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Simulation and optimization of the implantation of holmium atoms into metallic magnetic microcalorimeters for neutrino mass determination experiments

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ABSTRACT

Several novel experiments designed to investigate the electron neutrino mass in the sub-eV region are based on the calorimetric measurement of the ^{163}Ho electron capture spectrum. For this the ^{163}Ho source, with a required activity of the order of 1 to 100 Bq, needs to be enclosed in the detector, having a volume smaller than 10^{-3} mm^3. Ion implantation is presently considered to be the most reliable method to enclose this source in the detector homogeneously distributed in a well defined volume.

We have investigated the distribution of implanted holmium ions in different target materials and for different implantation energies by means of Monte Carlo simulations based on the SRIM software package. We show that, for a given implantation energy, a given target material and implantation area, the number of holmium ions that can be implanted in a single implantation run is limited. We discuss possible methods to overcome this saturation limit in order to fabricate detectors with an enclosed ^{163}Ho source of the activity required by the experiments.

1. Introduction

The calorimetric measurement of the electron capture spectrum of ^{163}Ho is a promising method to determine the electron neutrino mass [1,2]. The nuclide ^{163}Ho is the best candidate for such experiments among the electron capture decaying nuclides because it exhibits the lowest known energy that is available for the decay, namely $Q_{EC} = 2.833 \pm 0.030_{stat} \pm 0.015_{syst}$keV [3], and thus the relative statistical weight at the endpoint is highest. In such a measurement, the slight deviation of the electron capture spectrum at the endpoint due to a finite neutrino mass is measured. This approach was proposed many years ago [1], but only recently the much improved performance of novel low temperature microcalorimeters has reached a point where a competitive experiment for the determination of the electron neutrino mass by measuring a high resolution ^{163}Ho spectrum has become feasible. Low temperature microcalorimeters are energy dispersive detectors operated at mK temperatures where an energy deposition leads to a small increase of temperature which is measured by very sensitive sensors [4]. This increase of temperature scales proportional to the inverse of the detector heat capacity. Therefore, a small heat capacity is an important property of low temperature microcalorimeters and accordingly, these detectors are typically very small. The first ^{163}Ho spectrum with high resolution was obtained using metallic magnetic calorimeters (MMCs) [5,6]. In this pilot experiment ^{163}Ho atoms were enclosed in a particle absorber made of gold with a total volume of less than 1/1000 mm^3 which is thermally connected to a paramagnetic temperature sensor which is located in a small magnetic field [7]. Today, low temperature microcalorimeters are the detectors of choice for three large international collaborations aiming at the investigation of the electron neutrino mass in the sub-eV range via the analysis of the endpoint region of the ^{163}Ho electron capture spectrum.

The ECHo [8] (Electron Capture ^{163}Ho experiment) collaboration is planning to use arrays of metallic magnetic calorimeters [5]. In contrast, the HOLMES [9] (HOLMium Experiment for neutrino mass Search) collaboration as well as the NuMECS [10] (Neutrino Mass via Electron Capture Spectroscopy) collaboration plan to use transition edge sensor (TES) [11,12] arrays.

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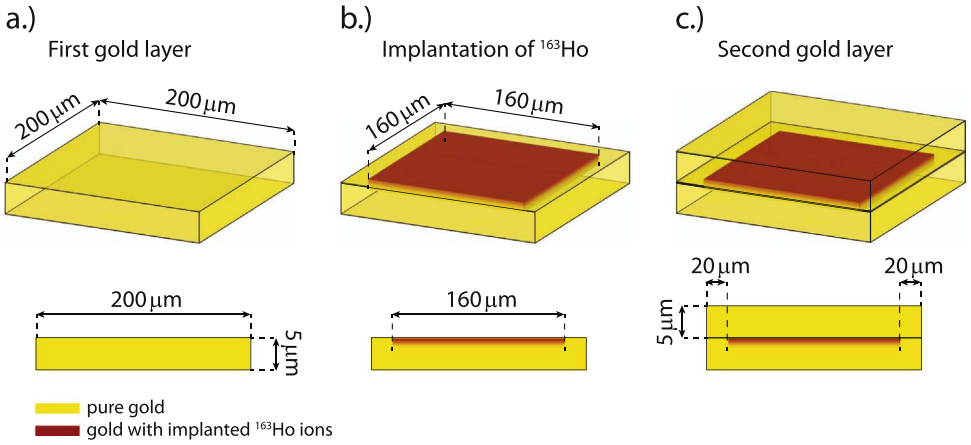

Fig. 1. Fabrication steps of the detector absorbers for the ECHo experiment with embedded ^{163}Ho source: a) A 200 µm × 200 µm × 5 µm large first gold layer is microfabricated. b) The ^{163}Ho ions are implanted into the gold layer within a reduced implantation area of 160 µm × 160 µm. c) A second gold layer with same dimensions as the first one is deposited on top. After this last step, the ^{163}Ho source is fully enclosed inside the absorber.

