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On the linearity of the high-temperature emission from ^{7}LiF:Mg,Ti (TLD-700)

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ABSTRACT

It is known since the early 1970s [e.g., Jähnert, B., 1972. The response of TLD-700 thermoluminescent dosemeters to protons and alpha particles. Health Phys. 23, 112–114.] that the high-temperature emission (HTE) from LiF:Mg,Ti thermoluminescence (TL) phosphors shows a distinctly different LET dependence than the dominant glow peak 5. This behaviour of the high-temperature structure can be attributed to the earlier onset of supralinearity compared to peak 5. The relative TL-efficiency of the high-temperature peaks after heavy ion irradiation with respect to ^{60}Co was calculated by Waligórski and Katz [1980a. Supralinearity of peak 5 and 6 in TLD-700. Nucl. Instrum. Meth. 175, 48–50; 1980b. Supralinearity of peak 5 and 6 in TLD-700. Nucl. Instrum. Meth. 172, 463–470.], demonstrating that levels far exceeding 1 can be reached. The HTE from LiF:Mg,Ti has been applied in various ways, e.g., to determine an "effective" LET under mixed ion field conditions and, subsequently, to correct the absorbed dose deposited in the crystal for TL-efficiency [Berger, T., 2003. Dose assessment in mixed radiation fields—special emphasis on space dosimetry. Ph.D. Thesis, Vienna University of Technology; Berger, T., Hajek, M., Fugger, M., Vana, N., 2006a. Efficiency corrected dose verification with thermoluminescence dosemeters in heavy ion beams. Radiat. Prot. Dosim. 120, 361–364; Berger, T., Reitz, G., Hajek, M., Vana, N., 2006b. Comparison of various techniques for the exact determination of absorbed dose in heavy ion fields using passive detectors. Adv. Space Res. 37, 1716–1721.]. This approach showed good results in the low dose region (≤100 mGy). A crucial requirement for this procedure is the linearity of the gamma dose–response of the HTE for the applied dose levels. The discussion whether a linear dose–response can be found is still ongoing: while some groups reported a linear dose–response [Pradhan, A.S., Rassow, J., Meissner, P., 1985. Dosimetry of d(14)+ Be neutrons with the two-peak method of LiF TLD-700. Phys. Med. Biol. 30, 1349–1354; Massillon-Jl, G., Gamboa-deBuen, I., Brandan, M.E., 2006. Onset of supralinear response in TLD-100 exposed to ^{60}Co gamma-rays. J. Phys. D: Appl. Phys. 39, 262–268.; Bilski, P., 2006. Response of various LiF thermoluminescent detectors to high energy ions—results of the ICCHIBAN experiment. Nucl. Instrum. Meth. Phys. Res. B 251, 121–126.] others measured a pronounced supralinearity even at very low doses [Horowitz, Y.S., Satinger, D., Puks, E., Oster, L., Podgalov, 2003. On the use of LiF:Mg, Ti TLDs in space—a critical review. Radiat. Prot. Dosim.. 106, 7–25.; Horowitz, Y.S., Oster, L., Datz, H., 2007. The thermoluminescence dose–response and other characteristics of the high-temperature TL in LiF:Mg, Ti (TLD-100). Radiat. Prot. Dosim. 124, 191–205.]. This paper focuses on the results from a linearity study of the HTE in the dose region between 1 and 500 mGy.

1. Introduction/scope

It is known since the early 1970s (e.g., Jähnert, 1972) that the high-temperature emission (HTE) from LiF:Mg,Ti thermoluminescence (TL) phosphors shows a distinctly different LET dependence than the dominant glow peak 5. This behaviour of the high-temperature structure can be attributed to the very high values of supralinearity compared to peak 5 which in turn causes an earlier onset of measureable supralinearity. Hoffmann and Prediger (1984) therefore concluded that LiF:Mg,Ti gives a two-parameter signal from which dose and LET may be derived. The relative TL-efficiency of the high-temperature peaks after heavy-ion irradiation with respect to ^{60}Co was calculated by Waligórski and Katz (1980a,b), demonstrating that levels far exceeding 1 can be reached. They further suggested that the high-temperature peaks in LiF:Mg,Ti would be good candidates for mimicking the response of biological systems to heavy-ion irradiation. The HTE from LiF:Mg,Ti has been applied in various ways, e.g., to determine an "effective" LET under mixed ion field conditions and, subsequently, to correct the absorbed dose deposited in the crystal for TL-efficiency (Berger, 2003; Berger et al., 2006a,b). This approach showed good results in the low-dose region (≤100 mGy). A crucial requirement for this

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procedure is the linearity of the gamma dose–response of the HTE for these doses. The discussion whether a linear dose–response can be found is still ongoing. A linear dose–response in the dose region applied for the TL-efficiency studies has been measured by Pradhan et al. (1985) and Massillon-JI et al. (2006) (Fig. 3). Horowitz et al. (2003, 2007) measured a pronounced supralinearity even at very low doses (see Fig. 6 in Horowitz et al., 2007), concluding from his experiments that the HTE from LiF:Mg,Ti is barely observable at low-dose levels of around 10 mGy (Fig. 7 in Horowitz et al., 2007). However, he stated that "there may be measurement protocols and batches for which a linear region exists and other protocols and batches for which no linear region exists". In the framework of the ICCHIBAN project (Yasuda et al., 2006), the relative HTE to peak 5 ratio with respect to ^{60}Co was evaluated for heavy charged particle (HCP) doses between 1 and 100 mGy. The results indicate an entirely dose-independent behaviour of the high-temperature ratio (HTR) in this dose region (Uchihori & Benton, 2004; Hajek et al., 2006). The same dose-independence of the HTE to peak 5 ratio in this low-dose region was observed by Bilski (2006) (Fig. 4).

