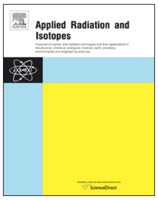
Applied Radiation and Isotopes 112 (2016) 165–176

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso



The Dortmund Low Background Facility — Low-background gamma ray spectrometry with an artificial overburden

Holger Gastrich [a], Claus Gößling [a], Reiner Klingenberg [a], Kevin Kröninger [a], Till Neddermann [a], Christian Nitsch [a,*], Thomas Quante [a], Kai Zuber [b]

[a] Technische Universität Dortmund, Lehrstuhl für Experimentelle Physik IV, Otto-Hahn-Str. 4, 44221 Dortmund, Germany
[b] Technische Universität Dresden, Institut für Kern-und Teilchenphysik, Zellescher Weg 19, 01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form
29 February 2016
Accepted 23 March 2016
Available online 25 March 2016

Keywords:
Low-background gamma ray spectrometry
Cosmic-muon veto
Background-reduction techniques
HPGe detector

ABSTRACT

The Dortmund Low Background Facility is an instrument for low-level gamma ray spectrometry with an artificial overburden of ten meters of water equivalent, an inner shielding, featuring a neutron absorber, and an active muon veto. An integral background count rate between 40 keV and 2700 keV of (2.528 ± 0.004)counts/(kg min) enables low-background gamma ray spectrometry with sensitivities in the range of some 10 mBq/kg within a week of measurement time.

1. Introduction

Modern gamma ray spectrometry is used in a variety of applications, ranging from monitoring of environmental samples to contamination control and material assaying for the usage in physics experiments. The latter is especially important for experiments built to search for rare phenomena like interactions of hypothetical WIMP particles in Dark Matter searches (Cline, 2014), neutrinos in general or neutrinoless double beta-decay (Barabash, 2010). The signals in such experiments are expected in the range of 1–5 MeV, i.e. the energy range of nuclear reactions. Furthermore, the expected event rates of the searched-for signals are as low as a few per day or even a few per year, depending on the physics case. Consequently, the background contributions, in particular those due to the intrinsic contamination of the detector or shielding materials, have to be kept as low as possible. Residual contaminations have to be known precisely so that background contributions in physics runs can be determined, e.g. by using Monte-Carlo simulations.

One such ultra-low-background project is COBRA, a future experiment with the aim to search for neutrinoless double beta-decay in several different isotopes using CdZnTe semiconductor detectors (Ebert et al., 2015). Since November 2013, the COBRA collaboration has operated a fully functional demonstrator with an array of 64 detectors at the Laboratori Nazionali del Gran Sasso (LNGS) underground laboratory (Ebert et al., 2016). An important keystone of the R&D phase of the COBRA experiment is the preselection of suitable materials based on in-depth material screening and radiopurity assays. Materials can be screened with very high sensitivity at ultra-low-background gamma ray spectrometry facilities such as the LNGS underground laboratory. By the rock overburden of 3800 m of water equivalent (m.w.e.) the muon flux is suppressed by six orders of magnitude (Bellini et al., 2012). Such laboratories can reach sensitivities as low as 10 μBq/kg for the natural occurring radionuclides (uranium and thorium) with the disadvantage of rather limited availability, long measuring periods and high construction costs (Heusser et al., 2006).

The Dortmund Low Background Facility (DLB) is a low-level gamma ray spectrometry laboratory designed for the detection of faint traces of radioactivity, and therefore enabling the screening of materials with a very high sensitivity with the initial motivation to support the COBRA collaboration. It is built above ground with an artificial overburden. Its high-purity germanium (HPGe) detector is installed in a multilayer inner shielding designed for surface operation and situated under nearly 400 t of overburden, corresponding to 10 m.w.e. of coverage. Between the inner shielding and the artificial overburden, an active muon veto consisting of plastic scintillators is used to suppress the muon-induced contribution to the integral background by approximately one order of magnitude. Detection limits in the range of several mBq/kg can be obtained for the primordial radionuclides from uranium and thorium. The facility is thus suited for radiopurity assays and material pre-selection.

---

[*] Corresponding author.
E-mail address: christian.nitsch@tu-dortmund.de (C. Nitsch).

http://dx.doi.org/10.1016/j.apradiso.2016.03.025
0969-8043/© 2016 Elsevier Ltd. All rights reserved.

In Section 2, a brief overview of the sources of background radiation for gamma ray spectrometers is given and concepts how to shield against these are introduced. The experimental setup, including the shielding concept and the readout chain of the gamma ray spectrometer, is described in Section 3. In Section 4 the spectroscopic properties of the detector system are presented. Section 5 summarizes the background level obtained with the DLB and discusses the remaining peaks in the background spectrum. The detection limits, reached with the current setup, are also presented. A summary is given in Section 6.

2. Sources of background radiation and design considerations

Background reduction is a crucial task for all gamma ray spectrometry laboratories aiming for sensitivities better than 1 Bq/kg. The sources of background radiation for a low-level gamma ray spectrometer can roughly be categorized into two groups: One are gamma rays from naturally occurring radioactivity including the radioimpurities of the detector setup and its environment, the other are airborne radon and cosmic ray induced gamma rays as well as direct interactions with atmospheric particles.

