Specific Heat of Holmium in Gold and Silver at Low Temperatures

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Abstract. The specific heat of dilute holmium alloys plays a major role in the optimization of low temperature microcalorimeters with enclosed \textsuperscript{163}Ho, such as the ones developed for the neutrino mass experiment ECHo. We investigate alloys with atomic concentrations of $x_{\text{Ho}} = 0.01\% - 4\%$ at temperatures between 10 mK and 800 mK. Due to the large total angular momentum $J = 8$ and nuclear spin $I = 7/2$ of holmium ions, the specific heat of Au:Ho and Ag:Ho depends on the detailed interplay of various interactions. This makes it difficult to accurately determine the specific heat of these materials numerically. Instead, we measure the specific heat of dilute holmium alloys by using three experimental set-ups optimized for different concentration and temperature ranges. The results from measurements on six holmium alloys demonstrate that the specific heat of these materials is dominated by a large Schottky anomaly with its maximum at $T \approx 250$ mK, which we attribute to hyperfine splitting and crystal field interactions. RKKY and dipole-dipole interactions between the holmium atoms cause additional, concentration-dependent effects. With regard to ECHo, we conclude that for typical operating temperatures of $T \leq 20$ mK, silver holmium alloys with $x_{\text{Ho}} \gtrsim 1\%$ are suited best.

Keywords: heat capacity, Schottky anomaly, dilute holmium alloys, metallic magnetic calorimeters, ECHo
1. Introduction

$^{163}$Ho is an unstable holmium isotope which undergoes electron capture with the energy $Q_{EC} = (2.833 \pm 0.030_{\text{stat}} \pm 0.015_{\text{syst}}) \text{ keV}$ \cite{1} available for the decay. Based on its half-life of $\tau_{1/2} = 4570 \text{ a}$, $2 \times 10^{12} \ 163^{\text{Ho}}$ atoms yield an activity of 10 Bq \cite{2}. Since more than 30 years this nucleus is considered to be the best candidate to be used in experiments for the determination of the effective electron neutrino mass \cite{3, 4, 5, 6, 7, 8, 9}. The best approach for this kind of experiment is to perform a calorimetric measurement of the electron capture spectrum, as was proposed in 1983 by De Rújula and Lusignoli \cite{3, 4}. Current technology is based on low temperature microcalorimeters \cite{10} where $^{163}$Ho atoms are enclosed in the particle absorber of the detector. Presently, two large experiments, namely ECHo \cite{11} and HOLMES \cite{12}, follow this approach.

As the name suggests, low temperature microcalorimeters are operated at very low temperatures below 100 mK. They typically have dimensions in the order of a few hundred micrometers and a thickness of a few micrometers. In these detectors, the energy released by the decay of implanted $^{163}$Ho leads to an increase in temperature, which is read out by a very sensitive thermometer. The temperature increase is proportional to the deposited energy and to the inverse of the total heat capacity of the detector. It follows that heat capacity is an important parameter for detector optimization.

In order to determine the heat capacity of the detector, it is necessary to gain a precise understanding of the contribution of the $\sim 10^{12}$ atoms of $^{163}$Ho, which are present in a dilute form in the absorber material. In commonly used hosts like gold and silver, holmium is present in the ionized state Ho$^{3+}$, which features a total electronic angular momentum of $J = 8$ and a nuclear moment of $I = 7/2$. Therefore, a non-negligible contribution due to magnetic interactions has to be expected.

The work we present was performed as a part of the detector optimization for the ECHo experiment \cite{11}. The ECHo experiment is designed to determine the effective electron neutrino mass using $^{163}$Ho enclosed in the particle absorbers of metallic magnetic calorimeters (MMCs). As temperature sensor, MMCs utilize a paramagnetic material sitting in a constant magnetic field. The temperature-dependent magnetization is then monitored using low-noise and high-bandwidth dc-SQUIDs \cite{13}, which provide the voltage signal to be amplified and read out. The necessary $^{163}$Ho source for the ECHo experiment was produced at the high-flux reactor at the Institut Laue-Langevin (ILL) and chemically extracted from an enriched $^{162}$Er target \cite{14}. To control precisely their localization, the $^{163}$Ho atoms are ionized and ion-implanted into the host. A mass separation step is added in between to assure high purity of the $^{163}$Ho and remove unwanted ionized species. This approach is used in ECHo and is also foreseen for HOLMES with some differences in the technological realization and, in particular, in the ion source \cite{15, 16}.