Unfortunately, the raw data behind these studies from the Atomic Institute of the Austrian Universities (ATI) has never been published. As the HTR is based on the integral of the composite high-temperature structure in LiF:Mg,Ti (248–310 °C, with peak 5 correlated at 220 °C) after exposure to heavy ions and ^{60}Co gamma rays, respectively, dose-independence of the HTR implies linear responses to doses from gamma rays and heavy ions. The primary goal of this paper is therefore to study the gamma dose–response of the high-temperature structure in ^{7}LiF:Mg,Ti (Harshaw TLD-700) for doses up to 500 mGy. Further, heavy-ion dose–responses are investigated for doses up to 100 mGy.

2. Materials and methods

2.1. Dosemeter annealing and readout

Before each exposure, the TLD-700 (Harshaw-Thermo Fisher Scientific) chips of size 6.4 × 6.4 × 0.89 mm obtained from the same batch were annealed according to a well-defined protocol at 400 °C for 1 h in air, followed by controlled slow cooling to room temperature (~24 h) in the oven. Fig. 1 shows the cooling rate of the applied annealing oven (Heraus KM 170, Heraeus Instruments GmbH, Hanau, Germany). The cooling rate (after switching off the heating) is strictly exponential and controlled by the heating capacity of the oven.

The glow curves were readout by contact heating on a Nikrothal 80 austenitic alloy planchet from room temperature to a maximum temperature of 480 °C at a linear heating rate $\beta = 5\,^{\circ}\mathrm{C\,s^{-1}}$. To minimize spurious chemiluminescence and triboluminescence the measurement chamber was first evacuated and during readout flooded with ultra-pure (5.0) dry N_2 gas. The reader (TL-DAT II), developed at the Atomic Institute of the Austrian Universities, employed the photon counting technique using a Thorn EMI 9635 QB photomultiplier (Thorn EMI Gencom, Inc., Fairfield, NJ, USA) with a bialkali photocathode (Vana et al., 1988). In order to attenuate the light incident on the photomultiplier tube, a neutral optical filter (NG3, Schott AG, Mainz, Germany) was used for doses above 20 mGy. After the first measurement, each TLD was measured a second time for the determination of the background signal comprised mainly of electronic noise (photomultiplier dark current) and black body radiation. Although background glow curves were measured for all chips, the background subtraction was achieved by an exponential fit to the black body radiation with a constant offset in the temperature region from 20 to 80 °C to account for electronic noise. This method proved to be more time efficient and superior to the manual analysis. As an example Fig. 2 shows a TLD-700 glow curve irradiated with 10 mGy of ^{60}Co gamma rays, as well as the exponential background fit and the "net" TLD-700 glow curve calculated by subtracting the fit from the raw data glow curve.

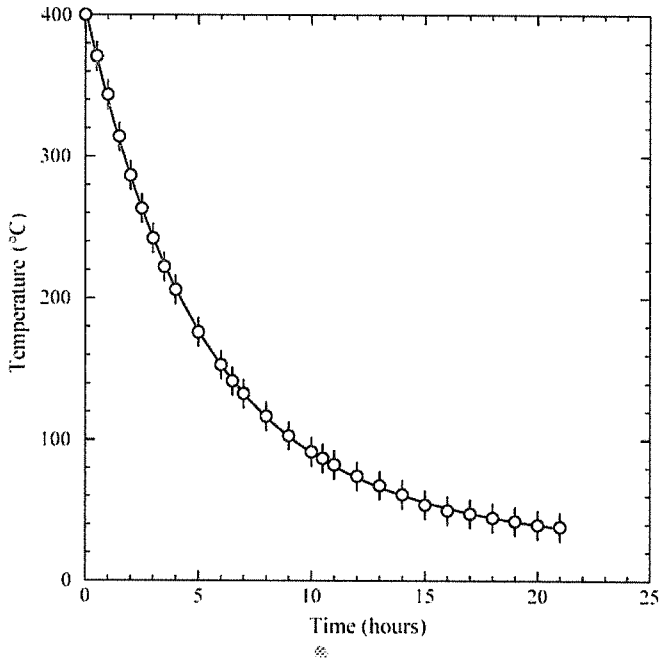

Fig. 1. Cooling rate of the Heraeus KM 170 annealing oven measured by a thermocouple temperature sensor after switching off the heating.

