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Influence of cosmic radiation spectrum and its variation on the relative efficiency of LiF thermoluminescent detectors – Calculations and measurements

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HIGHLIGHTS

- Monte Carlo calculations of cosmic-ray spectra and TL-efficiency for ISS orbits.
- Intercomparison of TL-efficiency data for LiF:Mg,Ti and LiF:Mg, Cu,P.
- LiF:Mg,Ti measure correctly doses at low Earth's orbit.
- Shielding thickness significantly affects LiF:Mg,Cu,P TL-efficiency.

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ABSTRACT

Lithium fluoride thermoluminescent detectors (TLD) were used for cosmic radiation dosimetry already in early 1960s. Since that time they have been constantly applied in numerous space missions for personal dosimetry, area monitoring, phantom measurements and dosimetry for biological experiments. The relative efficiency of TLDs, defined as the ratio of their response to a given radiation and to a reference radiation, is not constant, but depends on ionization density. This raises a question about the relative efficiency of TLDs exposed to the complex cosmic radiation spectrum encountered in Earth's orbit, which consists of a variety of particles, including heavy ions, the spectrum of which covers an extremely broad energy range. The present work is an attempt to find an answer to this question.

The particle energy spectra were calculated for realistic flight conditions of the International Space Station (ISS). The calculation of the Galactic Cosmic Ray (GCR) component was based on the input spectra generated with the DLR model for solar minimum (2009) and solar maximum (2000) conditions. Contributions of trapped protons were estimated based on the AP8 model for solar minimum and maximum taking into account the altitude variations of the ISS. The interactions of the primary particles with the ISS were simulated with GEANT4 using a shielding geometry derived from the mass distribution of the Columbus Laboratory of the ISS and several constant aluminum shieldings. The calculated spectra were convoluted with the experimental data on the relative TL efficiency measured for ions ranging from H to Xe at various particle accelerators for two commonly applied TL-materials, namely LiF:Mg,Ti and LiF:Mg,Cu,P.

The results showed the differences in the average TL-efficiency for these two TL-materials. For LiF:Mg,Ti the relative efficiency is within a few percent from unity for any of the analyzed values of shielding, altitude and solar cycle conditions. This means that one can assume cosmic radiation doses measured in Low Earth Orbit (LEO) with LiF:Mg,Ti detectors to be correct within such uncertainty. LiF:Mg,Cu,P underestimates the cosmic radiation doses by more than 15% in all cases. Altitude and solar cycle were found to have a very weak influence on the TL efficiency. In contrast, the influence of shielding thickness is quite significant. The reason for this is a change of contributions of radiation field components: trapped protons dominate at low shielding (97% of dose at 1 g/cm^2), but are negligible above 60 g/cm^2, as well as changes within GCR spectrum (increase of dose due to lower LET secondaries for higher shielding). Shielding thickness affects both TLD types in different ways: the efficiency of LiF:Mg,Cu,P increases with increasing shielding thickness, while the efficiency of LiF:Mg,Ti shows some fluctuations,

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with a weak minimum for 60 g/cm^2. The response ratio of these TLDs decreases monotonically with the shielding thickness and could be used as an indicator for the average shielding conditions in which the TLDs were exposed.

1. Introduction

Lithium fluoride based thermoluminescent detectors (TLD) are widely applied for dosimetry of cosmic radiation in space. The first reported application of LiF:Mg,Ti TL-detectors in measurements on Earth's orbit concerned already the Mercury-8 mission in 1962, which was the third US orbital spaceflight (Warren and Gill, 1964). Since that time, TLDs (mostly LiF-based) were used probably in almost all human space missions, as well as in numerous unmanned experiments. This includes such activities as operational dosimetry of astronauts (Straube et al., 2010), area monitoring (Hajek et al., 2006; Reitz et al., 2005; Berger, 2014), phantom experiments (Yasuda et al., 2000; Reitz et al., 2009; Berger et al., 2013) and dosimetry for biological experiments (Reitz et al., 2002; Vanhavere et al., 2008; Berger et al., 2012, 2015).