To perform a calorimetric measurement where all the energy released in the decay minus the energy taken away by the electron neutrino is detected, the ^{163}Ho source has to be enclosed in the particle absorbers of the microcalorimeters and surrounded by enough absorber material so that any electron and photon emitted in the ^{163}Ho decay is stopped in that volume. This is essential, since any form of energy losses other than that for neutrinos may cause systematics for the experiment. While the NuMECS collaboration proposed to incorporate the ^{163}Ho in the detectors by depositing drops of a solution containing this isotope into nanoporous gold absorbers [13], the ECHo and HOLMES collaborations follow the strategy to implant ^{163}Ho ions directly into the absorbers as it was done in the pilot experiment.

One big advantage of ion implantation is that radioactive nuclides which could be present in the source material following the production of ^{163}Ho or in the carrier material, such as ^{166m}Ho [14], are removed by mass selection during the implantation process [15]. This aspect is very important in particular for ^{166m}Ho since this holmium isotope cannot be separated chemically from ^{163}Ho and due to its inconvenient half-life of about 1200 years ^{166m}Ho residing inside the absorber would lead to an undesired background in the spectrum.

The ECHo collaboration is aiming for an activity of the order of 10 Bq of implanted radioactivity per individual detector pixel in order to keep the contribution to the background due to unresolved pile-up sufficiently low [16]. Therefore, about 2×10^{12} ^{163}Ho ions have to be implanted homogeneously within the central 160 µm × 160 µm area of a gold absorber film of 5 µm thickness and 200 µm × 200 µm overall size. This gold film shall afterwards be covered with a second 5 µm thick gold layer [7]. Fig. 1 shows the steps to embed the ^{163}Ho source within the detector absorbers. After those fabrication steps, the ^{163}Ho ions are fully enclosed within the absorber and surrounded by at least 5 µm of gold in each direction. In this way, it is ensured that all the energy emitted in the ^{163}Ho electron capture process, minus the energy taken away by the electron neutrino, is deposited within the absorber volume. In fact, the most penetrating particles emitted during this process are photons with an energy of about 2 keV, having an attenuation length in gold of $\lambda = 0.54$ µm, which is almost a factor of 10 smaller than the absorber thickness. The embedded ^{163}Ho source should be as homogeneously spread as possible within the central part of the absorber in order to stay in the limit of a solid solution of holmium in gold, where the system does not phase separate into regions of different stoichiometry [17,18]. This requirement, together with the rather large number of implanted ions that is necessary for obtaining 10 Bq, is a challenge for the optimization of the implantation process. In the following we will briefly review the relevant processes which occur when massive ions with considerably high kinetic energy impact on surfaces and we will present the results of simulations of the implantation processes under different conditions. On the basis of these results, we discuss possible methods to optimize the ^{163}Ho implantation process as part of the development work of the ECHo collaboration.

2. Simulations with SRIM

For the ECHo experiment we aim to reach a dilute concentration of ^{163}Ho ion-implanted in gold, which corresponds to a local concentration of up to 1%. In order to calculate the distribution of the implanted ions inside the absorber we have performed Monte Carlo simulations calculating the stopping range and straggling of an ensemble of energetic ions in matter. The calculations are based on SRIM[1] [19], a collection of software packages using a quantum mechanical treatment of ion-atom collisions. Besides SRIM, a couple of other similar Monte Carlo programs are available too, such as for example TRIDYN [20] and SDTrimSP [21]. However, we decided to use SRIM since in previous calculations we observed a very good agreement between SRIM simulations and experimental data for situations where atomic as well as molecular ions with masses between 1 u and 56 u and energies ranging from 13 keV to 150 keV impacted into microcalorimeter absorbers made of gold and of aluminum-coated gold [22].

In the simulations presented here, ions of the stable isotope ^{165}Ho, which are well-defined in SRIM, were accelerated up to 180 keV and brought to impact on layers of the different metals: gold, aluminum and silver as well as dilute alloys of holmium in gold, Au:Ho. The study was analyzed to reveal the relevance of the different processes which can occur after the impact of the massive ions.

When an incoming ion hits a target, it penetrates up to a certain depth depending on the type of ion, its energy and the target material. On its way, elastic and inelastic scattering processes with the target atoms take place, which lead to a change of direction of motion. In the ideal case, the penetrating ion stops inside the target. However, during the collisions, it can also happen that the ion changes its direction of motion in such a way that it leaves the target again and gets backscattered. Every backscattered ion obviously decreases the final number of implanted ions in the target. Another process that can occur following such collisions is that a recoiling ion or atom collides with a target atom (or atoms) near the surface and thereby transfers enough energy, such that the surface atom leaves the target. Such a removal of target atoms from the surface caused by incoming ions is called sputtering and obviously leads to a loss of target material. Moreover, not only target atoms but also previously implanted ions (in our case

[1] SRIM - The Stopping and Range of Ions in Matter, licence-free software, www.srim.org