As it is inadmissible to compare TLD data from different laboratories without detailed knowledge of the employed experimental protocols, a dedicated feature of the custom-designed TL-DAT II reader deserves particular attention. Readout of the TL phosphors is performed after prior evacuation to $\sim 2 \times 10^{-2}$ Torr in ultra-pure (5.0) dry N_2 atmosphere. Evacuation and N_2 atmosphere are two prerequisites to minimize spurious luminescence during readout and avoid adulterating the HTE. To underline the impact of the ultra-pure

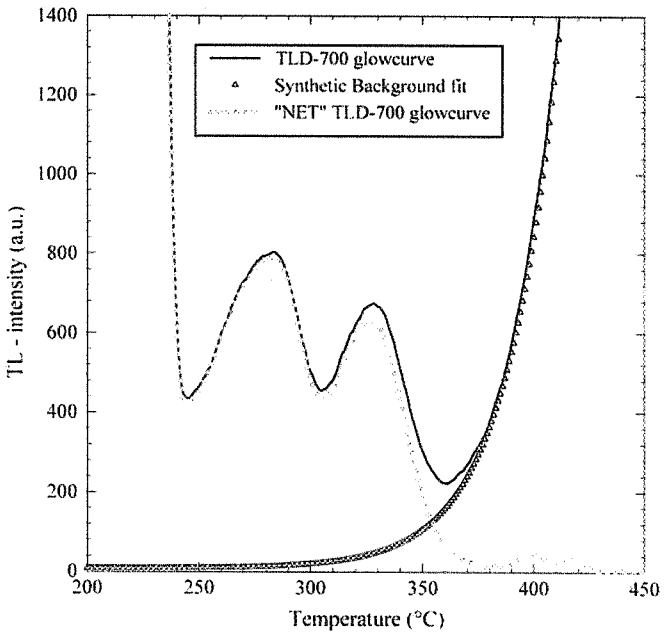

Fig. 2. TLD-700 glow curve after 10 mGy of ^{60}Co gamma irradiation (black) along with the exponential background fit (triangle up) and the "net" glow curve (dots) (zoomed in for a better view of the high-temperature emission).

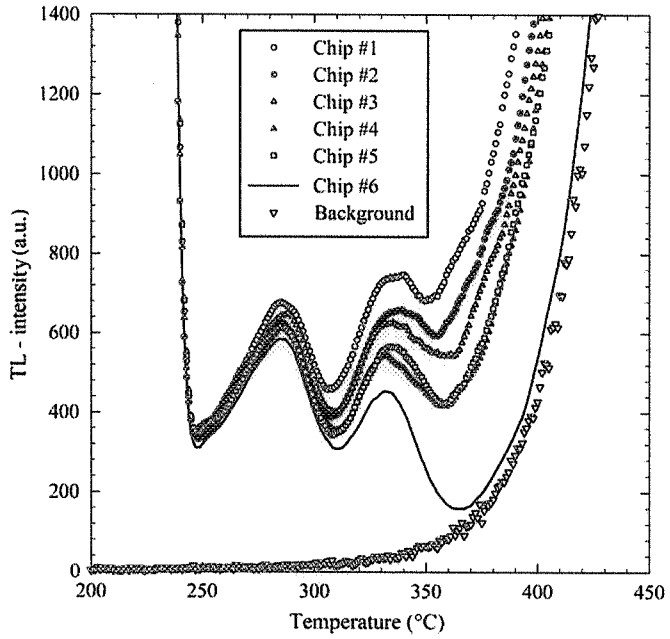

Fig. 3. TLD-700 glow curves after 9.85 mGy of ^{137}Cs gamma irradiation readout according to different protocols. Procedure # I (chips #1–5): sequential readouts without chamber evacuation, N_2 flushing for 10 s prior to and during readout; procedure # II (chip #6): without chamber evacuation, N_2 flushing for 1 h prior to and during readout.

N_2 gas flow and chamber evacuation, a couple of TLD-700 chips have been irradiated with 9.85 mGy of ^{137}Cs gamma rays and readout according to three different protocols (procedures # I–III). Procedure # I did not evacuate the chamber but only flush it with ultra-pure N_2 for 10 s prior to and during readout. For procedure #II the measurement chamber has been flushed with ultra-pure N_2 for 1 h prior to and during readout, again without evacuation of the chamber. Fig. 3 shows glow curves retrieved according to procedures # I and II. Glow

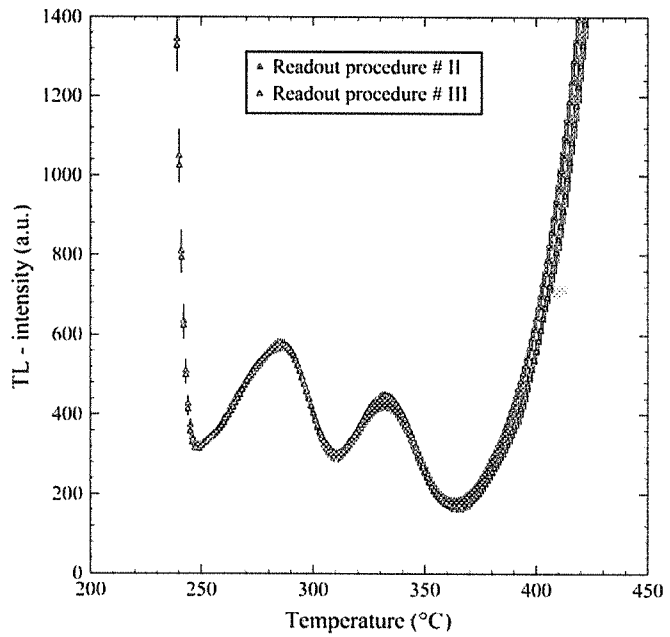

Fig. 4. TLD-700 glow curves after 9.85 mGy of ^{137}Cs gamma irradiation readout according to different protocols. Procedure # II: without chamber evacuation, N_2 flushing for 1 h prior to and during readout; procedure # III: with chamber evacuation, N_2 flushing for 10 s prior to and during readout (ATI standard protocol).

