Modeling the Response of Thermoluminescence Detectors Exposed to Low- and High-LET Radiation Fields

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Lithium fluoride thermoluminescence (TL) detectors, with different Li composition (Li-6 and Li-7) and various activators (LiF:Mg,Ti, LiF:Mg,Cu,P), are widely used for dosimetry in space. The primary radiation field in space is composed of fast electrons, protons and heavy charged particles (HCP). By its interaction with the structures of the spacecraft, this field may be modified inside the crew cabin. Therefore, calibration of TL detectors against a dose of γ-rays is not sufficient for relating the TL readout to absorbed dose or to quantities relevant in radiation protection, without suitable correction. We introduce and calculate the detection efficiency, η, relative to γ-ray dose, of lithium fluoride detectors after proton and heavy charged particle (HCP) irradiation. We calculate η for MCP-N (LiF:Mg,Cu,P) and for MTS-N(LiF:Mg,Ti) using microdosimetric models. The microdosimetric distributions used in these models (for HCP of charges between Z=1 to Z=8 and in the energy range between 0.3 MeV/amu and 20 MeV/amu) are calculated using an analytical model, based on the results of Monte Carlo simulated charged particle tracks using the MOCA-14 code. The ratio ηMCP-N/ηMTS-N for protons of stopping power (in water) below 10 keV/µm lies in the range between 0.65 and 1.0 and for HCP with Z>1 - between 0.3 and 0.6. The stopping power of the particle is found not to be a unique parameter to scale the response of TL detectors. The combination of response of LiF:Mg,Cu,P and LiF:Mg,Cu,P detectors can be more suitable for a dose correction in space radiation fields.

INTRODUCTION

Thermoluminescent detectors, such as e.g. LiF:Mg,Ti and LiF:Mg,Cu,P, are widely used in space dosimetry of ionizing radiation because they are small in size, sensitive and do not require any power supply. The response of these detectors is typically calibrated against Cs-137 or Co-60 γ-rays. It is difficult to express the response of TL detectors in terms of absorbed dose or dose equivalent since the radiation field is quite different from that used for calibration. Therefore, several approaches are used to determine the dose equivalent, e.g. by exploiting the increase of high-temperature peaks in LiF:Mg,Ti after high-LET irradiation¹² or combining TLD measurements with track-etched detectors³⁴. Another possibility is to apply two different types of LiF detectors, with almost the same atomic composition but different LET response. Such measurements should be supported by modeling the response of these detectors after doses of heavy charged particles (HCP) of different charge and energy.

Models of the HCP response of LiF:Mg,Ti and LiF:Mg,Cu,P have been developed by several authors using the concept of radial dose distribution, RDD, around the particle’s path⁴–⁸. If the HCP energy spectrum and fluence are known, which is rarely the case, these models can readily be applied to predict the response of TLDs. Another approach is to use microdosimetric models whereby the response is calculated basing on the knowledge of radiation energy deposited in microscopic volumes (microdosimetric distributions). These distributions, in principle, can be measured using Tissue Equivalent Proportional Counters, TEPC, or calculated. The
aims of this paper are to calculate the efficiency of HCP, relative to γ-rays, of MCP-N and MTS-N detectors using microdosimetric model and to discuss the application of these detectors in space dosimetry.

MATERIALS AND METHODS

a) TL detectors

MTS-N (LiF:Mg,Ti) and MCP-N (LiF:Mg,Cu,P) are sintered pellets of diameter 4.5 mm and 0.9 mm thick, developed at the Institute of Nuclear Physics, Kraków, Poland and commercially available from TLD Poland. To measure the γ-ray dose-response, irradiation with Cs-137 was performed at the Institute of Nuclear Physics at Kraków over the kerma range from 1 Gy to 700 Gy (see Fig.1 in reference 9). MCP-N detectors were annealed for 10 min at 240°C and cooled rapidly, while standard MTS-N detectors - for 1h in 400°C, followed by 2 h in 100°C. All TLDs were read out with a RA’94 reader which features platinum planchet heating and an EMI bialkali 9789QB PM with a BG-12 infrared filter. Glow-curves were measured using a linear ramp at a rate of 5°C.s⁻¹ to a maximum temperature of 350°C. For MCP-N detectors the entire glow-curve was recorded digitally. The detector response for MTS-N was represented by an integral over the main dosimetric peak (sum of peaks 3+4+5) without the high temperature peaks. At high doses (tens and hundreds of Gy) the supralinear peak 4 became well distinguishable.