2.1. Environmental radioactivity

The major sources of environmental radioactivity are almost exclusively gamma rays from the ^{235}U, ^{238}U and ^{232}Th decay chains and ^{40}K. The starting nuclides of those decay chains as well as ^{40}K are primordial nuclides that have existed since the beginning of the stellar nucleosynthesis. They can be found in many minerals and building materials. Table 1 gives values for their element's natural abundance in the earth's crust (Haynes, 2015) as well as the corresponding specific activities of the three most prominent sources for background (^{238}U, ^{232}Th and ^{40}K). The concentrations vary for different materials, with the highest activities found in granites (Heusser, 1995).

Although the surrounding of most spectrometers (e.g. concrete walls) can have rather high concentrations of primordial radionuclides, gamma rays from their decays can be shielded sufficiently by extra shielding of high-*Z* materials. It is recommended to use 10–15 cm of lead to shield the detector's vicinity. This amount of lead is sufficient to decrease the intensity of 3 MeV gamma rays by about three orders of magnitude. Photons with lower energies are even more suppressed. On the other hand, more lead can increase the background contribution from tertiary neutrons induced by cosmic ray muons via muon capture or by photonuclear reactions (Gilmore, 2008).

2.1.1. Airborne radon

Secular equilibrium, i.e. the state in which the activities of all daughter nuclides are equal to the activity of their relative parents, is rarely achieved for the primordial decay chains. Radon isotopes (especially ^{220}Rn and ^{222}Rn), for example, can escape from the matrix by recoil on ejection of the alpha particle or by diffusion, and thereby break the equilibrium of the decay chain within the matrix.

The radon isotope ^{222}Rn, originating from the ^{238}U decay chain, decays via ^{214}Pb (with 351.9 keV and 295.2 keV being the most prominent gamma rays) and ^{214}Bi (with 609.3 keV, 1764.5 keV and 1120.3 keV as most prominent gamma rays) with a half life of 3.8 d and is therefore more important in terms of background contribution for a gamma ray spectrometer. An average concentration in the air of about 40 Bq/m^3 makes ^{222}Rn by far the strongest source of airborne radioactivity (Heusser, 1995).

Table 1
Abundances of the primorial radionuclides from uranium and thorium as well as potassium in the earth's crust. Abundances are taken from Haynes (2015). Specific activities are calculated with values from Firestone (1996).

Element	Avg. abundance [mg/kg]	Specific activity [Bq/kg]
Uranium	2.7	33.6 (^{238}U)
Thorium	9.6	39.0 (^{232}Th)
Potassium	20,900	663.9 (^{40}K)

The isotope ^{220}Rn from the ^{232}Th decay chain has a half life of 55.6 s. This sub-chain decays rather quickly via ^{212}Pb (238.6 keV) with a half life of 10.6 h and ^{208}Tl (583.2 keV and 2614.5 keV) with a half life of 3.1 min. Hence, the concentration of ^{220}Rn is below 1% of the ^{222}Rn concentration (Heusser, 1995).

Finally, ^{219}Rn from the ^{235}U decay chain is negligible for most low-level gamma ray spectrometers due to short half lives and less intense gamma rays in this sub-chain.

Using filtrated air inside a gamma ray spectrometry laboratory can decrease the radon concentration. To minimize the possibility of sample contamination with radon, the sample chamber is often flushed with gaseous nitrogen that is boiling out of the detector cooling dewar. An air-tight sealing avoids the diffusion of radon through the detector shielding. Ultra-low-background facilities may even flush the sample preparation areas with gaseous nitrogen and store the sample under a protective atmosphere before the actual spectrometry measurement while radon is decaying.

2.1.2. Anthropogenic radionuclides

So-called anthropogenic radionuclides are introduced into nature by man. Commonly found is ^{137}Cs which is brought into the environment due to nuclear accidents and nuclear weapon testing (Gilmore, 2008). A commonly found contamination of steel is ^{60}Co which is induced during the industrial production process. The contamination is mainly coming from high-activity sources that were disposed as scrap and recycled into new steel products (Koehler et al., 2004).

All construction materials need to be carefully assessed for contaminations before the are assembled in a low-level environment. Lowest contaminations can be found in materials that are stored underground immediately after production, thus avoiding the exposure to cosmic rays and activation in the material. Suitable examples are steel from the early twentieth century or 2000-year-old roman lead, that can be found within sunken roman ships in the Mediterranean Sea or Black Sea.

2.2. Cosmic rays

The remaining peaks in the background spectra of modern low-level germanium facilities are mainly induced by cosmic radiation.

The primary cosmic rays reaching the earth from outside of our solar system (galactic cosmic rays) or directly from the sun (solar cosmic rays) are high energetic particles consisting mainly of protons and alpha particles. By interacting with nuclei of the outer atmosphere, they produce a variety of secondary cosmic ray particles that propagate towards the surface of the earth in hadronic and electromagnetic cascades.

The secondary cosmic rays are divided into two components, a soft component containing electrons, positrons and photons, and a hard component consisting of protons, neutrons and muons. The typical flux for cosmic muons with a mean energy of about 3 GeV at sea-level is 190 m^{-2} s^{-1}. The relative fluxes of other particles compared to the muon flux are 0.34 for neutrons, 0.24 for electrons, 0.009 for protons and 0.0007 for pions (Povinec et al., 2008).

Cosmic rays can show variations in energy and flux, both periodic and aperiodic. A possible influence is the atmospheric pressure if a denser atmosphere needs to be penetrated. That induces an annual modulation of the muon flux of about $(1.29 \pm 07)\%$ relative amplitude with a phase of (179 ± 6) d (Bellini et al., 2012).