Table 1
High-temperature emission (HTE, 248–310 °C) after exposure to 9.85 mGy of ^{137}Cs gamma rays following different readout procedures

Chip #	Readout procedure #		HTE (248–310 °C)
1	I	w/o Chamber evacuation, N_2 flushing for	33,029
2		10 s prior to and during readout	30,910
3			31,503
4			29,874
5			29,886
6	II	w/o Chamber evacuation, N_2 flushing for	27,987
7		1 h prior to and during readout	27,839
8	III	With chamber evacuation, N_2 flushing for	27,963
9		10 s prior to and during readout	27,629

The glow curves were normalized to the arbitrary peak 5 intensity of 10,000 counts.

curves #1–5 have been revealed from sequential readouts according to procedure #I; glow curve #6 has been measured following procedure # II. For procedure # I, the HTE of the recorded glow curves is adulterated by chemiluminescence, particularly for temperatures $\geq$360 °C. Although this adulteration seems to decrease asymptotically with the number of readout processes due to N_2 accumulation in the chamber (despite the necessity to access the chamber for manual sample exchange), it cannot be neglected even after the fifth readout. A 1 h flushing of the chamber with ultra-pure N_2 eliminates residual gases and reduces spurious emissions to a level that would be present even after evacuation (procedure # III, Fig. 4). Table 1 compares the high-temperature emissions (248–310 °C) for procedures # I and II with the ATI standard experimental protocol (procedure # III). The integrated HTE determined from procedures # II and III are essentially equivalent.

2.2. Methods of analysis

For further data evaluation, the peak 5 maxima of the glow curves were correlated at 220 °C. For the evaluation of the high-temperature region, the integral from 248 to 310 °C was applied. This integral covers mainly peak 7 of the glow curve, with minor contributions from peaks 6 and 8. As an example, Fig. 5 presents

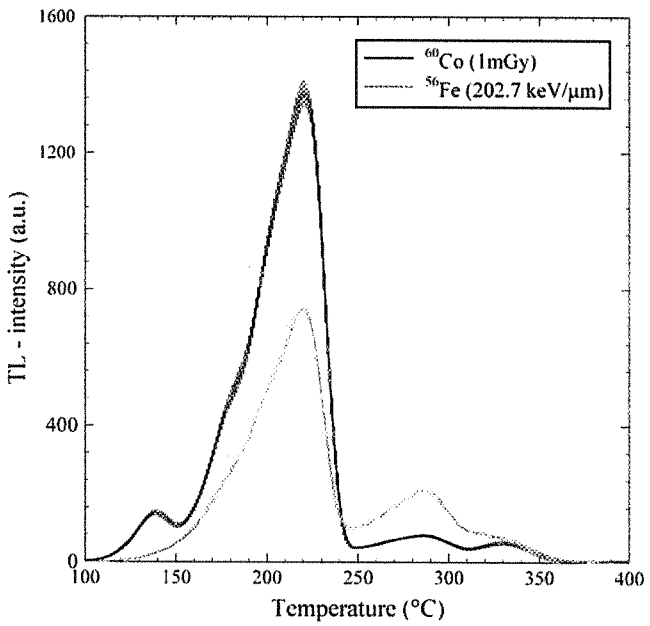

Fig. 5. TLD-700 glow curves after 1 mGy of ^{60}Co gamma rays (black) and 1 mGy of ^{56}Fe ions at 202.7 keV μm^{-1} (grey). The presented data are averages over six chips. Error bars indicate 1 standard deviation (SD).

