×10^{10} ^{163}Ho electron capture (EC) events are collected within one year of measuring time using 100 detectors each loaded with 10 Bq of ^{163}Ho. The fraction of EC events in the last 10 eV before Q_{EC}, the region of interest (ROI), is very sensitive to the Q–value of the decay. After a long-standing confusion about the exact value of Q_{EC}, when the published values ranged from 2.3 keV to 2.8 keV, the issue has been settled by the measurement of the mass–difference $m_{^{163}\text{Ho}} - m_{^{163}\text{Dy}} = 2833 \pm 30 \pm 15\,\text{eV}$ with the Penning–trap mass spectrometer SHIPTRAP[1]. A fraction of $\sim 7 \times 10^{-10}$ ^{163}Ho EC events are expected within the ROI for this value of Q_{EC}. Thus a count rate of $\sim 6 \times 10^{-5}$ counts/eV/day/detector is expected in this part of the spectrum. In order to disentangle the signal from the background,the total background must be below this count rate. The background for the experiment comes from a variety of sources: (1) Irreducible background from the pile–up of ^{163}Ho ECs which depends on the activity of ^{163}Ho per detector, (2) bulk contaminations of the detectors which introduced by coimplanted isotopes with the ^{163}Ho like $^{166\text{m}}$Ho, (3) ambient radioactivity including the secondary radiation of fluorescence, PIXE and auger electrons after the primary decay and (4) cosmogenic muons and the cascades of secondary particles produced.

Monte–Carlo simulations are an important tool for the investigation of detector performance and background effects on the measurement. The high energy physics standard Monte–Carlo

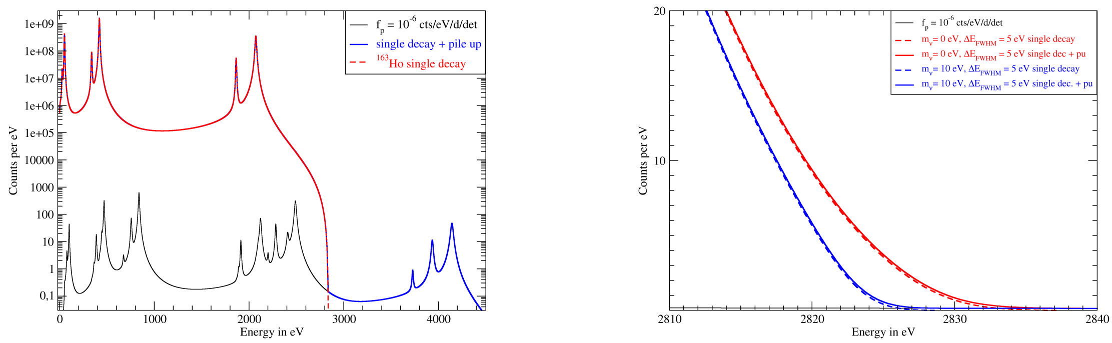

Figure 1. The ^{163}Ho spectrum for a pile–up rate of $f_p = 10^{-6}$ and a total number of 3.2×10^{10} ^{163}Ho decays. The left figure shows the single event contribution in red, the pile–up contribution in black and the sum in blue for $m_\nu = 0\,\mathrm{eV}$ and a detector resolution of $\Delta E_{\mathrm{FWHM}} = 5\,\mathrm{eV}$. The right figure zooms into the endpoint region. The red plot shows the spectrum for $m_\nu = 0\,\mathrm{eV}$, the blue one shows the spectrum for $m_\nu = 10\,\mathrm{eV}$.

simulation framework GEANT4.10.0.1[2, 3] and the ROOT framework for data processing and analysis are used as basis for our simulations. GEANT4 simulations for the ECHo experiment have to take into account the following peculiarities, (1) the energetic ROI in the ECHo experiment at 0–5 keV is very low with respect to the energy ranges used in GEANT4 applications, (2) the detector geometry of $\sim 200\,\mu\mathrm{m} \times \sim 200\,\mu\mathrm{m} \times 10\,\mu\mathrm{m}$ is tiny compared to standard sizes in high energy physics experiments, (3) the correct creation and propagation of secondary low energy particles in processes like fluorescence, ion sputtering and decay processes must be validated and (4) the sources of interest in GEANT4 like the EC of ^{163}Ho with forbidden K– and L–shell capture and the background from the decay of the long–lived isomer $^{166\mathrm{m}}$Ho are quite exotic in the context of standard applications in GEANT4.