Here we present two approaches to determine the specific heat of several dilute alloys. The first approach determines the holmium contribution to the heat capacity
by comparing the signal size of two identical detectors, one with ion-implanted $^{163}$Ho and one without. The second method is a calorimetric measurement of the specific heat based on the relaxation method [17]. As a host material, the ECHo collaboration plans to use a thin silver layer in future, instead of previously used gold. Thus, we performed measurements on both potential alloys.

2. Theoretical Background

The heat capacity of a sample at constant volume is given by $C_V = (\partial U/\partial T)_V$, where $U$ symbolizes the internal energy. As the heat capacity at constant volume $C_V$ and at constant pressure $C_p$ is very similar for the samples considered here, we will not distinguish between $C_V$ and $C_p$ and omit the index. Since we are interested in the contribution of holmium to the heat capacity of gold and silver doped with holmium, we will in the following only discuss the intensive quantity $c_{Ho} = (C - C_M)/N$, where $N$ denotes the total number of holmium ions in the respective sample and $C_M$ ($M = Au, Ag$) the known electronic and phononic contributions of the undoped host material [18]. In doing so, minor changes of the sample’s electronic or phononic contributions due to the holmium doping are mapped to the individual holmium atoms. Hence, their interplay with the host material will be reflected adequately in $c_{Ho}$.

Most relevant for the description of the specific heat of holmium in metallic hosts at temperatures below 1 K are the hyperfine splitting and crystal field effects. As holmium concentrations in our samples are very low, we can describe the alloys as solid solutions and assume that the fcc structure of the host material is maintained [19]. The holmium occupies regular lattice places and three electrons of the outer shells delocalize in the conduction band, resulting in Ho$^{3+}$ ions. According to Hund’s rules, we therefore find $S = 2$, $L = 6$, and $J = 8$ for the spin, angular momentum, and total angular momentum quantum numbers. The partially filled inner 4f-shell is shielded by the fully occupied 5s- and 5p-shells and hence the resulting Hamiltonian accounting for hyperfine splitting is given by $H_{hf} \propto \vec{I} \cdot \vec{J}$, where $I = 7/2$ denotes the nuclear spin quantum number [20, 21]. A hyperfine energy level splitting in the range of 0.3 K$k_B$ is expected [22].

We should note here that a number of the results presented within this paper have been measured with $^{165}$Ho samples, while the ECHo experiment uses $^{163}$Ho. As both isotopes have the identical nuclear spin $I$ and an almost identical nuclear moment ($^{163}$Ho: 4.23 $\mu_N$, $^{165}$Ho: 4.17 $\mu_N$) [20], we do not expect noticeable differences in the specific heat data discussed here.

Besides the hyperfine splitting, we need to consider crystal field effects. The charge distribution of the electronic 4f shell has a complex shape described by moments of higher order and hence interactions with electric field gradients of the lattice break the 17-fold degeneracy of the $J = 8$ ground state leading to a number of multiplets. Simulations indicate that the lowest excited crystal field multiplet is located below 1 K$k_B$ and hence is the source of a Schottky anomaly in our temperature region of interest [23]. In fact, the hyperfine- and crystal field splitting cannot be separated from each other as they
are coupled in $J$ and we expect a single, more complex Schottky peak. Specific heat measurements of pure holmium support this [22].

Another observable effect originates from the pairwise interaction between holmium ions: Magnetic dipole-dipole interactions scale with $1/r^3$, where $r$ is the distance between the two holmium ions. Since the average distance $\hat{r}$ scales with $1/\sqrt{x_{Ho}}$, this interaction is concentration-dependent. As our data will show, contributions to the specific heat of a specific alloy will shift to lower temperatures for samples with lower concentration. The same is true for the RKKY-interaction [24, 25, 26], which also scales with $1/r^3$. However, since this interaction is mediated indirectly by conduction electrons, its strength also depends on the host material. In the case of pure metals (Au, Ag) doped with erbium, the magnetic interactions have been shown to be relevant at temperatures below 100 mK and are roughly 2–3 times stronger in silver than in gold [10, 27, 28].