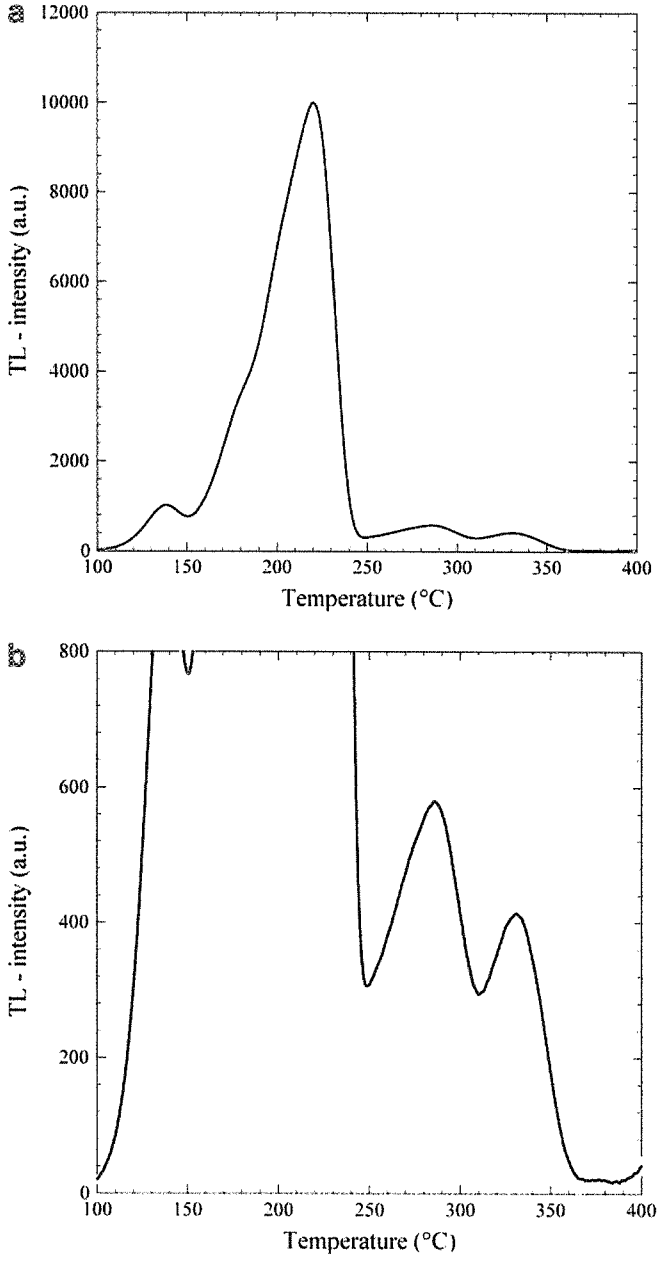

Fig. 6. a. TLD-700 glow curve after 2.2 mGy ^{60}Co gamma irradiation (average over 16 chips). b. TLD-700 glow curve after 2.2 mGy ^{60}Co gamma irradiation (average over 16 chips) with enlarged high-temperature structure. Error bars indicate 1 standard deviation (SD).

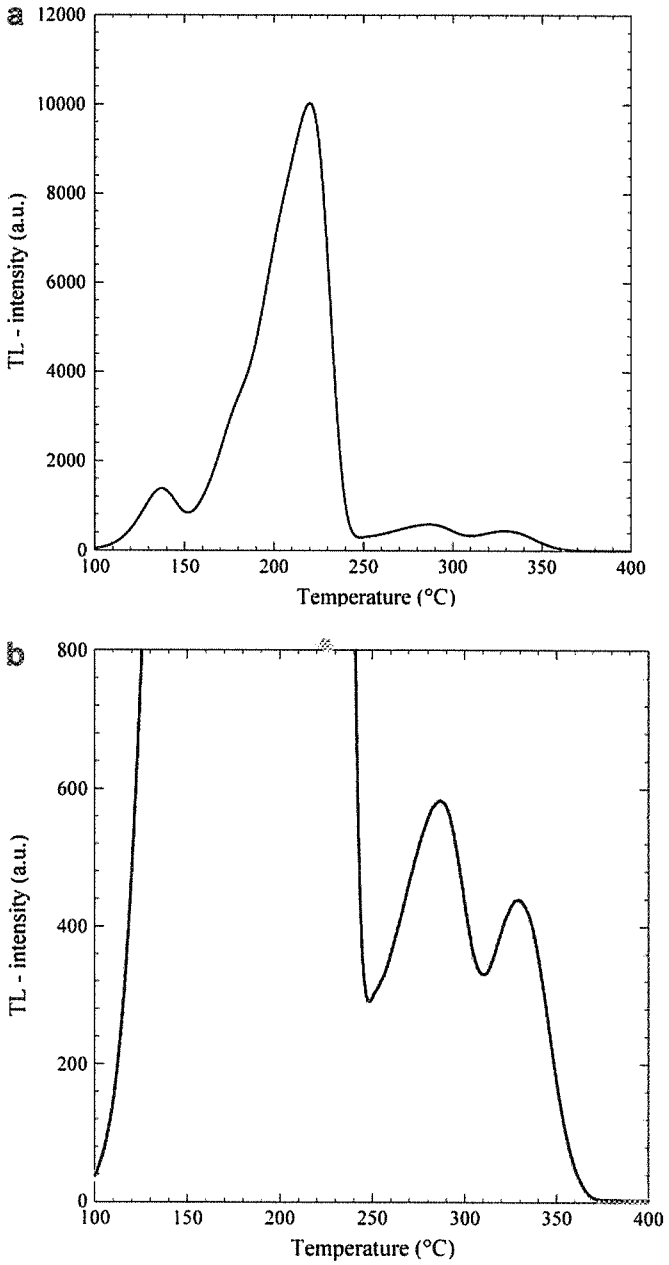

Fig. 7. a. TLD-700 glow curve after 95 mGy ^{60}Co gamma irradiation (average over 16 chips). b. TLD-700 glow curve after 95 mGy ^{60}Co gamma irradiation (average over 16 chips) with enlarged high-temperature structure. Error bars indicate 1 standard deviation (SD). Note the equivalence of the HTE to Fig. 6b.

sample glow curves from TLD-700 detectors exposed to doses of 1 mGy from ^{60}Co gamma rays and ^{56}Fe ions of 202.7 keV μm^{-1}. The HTE is clearly visible in both cases, even at this low-dose levels. Notable is also the decreasing efficiency of the main peak 5 at 220 °C for the high-LET ^{56}Fe irradiation, while the efficiency of the high-temperature emission increases with respect to ^{60}Co gamma irradiation.