2. Pile–up

Pile–up occurs when two decays within the same absorber cannot be resolved as separate events. Typically, two events cannot be resolved if the time difference between them is less than the rise–time τ_{rise} of the signal. The ECHo detectors are expected to be loaded with 10 Bq of ^{163}Ho, to provide an energy resolution of $\sim 5\,\mathrm{eV}$ and a signal rise time of $\sim 100\,\mathrm{ns}$. Thus the fraction of the indiscriminable pile–up events to all EC events is $f_{\mathrm{pu}} = A_{^{163}\mathrm{Ho}}\tau_{\mathrm{rise}} = 10\ \mathrm{Bq} \cdot 10^{-7}\ \mathrm{s} = 10^{-6}$, where $A_{^{163}\mathrm{Ho}}$ is the activity of ^{163}Ho per single detector and τ_{rise} is the rise–time of the signal. Near the endpoint of the spectrum of 2.833 keV, only a fraction of 3×10^{-10} of all events are pile–up events, as can be seen in Fig.1. This translates to a background due to pile–up of 2.6×10^{-5} counts/eV/day/detector, which is already $\sim 40\,\%$ of the total expected signal rate. The sum of all other contributions to the background must be reduced to a level below the contribution of the pile–up.

3. Background from coimplanted contaminants

Radioactive contaminants are present in the raw materials and may be further accumulated during the storage and the assembly of the experimental setup due to cosmogenic activation and exposure to Rn contaminated air and dust particles. The most sensitive parts of the ECHo

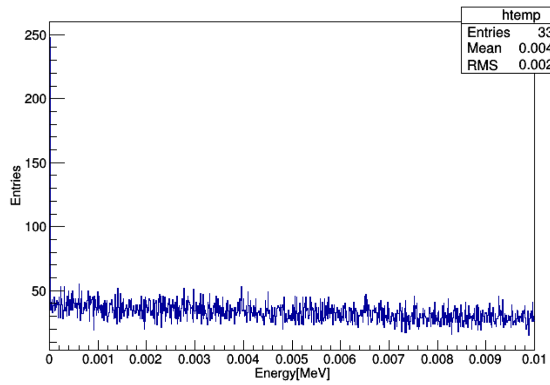

Figure 2. Energy deposition in the gold absorber of an ECHo detector for 10^6 $^{166\mathrm{m}}$Ho decays with a binning of 10 eV. A flat spectrum is observed across the ROI with 40 counts/ eV per 1000000 primary events, i.e. a fraction of 4×10^{-5} of all decays will be found within a 10 eV bin around the ROI.