Based on this information, we investigate the influence of holmium concentration $x_{Ho}$, temperature, and host material on the specific heat of dilute holmium alloys. A brief summary of these parameters follows:

**Holmium Concentration** In the ECHo experiment, each detector will contain about $2 \times 10^{12}$ holmium ions corresponding to an activity of 10 Bq. The ions will be implanted in an area of $150 \times 150 \mu m^2$, resulting in a concentration of about 1% for an estimated implantation depth of about 5 nm [29]. Nevertheless, we investigated samples with atomic holmium concentrations between $x_{Ho} = 0.0162\%$ and 4%, in order to obtain information on the concentration dependence.

**Temperature** In ECHo, the MMC detectors containing $^{163}$Ho are operated at a temperature of about 20 mK. We have performed heat capacity measurements between 10 mK and 800 mK in order to obtain a more detailed understanding of the different contributions to the specific heat. This broad temperature range allows us to precisely determine the position of the Schottky peak and characterize the tail towards low temperature.

**Host Material** The initial choice for the host material for ECHo was gold, resulting in a number of studies of alloys of gold and holmium. However, the nuclear quadrupole moment of gold may affect the detector’s performance. This has been observed for Au:Er alloys [30, 31]. As a result, new prototypes of MMCs for the ECHo experiment have recently been produced, in which $^{163}$Ho was implanted into a thin silver layer (of the order of 100 nm) grown on the original gold absorber layer. Here, we present a comparison of Au:Ho and Ag:Ho.
Table 1. Overview of the different samples S1 – S6 investigated in this work. For each sample, the host material, its holmium concentration $x_{\text{Ho}}$, and the platform used for the respective measurement are given.

| Name | Host Material | $x_{\text{Ho}}$ [%] | Platform |
|------|---------------|----------------------|----------|
| S1   | Au            | 0 – 4                | 1        |
| S2   | Au            | 1.2                  | 2        |
| S3   | Au            | 0.12                 | 2        |
| S4   | Ag            | 1.66                 | 2        |
| S5   | Ag            | 0.184                | 2        |
| S6   | Ag            | 0.0162               | 3        |

3. Experimental

3.1. Samples

We produced six samples, each based on gold (6N) or silver (5N) and doped with holmium at a (sub-)percent level. An overview appears in table 1.

Sample 1 is the absorber of a metallic magnetic calorimeter, which is made of electroplated gold with ion-implanted $^{163}$Ho. The ion implantation was done at the 30 kV magnetic mass separator RISIKO facility in Mainz, Germany [32]. The sample’s holmium concentration was estimated by activity measurements (0.9 Bq) and through SRIM simulations [33] of the implantation profile [29]. As a result, we expect a spatially varying concentration ranging from 0 % to 4 % for this sample, where 90 % of the ions are located in regions with holmium concentrations above 0.4 %.

All other samples S2 – S6 were prepared by arc-melting in a clean argon plasma resulting in a homogeneous holmium concentration throughout the sample. For these alloys we used the stable isotope $^{165}$Ho, which has a natural abundance of 100 %. The holmium concentrations $x_{\text{Ho}}$ of the gold-based samples S2 and S3 were determined by the mixing ratios of the source materials with an estimated accuracy of about 10 %. In order to obtain the holmium concentration of samples S4 – S6, we performed magnetization measurements‡ between 2 K and 300 K. Using the crystal field parameters $W = -0.373$ and $x = -0.375$ for holmium in silver [23, 34], $x_{\text{Ho}}$ could be determined within an estimated error of 5 %.

3.2. Gradiometric microcalorimeter

A precise measurement of the contribution of implanted $^{163}$Ho to the total heat capacity of an MMC can be performed by monitoring the change of temperature of two identical pixels under the same deposition of energy, where one pixel is implanted with $^{163}$Ho and the other is not. In this way, we benefit from the gradiometric layout of the underlying double meander, where both pixels are read out by the same SQUID [10, 35]. In the

‡ MPMS XL-5 SQUID Magnetometer by Quantum Design, Inc., 10307 Pacific Center Court, San Diego, CA 92121, USA.
ECHo-1k chip, which was used here, seven such pixel pairs fulfill this requirement, in that only one of the two pixels has $^{163}$Ho implanted in the gold absorber [11]. In the actual ECHo experiment these asymmetrically doped meanders are used for an in-situ background measurement during data acquisition.