2.3. Irradiation conditions

^{60}Co gamma rays were used for the calibration of the TL detectors. Each chip has been assigned an individual calibration factor. All gamma irradiations were performed in air approximately 24 h after annealing of the TLD-700 crystals, using a therapeutic ^{60}Co calibration source with pneumatic shutter (Philips Theratron) of the Department of Radiotherapy and Radiobiology, Medical University of Vienna, Austria. The detectors were sealed in polystyrene holders (1 mm thickness) that have also been used for the further heavy charged particle irradiations. A Farmer-type high-precision ionization chamber calibrated by the Federal Office of Metrology and Surveying (BEV), Vienna, Austria, was employed for determining absorbed dose to water, using correction factors for temperature and air pressure.

The heavy charged particle irradiations were performed at the Heavy Ion Medical Accelerator (HIMAC) of the National Institute of Radiological Sciences (NIRS), Chiba, Japan, in the framework of the ICCHIBAN inter-calibration programme (Uchihori & Benton, 2004; Yasuda et al., 2006). Fully ionized nuclei were supplied by four stable, long-lived ion sources of the electron cyclotron resonance (ECR) and the Penning ionization gauge (PIG) type. Before the ionized particles

were injected into the synchrotron, they were accelerated in two linear accelerator (LINAC) stages consisting of a radio-frequency quadrupole (RFQ) and an Alvarez LINAC. The heavy ion beams were then transported to a pair of synchrotron rings and further accelerated to a maximum energy of 800 MeV amu^{-1}. All irradiations were carried out in the Biological Irradiation Room where a maximum beam diameter of 10 cm can be obtained by using a pair of wobbler magnets and a scatterer. The particle fluence was monitored by a scintillation counter. Reference doses were retrieved from a high-precision Farmer-type ionization chamber of 1 mm water-equivalent thickness installed upstream of the target which was also used to check uniformity of the beam in one dimension, yielding maximum fluctuations of <5% over the circular beam area for the employed ion species. The TL crystals were sealed in polystyrene holders of 1 mm thickness and exposed to doses of 1, 10, 50 and 100 mGy from the following ion beams (the energy corresponds to the particle energy on exit from the synchrotron): 150 MeV amu^{-1} ^{4}He, 400 MeV amu^{-1} ^{12}C, 490 MeV amu^{-1} ^{28}Si and 500 MeV amu^{-1} ^{56}Fe. The actual energy and the corresponding LET values were calculated for all irradiation conditions by means of the SRIM/TRIM 2006 Monte Carlo code (Ziegler et al., 1985) based on the ion range in water obtained from a Bragg curve measurement.

3. Results

3.1. Gamma dose–response

^{60}Co gamma irradiations have been performed at dose levels ranging from 2.2 to 508.1 mGy. At each dose level, up to 16 TLD chips have been analyzed. Figs. 6a and 7a show the glow curves from TLD-700 detectors exposed to 2.2 mGy and 95 mGy of ^{60}Co gamma radiation. To ease intercomparison, the glow curves were normalized to 10,000 counts (peak 5 correlated at 220 °C). The presented glow curves are averages over 16 chips. For both doses, the HTE is clearly visible. Figs. 6b and 7b enlarge the HTE for the previous glow curves, the error bars indicating 1 SD. At both doses (2.2 and 95 mGy), the high-temperature structure ranging from 248 to 310 °C (containing primarily peak 7 of the glow curve) is entirely equivalent (after normalization to peak 5).

The dose–response function or supralinearity function $f(D)$ calculated for the high-temperature emission in the dose region from 2.2 to 508.1 mGy is given by:

$$f(D) = \frac{F(D)/D}{F(D_0)/D_0} \quad (1)$$

where $F(D)$ is the TL signal obtained at a dose D and $F(D_0)$ is the TL signal at a low dose D_0 (for this work 46.9 mGy) where the TL response of the high-temperature emission is linear. Table 2 and Fig. 8 show the dose–response function $f(D)$ of the integral HTE