b) Calculation

The dose response of TL detectors is characterised by linearity index \( f(D) \) defined as a ratio of TL signal \( R(D) \) per unit absorbed dose \( D \), normalised to the signal at low dose, \( D_0 \), where the signal is still linear.

\[
f(D) = \left[ \frac{R(D)}{D} \right]_{D_0} \quad (1)
\]

Within this paper the term “supralinearity” is used for detectors which show \( f(D) > 1 \) before the saturation and “sublinearity” for those with \( f(D) < 1 \).

The relative efficiency of LiF:Mg,Cu,P (MCP-N) detectors was calculated using the microdosimetric one-hit detector model\(^{10} \). In this model the linearity index, \( f(D) \), for the \( i \)-th ion of a given energy is calculated as:

\[
f_{i}(z) = \frac{D}{z_{F}} \left[ 1 - e^{-\alpha z} \right] f_{i}(z) dz
\]

where \( D \) is the absorbed dose, \( f_{i}(z) \) is the distribution of local doses, called in microdosimetric terminology the frequency distribution of specific energy, \( z \), and \( z_{F} \) is the mean specific energy. In microdosimetry the term “low dose” is used when \( D \ll z_{F} \). The expression \( r(z) = 1 - e^{-\alpha z} \) is the response function of the one-hit model with the saturation parameter, \( \alpha \), which determines the probability of effect after an energy deposition event. \( f_{i}(z) \) for HCP (from protons \( Z = 1 \) to oxygen ions \( Z = 8 \), in the energy range from 0.3 MeV/amu to 20 MeV/amu) were calculated using an analytical model\(^{11} \), which was developed basing on the results of a Monte Carlo calculation of particle tracks in water.

\[ a \]

\[ b \]

Fig. 1. Relative TL efficiency, \( \eta \), of a) LiF:Mg,Ti (MTS-N) and b) LiF:Mg,Cu,P (MCP-N) detectors after doses of monoenergetic ions, calculated using the microdosimetric model described in text. No slowing-down of the ions is assumed in the detector.
vapour using the MOCA-14 code. $f_i(z)$ for $\gamma$-rays were calculated using Monte Carlo-simulated tracks in water vapour generated with the TRION code\(^2\). The relative efficiency, $\eta$, for a given ion energy (index $i$) was calculated as follows:

$$\eta = \frac{1}{\frac{1}{c_{F}} \int_{0}^{\infty} r(z) f_i^{C_{F}}(z) dz}$$

$$= \frac{1}{\frac{1}{c_{F}} \int_{0}^{\infty} r(z) f_i^{C_{F}}(z) dz}$$

The relative heavy ion TL efficiency of MTS-N was calculated using a method adopted from Geiss et al.\(^6\) who fold the dose response function for TLD-100, obtained from experiments with X-rays, with the computed radial dose distribution. In the present work, the measured dose-response curve of MTS-N detectors $R_{MTS}(D)$ (Cs-137 $\gamma$-rays) was folded with the calculated local dose distribution (microdosimetric distribution) evaluated for monoenergetic ions of different energy. It was assumed in these calculations, similarly as in the approach applied by Geiss\(^7\), that the response function $R_{MTS}(D)$ can be applied as the $r(z)$ function in Eq. 3. The measured dose response of MTS-N detectors for Cs-137 gamma-rays was fitted\(^9\), using the non-linear Marquardt method in the Origin 5.0 fitting procedure, with the function: $R_{MTS}(D) = A(1-\exp(-\alpha D)) + (1-A)(1-\exp(-\beta D^2))$, yielding the following values of the fitted parameters: $A = 0.362 \pm 0.015$, $\alpha = 7.3 \times 10^{-4} \pm 0.4 \times 10^{-4}$ Gy\(^{-1}\) and $\beta = 3.92 \times 10^{-6} \pm 0.24 \times 10^{-6}$ Gy\(^{-2}\). Details on the technique used to calculate $f(z)$ distributions for X-rays have been published elsewhere\(^10\).