detectors are the absorber and the sensor, other parts of the detector chips are either insensitive or energy depositions can be discriminated from events in the proper detector by pulse shape discrimination[4]. Dangerous bulk sources are radioisotopes coimplanted with ^{163}Ho in the detector chip[5]. $^{166\mathrm{m}}$Ho, a long–lived β–emitter ($\tau_{1/2} = 1200\,\mathrm{a}$, $Q = 1854.7$ keV) has two low energy β–decay branches($E_{\beta_{\mathrm{mean}}} = 8.38\,\mathrm{keV}$, $E_{\beta_{\mathrm{mean}}} = 19.02\,\mathrm{keV}$) which provide a dangerous background in the ROI of the ECHo experiment. This isotope is coproduced with ^{163}Ho in the neutron irradiation of erbium. After irradiation, the ratio of $^{166\mathrm{m}}$Ho to ^{163}Ho has been measured to be 10^{-5} which is reduced by mass separation to the order of 10^{-10} in the implantation process. The exact ratio of the implanted holmium has to be measured to infer the induced background. The $^{166\mathrm{m}}$Ho/^{163}Ho ratio is obtained by two measurements, the activity of the $^{166\mathrm{m}}$Ho is determined via γ–spectroscopy of the deexcitation γs with high purity Germanium (HPGe) detectors at the UGL Tübingen and at Felsenkeller at TU Dresden and the ^{163}Ho activity has to be seperately with neutron activation analysis (NAA) due to the low Q–value of the ^{163}Ho decay of 2.833 keV. $^{166\mathrm{m}}$Ho measurements with a sample of implanted Ho in gold have resulted in a preliminary upper limit on the $^{166\mathrm{m}}$Ho activity of 0.37 mBq (95% C.L.) which amounts to the presence of less than 2×10^7 atoms of $^{166\mathrm{m}}$Ho. Since the activation of gold prevents the measurement of the ^{163}Ho activity, a new sample is prepared where the holmium is implanted in a carbon matrix.

A simulation in GEANT4 has been setup for the internal contamination of the detectors with $^{166\mathrm{m}}$Ho in order to determine the induced background in the ROI around 2.5–3.5 keV. The geometry of a single detector was modeled in GEANT4 with an Au absorber of the size $190\,\mu\mathrm{m} \times 190\,\mu\mathrm{m} \times 10\,\mu\mathrm{m}$ connected by small gold stems to the Au:Er sensor. The $^{166\mathrm{m}}$Ho was placed in the middle plane of the absorber and its decay was handled by the *G4RadioactiveDecay* physical process which had to be modified. In Fig.2, the energy deposition in the absorber up to 10 keV of 10^6 simulated $^{166\mathrm{m}}$Ho decays is shown. With a ratio of $^{166\mathrm{m}}$Ho to ^{163}Ho of 10^{-10}, the background contribution of $^{166\mathrm{m}}$Ho is 10^{-10} counts/eV/day/detector, well below the background due to pile–up.

In GEANT4.10.0.1, the *G4RadioactiveDecay* process had to be modified since the decay of metastable isotopes in GEANT4 identified the metastable isotope in the decay process not by its excitation energy above ground state but by an index n of which was just a counter of the number of metastable states above ground level. Unless the index n was equal to 9, the

metastable isotope was forced to decay to its ground state via internal conversion. For the simulation, we modified the decay process that the long–lived metastable isotope $^{166\mathrm{m}}$Ho at 5.969 keV decayed correctly via beta–decay again.
Short lived β–emitters with low endpoint energies are dangerous contaminants. One isotope special interest is ^{210}Pb $((\tau_{1/2} = 22.2\,\mathrm{a},\ Q = 63.5\,\mathrm{keV})$ which is part of the uranium decay chain and can be deposited on surfaces from radon in the air. A simulation of ^{210}Pb and its daughter nuclei as a bulk contamination in the gold absorber of the detector was investigated. ^{210}Pb is an interesting sources since it can be build up by the exposure to Radon contaminated air during the storage of the detectors. In the simulation of ^{210}Pb as a bulk contamination, it was evenly distributed throughout the gold absorber of the detector. for a total activity of $A_{^{210}\mathrm{Pb}} = 5\,\mathrm{mBq}$, its induced background was as strong as the background due to the pile–up of ^{163}Ho events in the ROI. While the background in the ROI is flat, strong lines around 2.734 keV due to excitations of the M–shell in the Au of the absorber were observed. This amounts to only 5.0×10^{6} ^{210}Pb nuclei in the detector. Thus any contamination with ^{210}Pb and its progenitors has to be strictly avoided.