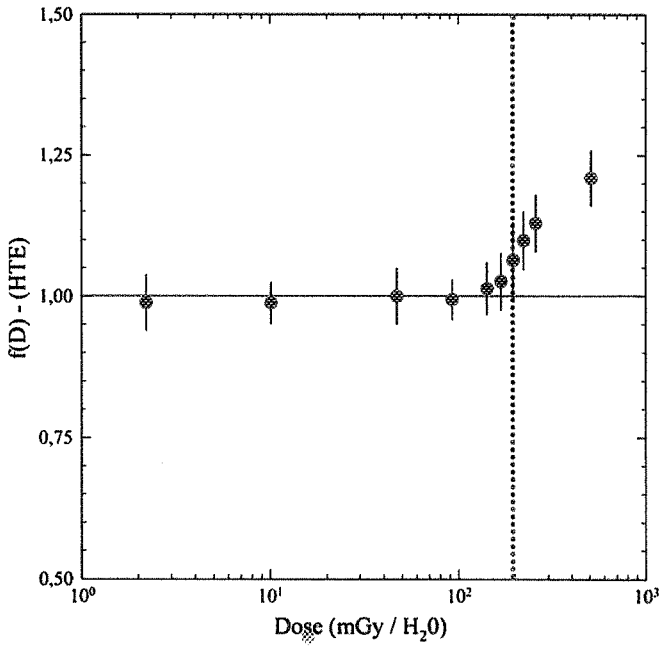

Fig. 8. $f(D)$ for the high-temperature emission (248–310 °C) from TLD-700 in the dose region between 2.2 and 508.1 mGy.

(248–310 °C) for the applied dose values. The dose–response $f(D)$ is linear (within one SD) up to 168.4 mGy. From 195.2 mGy, the increase over unity becomes statistically significant. The dose–response increased up to 1.209 ± 0.049 at 508.1 mGy. Therefore, the dose–response of the high-temperature emission (applying the mentioned annealing and readout procedures) is linear up to around 200 mGy, with a further increase up to 1.2 at a dose level of 500 mGy.

As additional information, the signal-to-noise ratio (S/N) for the high-temperature region has been calculated for the investigated doses from 2.2 to 508.1 mGy. The S/N is based on the measured TL signal (248–310 °C) divided by the fitted background curve in the same temperature region. The following Table 3 gives the S/N for absorbed doses from 2.2 to 508.1 mGy. All data are averaged over a minimum of six TLDs. The ratio is already >6 at dose levels of 2.2 mGy. The lower detection limit for the high-temperature interval was calculated to be ~1 mGy, which is also supported by measurements (Fig. 5).

3.2. Heavy-ion dose–response

Besides the ^{60}Co gamma irradiations, exposures to four different ion species have been realized in the framework of the ICCHIBAN

Table 2
$f(D)$ for the high-temperature emission from TLD-700 (SD calculated under consideration of error propagation)

Absorbed dose to H_2O (mGy)	$f(D)$ – (HTE) (248–310 °C)	σ
2.2	0.989	0.050
10.1	0.988	0.037
46.9	1.000	0.050
92.6	0.994	0.035
141.7	1.014	0.046
168.4	1.026	0.050
195.2	1.064	0.067
221.9	1.099	0.051
257.7	1.129	0.051
508.1	1.209	0.049

Table 3
Signal/noise ratio for the high-temperature emission

Absorbed dose to H_2O (mGy)	Signal/noise ratio	σ
2.2	6.2	1.2
10.1	25.2	4.1
46.9	21.5	1.8
92.6	45.2	14.7
141.7	86.7	19.7
168.4	118.6	9.2
257.7	126.3	16.2
508.1	242.6	26.9

Note that for absorbed doses above 20 mGy a neutral optical filter (NG3, Schott AG, Mainz, Germany) was applied.

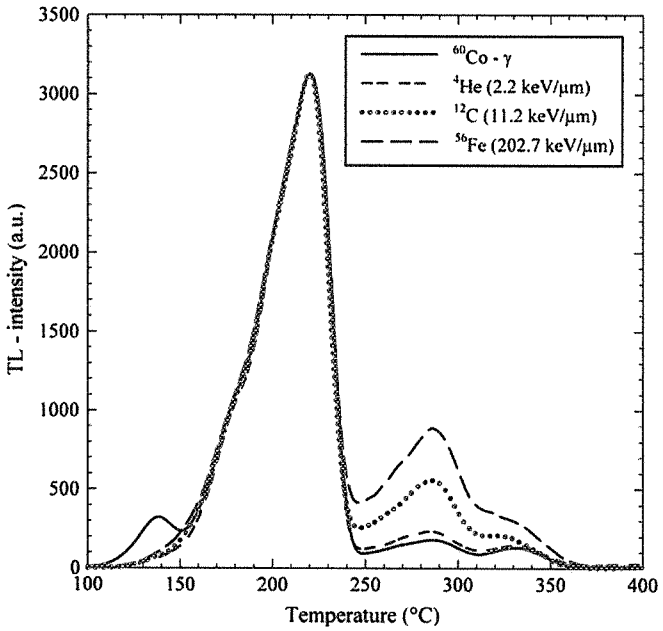

Fig. 9. TLD-700 glow curve after 1 mGy of ^{60}Co gamma rays and 1 mGy of different heavy ions. Glow curves have been normalized to peak 5 height. The high-temperature emission increases with increasing LET of the particle.