One of these seven asymmetric pixel pairs present on the ECHo-1k detector chip was used for the heat capacity experiment. The 5.89 keV $K_\alpha$ x-ray photons of an external $^{55}$Fe source were used to probe the thermal response of both pixels under investigation. A schematic drawing of the experimental set-up appears in figure 1. The deposition of energy $\Delta E$ in the detector leads to an increase of temperature $\Delta T = \Delta E/C$, where $C$ is the total heat capacity of the detector. This change of temperature leads to a change in magnetization, which is detected as a change of magnetic flux in a suitable superconducting coil. As flux to voltage converter a two-stage SQUID set-up operated in flux-locked-loop mode is used [13]. The voltage signal has the shape of a pulse, where the amplitude is proportional to the initial temperature increase of the detector and is thus also proportional to the deposited energy. The rise time depends on the electron-spin coupling in the sensor, while the decay time is defined by the ratio of the detector’s heat capacity and the thermal conductance of the link to the heat bath. An additional contribution to the detector’s heat capacity due to the implanted $^{163}$Ho leads to a smaller signal size and to a larger decay time constant.

Figure 2 shows two curves acquired with the two pixels of the discussed gradiometric detector at a temperature of 58 mK. Each curve is the average of about 1000 single $K_\alpha$ pulses. The signal corresponding to the detector without $^{163}$Ho appears in black,
Figure 2. Comparison of two signals for an energy input of 5.89 keV at $T_b = 58$ mK originating from a radioactive $^{55}$Fe source. Each curve is the result of averaging over roughly 1000 pulses. A clear difference in pulse height and decay time due to the implanted $^{163}$Ho is observable.

while the one corresponding to the detector with $^{163}$Ho appears in blue. Since all the components of the two pixels are identical except for the $^{163}$Ho, the additional contribution due to the implanted $^{163}$Ho ions to the total heat capacity of the detector causes the difference in the pulse profile. In particular, the Ho-implanted pixel shows a lower pulse amplitude and an additional exponential decrease for $t \lesssim 0.1$ ms, which is even more visible at higher bath temperatures due to the larger Schottky contribution of $^{163}$Ho. Hence, we attribute this decay to internal relaxations within the holmium spin system. The portion of the blue pulse after this initial steep decay contains the full information on the holmium subsystem. Thus, we extract a pulse height (red arrows) fully sensitive to the holmium subsystem by extrapolating an exponential fit (red dot-dashed lines in figure 2) back to $t = 0$ ms. By experimental determination of the parameters of the read-out chain and the thermodynamic properties of the detector, a voltage to temperature conversion is calculated and the heat capacity of both pixels is extracted. In particular, we use the difference in pulse height to extract the heat capacity contribution of the $^{163}$Ho ions and then normalize this by means of the measured activity (see section 3.1) and the known decay half-life.

3.3. Direct Calorimetric Measurements

In order to determine the specific heat of samples S2 – S6 between 20 mK and 800 mK, we used two different set-ups based on the well-established relaxation method: The
samples are placed on a platform using an adhesive ($\approx 0.5\text{mg}$ of Apiezon N grease$^\S$) and the time-resolved temperature response of the platform during the application of a well-defined heat pulse is monitored. A standard pulse-fitting method is applied to extract the heat capacity following the concept of Hwang et al.$^\text{[17]}

Platform 2 is based on a commercially available system$^\parallel$ with an addenda heat capacity of about $4\text{nJ/K}$ and a temperature resolution of $1\mu\text{K}/\sqrt{\text{Hz}}$ at $50\text{mK}$. Typically, we are limited to temperatures above $30\text{mK}$ with this platform. Further details of the set-up are laid out elsewhere$^\text{[36, 28]}$

Platform 3 is based on a novel micro-fabricated chip with a Ag:Er thermometer and SQUID readout that has been developed in house$^\text{[28]}$. The platform features a very low addenda heat capacity of less than $0.4\text{nJ/K}$ and a temperature resolution of $30\text{nK}/\sqrt{\text{Hz}}$ at $50\text{mK}$, allowing us to measure samples with very low heat capacities. In particular, it enabled the measurement of sample S6.