The cosmic radiation spectrum is extremely complex and consists of a variety of particles with very broad energy and linear energy transfer (LET) range. The main components of the cosmic radiation at the low Earth's orbit are Galactic Cosmic Rays (GCR) consisting mainly of ionized nuclei, ranging from hydrogen to the heaviest elements, and trapped protons (TP) in the Earth's radiation belts. The cosmic radiation spectrum varies with the solar cycle, altitude, latitude, as well as with the shielding thickness of a spacecraft (Durante and Cucinotta, 2011). On the other hand, it is well known that TL efficiency is not constant, but depends on radiation type and LET (e.g. Horowitz et al., 2001). Therefore the questions arise what is the effective efficiency of TL detectors to this complex cosmic radiation spectrum and how is it affected by the spectrum's variability? This also leads to a basic practical question: are doses in space correctly measured with TLDs or not? An attempt to answer these questions was undertaken a few years ago (Bilski, 2011), by folding experimental efficiency data for LiF:Mg,Ti and LiF:Mg,Cu,P TL detectors with generated exemplary cosmic radiation spectra. At that time, the approach contained several simplifications and now, we revisited this problem armed with better tools. Firstly, in the past the efficiency vs. LET relationship was approximated with a single function, while in fact this relationship consists of separate functional branches for each ion (Horowitz et al., 2001; Olko et al., 2006). Presently, having available more reliable data on efficiency for protons and helium ions, we were able to describe these two important components of the spectrum with separate functions, which are significantly different from the generalized one. The second main difference lies in the method of cosmic radiation spectra calculation. Previously the CREME96 software package based on phenomenological models (Tylka et al., 1997) was used. In the present work we applied Monte Carlo simulations using Geant4 code, with the most up to date input spectra. Calculations were performed also for a realistic shielding distribution of the Columbus module of the International Space Station. The effective TL efficiency was finally calculated in a similar manner as previously, by folding functions fitted to the experimental values with the simulated spectra.

2. Calculations of the cosmic radiation spectra

2.1. Calculations of the cosmic radiation spectra — methods

To estimate the efficiency of TLDs in a radiation field caused by cosmic radiation, several shielding configurations have been simulated and the resulting particle fluxes behind the shielding have been calculated. One setup was derived from a shielding distribution describing the European Columbus module based on a CAD model (Stoffle et al., 2012). For this setup a spherical geometry was used in which aluminum shell sectors with a thickness corresponding to a given shielding and the related solid angle fraction derived from the shielding distribution were created. A step function of shielding thicknesses with the corresponding fractions of solid angles is derived from the shielding distribution. For each value of shielding a sector in a spherical geometry is created with the corresponding solid angle fraction. Fig. 1 illustrates this method exemplarily for a very simple distribution of four shielding thicknesses (s_0 to s_3) with corresponding solid angles ($\Delta\Omega_0$ to $\Delta\Omega_3$) by showing the 2D-projection of the resulting shielding geometry. In the simulations used in this work, the geometry is much more complex: 178 segments with corresponding thicknesses.

In addition to this shielding distribution derived geometry, different aluminum shells with fixed thicknesses were used for the simulations to investigate the general behavior of the efficiency with shielding thickness: 1 g/cm^2, 15 g/cm^2, 30 g/cm^2, 60 g/cm^2, 100 g/cm^2 and 200 g/cm^2.

The irradiation of the above mentioned geometries was then simulated with GEANT4.10.01.p01 (Agostinelli et al., 2003; Allison et al., 2006) for GCR and trapped proton input spectra. The energy spectra of the GCR primary particles were taken using the DLR model (based on the work from Matthiä et al. (2013)) for a kinetic energy per nucleon ranging between 10 MeV/A and 200 GeV/A for solar maximum and minimum and scaled by the geomagnetic transmission function from the CREME framework (Tylka et al., 1997; *https://creme.isde.vanderbilt.edu/*) for an average ISS orbit. The solar minimum and maximum settings corresponded to the conditions encountered in the last months of 2009 (deep solar minimum) and in the summer 2000 (solar maximum) respectively

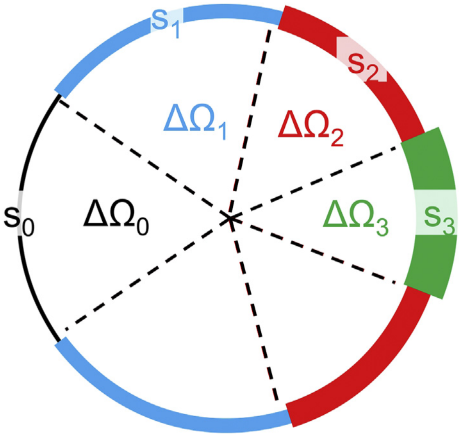

Fig. 1. 2D-projection of a shielding geometry derived from a solid angle distribution to illustrate the method used in this work. In this example a simple distribution with four shielding thicknesses (s_0 to s_3) with corresponding solid angles ($\Delta\Omega_0$ to $\Delta\Omega_3$) is used. The geometry used in this work consists of 178 segments with corresponding thicknesses.