4. Ambient Radioactivity and Fluorescence

The electromagnetic physics lists provided with GEANT4 have been checked for their ability to reproduce the full spectra of fluorescence X–rays, Auger electrons and particle induced X–rays(PIXE) and ensure that the secondary electrons and X–rays are produced as dynamic particles with are propagated through the simulated setup.
The test setup was given by a detector made from gold beneath a very thin target which was hit by the test particle beam. The X-rays which were emitted perpendicular to the beam direction hit the gold detector and the type of particle, its kinetic energy and the deposited energy were collected into a detector spectrum. The energies and ratios of the given lines were then compared to the literature and were found to be in good agreement. The Penelope physics list and the LivermoreEm physics list provided dynamic secondary particle production with the expected energies and ratios between the different lines. For the simulations for the ECHo experiment, the LivermoreEm which includes more atomic shells for the calculation of the secondary particles was selected.
Radioactive decays in the surroundings of the the detectors will provide additional backgrounds. Direct hits of the primary decay products on the absorber or the detector will generally deposit too much energy to interfere with the small ROI of the ECHo experiment around 2.8 keV. However, the decays can produce secondary electrons, X–rays and even sputtered nuclei with rather low energies which can contribute to the background in the ROI of the ECHo experiment. For the investigation of such background contributions, the usage of Monte–Carlo simulations is mandatory. The reliability of the model of the physical processes in the simulation tool is of premier concern for the correct simulation of low energy backgrounds induced by secondaries as encountered in the setup of the ECHo experiment. The model has to be tested if it images the physical process well enough. With respect for the situation of the ECHo experiment, this requires that the model is valid down to energies in the keV range. Apart from testing the simulation code in general, this requires the setup of dedicated measurements to benchmark the simulation.
One study involved the common low energy calibration source ^{55}Fe as an external source, which can be easily crosschecked with measurements of an appropriate setup. In the case of ^{55}Fe on the surface of the detector, a total activity of $A_{^{55}\mathrm{Fe}} = 5.5\,\mathrm{mBq}$ is sufficient to provide a background of the strength of the pile–up of ^{163}Ho decays.

5. Muons

Another critical background contribution is given by the muons which are produced by the cosmogenic radiation in the upper atmosphere. The high energy cosmogenic muons can produce large showers of secondary particles as they pass the material of the experimental setup around the sensors, but the exact rate depends crucially on the geometrical details of the experimental setup. A rough estimate of the level of cosmogenic background which can be expected for the ECHo experiment can be taken from the background seen by the MIBETA experiment which reported a flat background of 1.5×10^{-4} counts/eV/day/detector while operating micro–calorimeters to determine the endpoint of the β–decay of ^{187}Re at 2.47 keV[6]. A cosmogenic background contribution on this level demands that the experimental setup is operated within an active muon veto and/or located in a deep underground laboratory. A simulation of the cosmogenic background seen in the ECHo setup is planned. Furthermore, a simulation of the muons and their secondary particle showers is required fro the design and the determination of the efficiency of the muon veto.

6. Conclusion

Background control and analysis is an important part of the efforts of the ECHo experiment. The material screening of the residual gold from the chip preparation with the HP–Ge detectors at UGL Tübingen and Felsenkeller Dresden has been completed. No lines from the decay of ^{166m}Ho have been detected in the two measurements, limiting the amount of ^{166m}Ho in the sample to be less than 2×10^7 atoms. In order to determine the ratio of ^{166m}Ho/^{163}Ho, a new sample has to be prepared to allow the determination of the activity of ^{163}Ho with neutron activation analysis. For the upcoming measurement, the HP–Ge detector at UGL Tübingen can be now operated with a recently installed muon veto around the setup. It has been verified that GEANT4 allows the simulation of radiactive background in the ECHo experiment, i.e. fluorescence, PIXE and Auger electron emission processes with propagating secondary particles is supported by GEANT4. This has been tested with simulations of calibration sources like ^{55}Fe. First simulation runs have been conducted with a simplified detector geometry and first results on the dangerous levels of contaminations like ^{166m}Ho and ^{210}Pb have been obtained. Further simulations on the full natural decay chains and contaminations like ^{40}K are under investigation.

Acknowledgments

Acknowledgments The ECHo experiment is funded by the DFG Research Unit FOR 2202 "Neutrino Mass Determination by Electron Capture in Holmium–163 ECHo".

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