4. Results and Discussion

4.1. Specific Heat of Au:Ho

The specific heat per holmium ion of the three Au:Ho samples appears in figure 3 together with the published specific heat of bulk holmium$^\text{[22, 37]}$. The indicated error bars for sample S1 are based on a comparison of eleven symmetric pixel pairs on the same ECHO-1k detector chip and their observed differences in pulse height for an equal energy input. Additionally, errors in the experimentally determined parameters used for voltage to temperature conversion were taken into account. The error bars of the other samples represent a statistical error from averaging over typically 10 repeated measurements. Scaling errors for the individual data points due to the uncertainty in holmium concentration (as discussed in section 3.1) are negligible for our analysis and not included.

The specific heat of bulk holmium is well understood$^\text{[22]}$. Its Schottky anomaly has a peak of roughly $0.9k_B$ at $250\text{mK}$, which is almost entirely caused by magnetic hyperfine splitting in combination with crystal field effects, since the Néel temperature of holmium is $133\text{K}$$^\text{[38]}$ and the $4f$ moments of the holmium ions cannot be thermally excited at the temperatures of interest, below $1\text{K}$.

We start the discussion of our results with sample S2. The general shape of its specific heat curve resembles that of bulk holmium. At first glance, this is surprising given the difference in holmium concentration of two orders of magnitude. However, the similarity is understandable since in both cases the hyperfine splitting dominates the specific heat as the magnetic correlations suppress the dynamics of the $4f$ magnetic moments.

$^\S$ Apiezon Products, MI Materials Ltd, Hibernia Way, Trafford Park, Manchester M32 0ZD, United Kingdom

$^\parallel$ DR Heat Cap Puck QD-P107H by Quantum Design, Inc., 10307 Pacific Center Court, San Diego, CA 92121, USA.
A closer inspection reveals that the maximum of the Schottky anomaly is slightly reduced and occurs at somewhat higher temperatures with respect to bulk holmium. Since the effective crystal fields in the alloy Au:Ho differ from bulk holmium, this can be understood qualitatively. The most notable difference, however, is that a large additional contribution to the specific heat appears at temperatures well below 100 mK. We attribute this to holmium ions, whose magnetic correlations are small enough to contribute to the dynamics at these temperatures. Due to the random spatial distribution of ions, the interaction strengths vary, which leads qualitatively to the observed low temperature tail.

This explanation is supported by the fact that for sample S3, where the concentration is lowered by another order of magnitude, this contribution to the specific heat is further enhanced. Due to the reduced holmium concentration in this sample and the resulting increase of the average distance between holmium ions, more and more magnetic moments can contribute to the dynamics. As also observed in sample S2, there is a slightly enhanced contribution compared to bulk holmium on the high temperature side of its maximum. In addition, the maximum itself is also shifted towards higher temperatures and lower values.

Of particular interest is the comparison with sample S1, since both the sample preparation and measurement technique are completely different. In addition, we are working with the radioactive holmium isotope $^{163}$Ho. Despite these differences, we observe a remarkable quantitative agreement to the data of sample S2. This agreement

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**Figure 3.** Measured specific heat of samples S1, S2, and S3. The solid line represents the specific heat of bulk holmium.
has two important implications: First, it shows that possible defects generated by the implantation procedure play only a marginal role for the specific heat. Second, since platform 1 determines the specific heat on a timescale of ms, while measurements performed with platform 2 are sensitive on a timescale of seconds to minutes, we conclude that the observed degrees of freedom are the same and the contributing degrees of freedom relax thermally within ms.

As mentioned in section 3.1, the holmium concentration varies spatially between 0% and 4% in sample S1 [29]. The comparison with sample S2 indicates that the effective concentration seems to be close to 1.2% for sample S1.

4.2. Specific Heat of Ag:Ho

Figure 4 shows the specific heat per Ho ion for the Ag:Ho samples S4, S5, and S6. For comparison, we also display the specific heat of bulk holmium and of sample S2.

In silver holmium alloys we recognize many of the features we observed for holmium in gold: The high temperature region is almost independent of the concentration while at medium and at low temperatures we see the same concentration-dependent effects.

However, two differences between gold and silver as host material stand out. For that, we compare first samples S2 and S4, which have a similar concentration but a different host material. They show a difference in the location and height of the main Schottky peak. In order to understand this effect, we performed simulations for holmium
ions in both gold and silver, based on a simplified model only including hyperfine splitting and crystal field effects. We found that for Au:Ho, the maximum of the Schottky anomaly is shifted by 25 mK towards higher temperatures and is $0.07 \ k_B$ lower compared to Ag:Ho. Since this matches almost perfectly with the observed differences between samples S2 and S4, we conclude that indeed the difference in the crystal field in the two host materials is responsible for these effects and may also be responsible for the shift with respect to bulk holmium.