**RESULTS AND DISCUSSION**

The calculated value of $\eta$ for MTS-N and MCP-N detectors, differential with regard to stopping power (passing through an infinitesimally thin detector), are plotted against HCP stopping power in water in Fig. 1a and Fig. 1b. The calculated ratio of $\eta$ for MTS-N and MCP-N are plotted in Fig. 2. The calculated response of MCP-N and MTS-N detectors, for different heavy charged particles with the same stopping power is not a unique function of the particle’s stopping power. For the same value of stopping power, the velocity of the particle with a higher charge must be higher. This leads to a higher range of $\delta$-rays, lower local ionization density and, as a consequence, to a higher value of $\eta$. Therefore, the stopping power is not a good parameter to scale the LET response of LiF detectors and the LET-spectrum alone is not sufficient to predict the response of these detectors after a dose of HCPs. Calculated $\eta$ for particles with the same stopping power grows with increasing $Z$, similarly as shown in experiments of Benton et al.\(^4\) and Geiss et al.\(^7\). A fast decrease of efficiency for the high-sensitive MCP-N (LiF:Mg,Cu,P) detectors is caused by saturation of their sublinear TL signal response after high local energy deposits. The relative efficiency of LiF:Mg,Ti (MTS-N) detectors is higher, as compared to MCP-N because for the MTS-N dose response, $R(D)$ is supralinear.

The calculated $\eta_{MTS,N}$ for 20 MeV protons is 1.08 as compared to the value, $\eta=1.2$ measured for 62 MeV protons at the Paul Schaerer Institute, PSI, in an ocular melanoma treatment field\(^2\). $\eta>1$ for TLD-100 for 20–40 MeV protons was also reported by Vessue\(^13\) after his experiments at PSI. TL output per unit absorbed dose higher than that for Co-60 $\gamma$-rays\(^8\) can also be explained as a microdosimetric effect, due to the deposition of a fraction of energy in the supralinear part of dose response. Also other measured values of $\eta$ for proton\(^4,15\) and $\alpha$-particle\(^4,14\) irradiation of TLD-700 do not contradict the calculations (see Fig. 1a). Experimental data for slow HCP in MCP-N, shown in Fig. 1b, is limited to $\alpha$-particles\(^6\).

This difference in LET sensitivity of LiF:Mg,Ti and LiF:Mg,Cu,P detectors could be applied to refine an estimation of dose measured during space flights. For protons the relative detection efficiency for LiF:Mg,Ti detectors (both obtained from experiment and calculation) decreases 10-15% within the LET range from 1 to 10keV/µm and 50% for LiF:Mg,Cu,P detectors. Since LiF:Mg,Cu,P detectors show approximately 2–3 times lower response for doses of high-LET particles, the ratio of response LiF:Mg,Cu,P/LiF:Mg,Ti can be used as an indicator of contribution...
densely ionizing particles, which is related e.g. to the radiation field, shielding etc. In the recent dose–mapping experiment on board of the International Space Station, the ratio of the measured response of LiF:Mg,Cu,P (TLD700H) to LiF:Mg,Ti (TLD700) was found to be 0.88±0.02, which corresponds to an effective LET of 5 keV/μm. However, without a detailed knowledge of the radiation spectrum calculation of the response for both LiF detectors cannot be performed reliably.

CONCLUSIONS

It is possible to calculate the response of LiF:Mg,Ti and LiF:Mg,Cu,P detectors after a dose of heavy charged particles using microdosimetric modelling. The response of these detectors is not a unique function of LET. The high-LET response of high-sensitive LiF:Mg,Cu,P detectors is lower compared to that of LiF:Mg,Ti. The combination of response of LiF:Mg,Cu,P and LiF:Mg,Cu,P detectors can be more suitable for a dose correction in space radiation fields.

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