The second observation is that already at lower holmium contents the concentration-dependent broadening of the Schottky peak in silver is equivalent to the broadening in gold, indicating a somewhat stronger RKKY interaction in silver. A similar trend was reported for Er ions in gold and silver [39].

4.3. Implications for the ECHo Project

Our analysis of the specific heat of dilute alloys of holmium in gold and silver results in a number of implications for the ECHo project. These relate to the three parameters mentioned in chapter 2.

Holmium Concentration  The holmium concentration of the alloys has a direct impact on the specific heat of the material. At temperatures of $T \lesssim 50 \text{ mK}$, the specific heat per holmium ion of alloys with a high $x_{\text{Ho}}$ is lower than that of alloys with a lower $x_{\text{Ho}}$. Thus, a high concentration of holmium ions is preferable. Comparing sample S4 to bulk holmium indicates that a concentration $\gtrsim 2\%$ does not yield further improvements regarding the low temperature specific heat. The results of the gold-based sample S2, on the other hand, still display a difference in height and slope, indicating that a further increase in $x_{\text{Ho}}$ might be beneficial. This is a consequence of the stronger RKKY-interaction in silver-based alloys. These limits are reachable with current implantation techniques.

Temperature  We observe a large Schottky anomaly with a maximum at roughly 250 mK for all samples under investigation. The typical operating temperature of MMCs ($T \leq 20 \text{ mK}$) is in the regime where the contribution to the total heat capacity due to the presence of $^{163}\text{Ho}$ ions is much smaller than at the peak. In addition, due to the good agreement between the measurement performed with the gradiometric microcalorimeter and the one performed through direct calorimetric measurements, we can state that contributions due to defects induced by the implantation process, if any exist, are marginal compared to the magnetic interactions of the holmium ions.

Host Material  Our experiments have demonstrated that the choice of host material affects both the peak of the Schottky anomaly at around 250 mK, and the low temperature flank at $T \lesssim 20 \text{ mK}$. In general, silver seems to be preferable, since at

¶ These simulations are based on unpublished work by S. Hähnle.
low temperatures, the specific heat of silver alloys is lower than that of gold alloys with an identical holmium concentration. In order for the detector to maintain good stopping power when using silver, a thin layer of Ag:Ho may be surrounded with gold.

In addition to these three parameters regarding the specific heat of holmium alloys, our data allow us to draw conclusions regarding the total number of holmium ions which may be implanted into an ECHo absorber. This number is limited by the goal of keeping the heat capacity contribution of the implanted $^{163}$Ho ions below the heat capacities of the paramagnetic sensor and of the absorber material. Our measurements of the Au:Ho sample S1 yield a heat capacity of 3.3 pJ/K at 20 mK for the non-implanted pixel of the gradiometric set-up. For the specific heat per $^{163}$Ho ion, we obtain a value of 0.05 $k_B$ at $T = 20$ mK (see figure 3). The foreseen activity of the ECHo experiment is 10 Bq per pixel, which is equivalent to $2 \times 10^{12}$ $^{163}$Ho ions. Thus, our measurements show that the implanted ions will increase the specific heat per pixel by only about 42%.

5. Conclusion

The knowledge of the heat capacity of dilute alloys of holmium in host materials such as gold and silver is a vital information for the optimization of the metallic magnetic calorimeters developed for the ECHo experiment. We performed heat capacity measurements of three Au:Ho alloys with concentrations of 0 – 4%, 1.2%, and 0.12% and of three Ag:Ho alloys with concentrations of 1.66%, 0.184%, and 0.0162%. For all samples we observed a large Schottky anomaly centered at about 250 mK and reaching a height of about 0.9 $k_B$, similar to the one measured for bulk Ho. The shape of the Schottky anomaly depends on both the holmium concentration and the host material.

The results demonstrate that at the typical operating temperature of MMC detectors the specific heat contribution of holmium ions is sufficiently low that the ECHo experiment can be carried out with the foreseen activity of 10 Bq per pixel. Additionally, our measurements demonstrate silver to be the more suitable host material in terms of heat capacity.

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