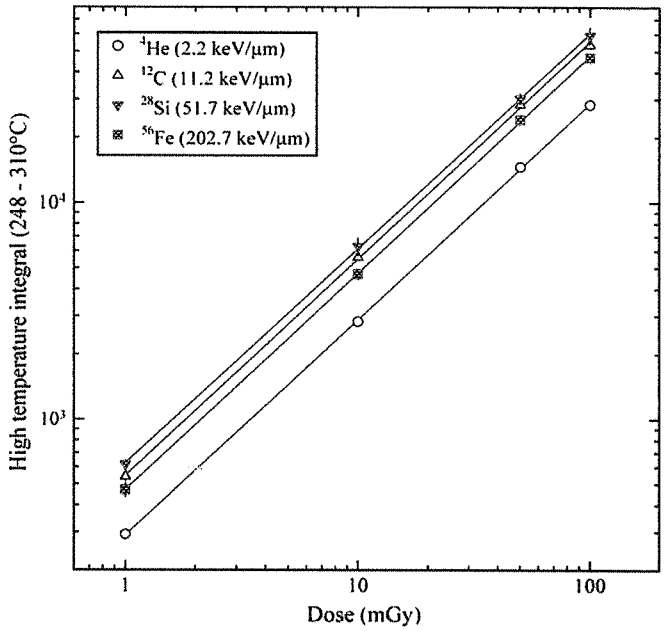

Fig. 11. Dose dependence of the integral high-temperature emission (248–310 °C) in the dose region between 1 and 100 mGy from different heavy ions.

project at the HIMAC in May 2002. Fig. 9 demonstrates that the HTE increases with increasing LET (all glow curves normalized to peak 5 intensity) and that the HTE is already clearly visible after 1 mGy of heavy-ion irradiations. Fig. 10 shows the TLD-700 glow curves (averages over 4 detectors) after irradiation of 1, 10, 50 and 100 mGy of ^{28}Si ions. The high-temperature structure is clearly visible for all the four dose regimes applied.

For these four different doses the HTE integral has been evaluated for the four ions under study. The dose dependent HTE integral is shown in Fig. 11 and it confirms that for the applied TL detector batch and annealing procedure a linear dose–response is observed for the dose region from 1 to 100 mGy.

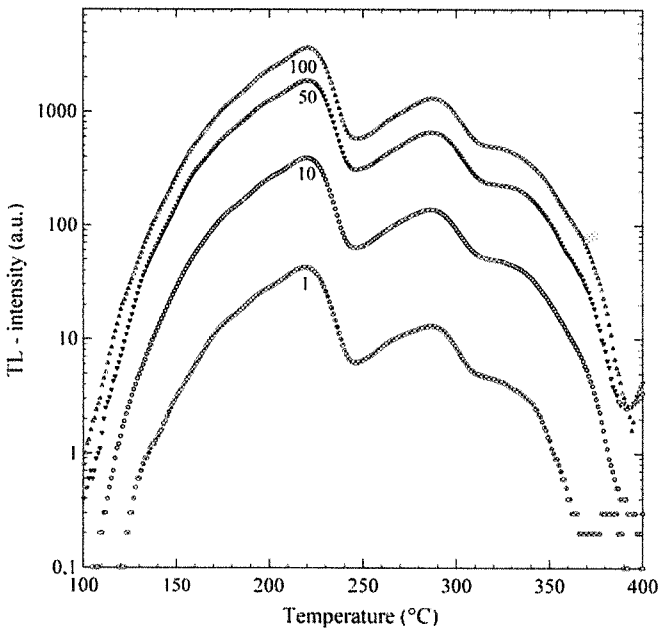

Fig. 10. TLD-700 glow curves after irradiation with 1, 10, 50 and 100 mGy of ^{28}Si (51.7 keV μm^{-1}).

4. Discussion

Shachar and Horowitz (1988) reported supralinearity for the gamma dose–response of peak 7 down to the lowest measureable dose of ~2.5 mGy (observation of peak 7 after CGCD, corresponding to a TL signal intensity of 110 ± 50 counts). Pradhan et al. (1985) demonstrated that "peak 7 rises linearly (within 6%) in the ^{60}Co gamma ray absorbed dose range from 0.03 to 0.15 Gy". Massillon-JI et al. (2006) estimated $f(D) = 1$ for the deconvoluted peak 7 in TLD-100 for doses from 4 up to ~100 mGy. Bilski (2006) reported a linear HTE to peak 5 ratio for doses from 10 to 100 mGy and a lower detection threshold for the high-temperature emission of ~5 mGy after ^{60}Co gamma radiation (Bilski, 2007). All groups used fast cooling following the high-temperature anneal of the chips. The cooling rate influences the intensity of the high-temperature emission as can be seen from Fig. 12 which shows glow curves irradiated with 2.2 mGy (slow cooling) and 4.5 mGy (fast cooling at 5 °C s^{-1}) normalized to the same peak 5 height at 10,000 counts. The differences in the high-temperature structure are clearly visible. While the normally applied annealing procedure with the slow cool down shows a structurized high-temperature emission, the fast cool down procedure reduces the high-temperature structure dramatically. Therefore, subtraction of the background signal becomes crucial for groups applying fast cooling, compared to the slow cooling rate applied by ATI. Slow cooling enhances the signal-to-noise ratio and, therefore, also increases the lower detection limit for the high-temperature emission. However, chamber evacuation and flushing with ultra-pure (5.0) dry N_2 gas are essential prerequisites to avoid adulteration of the HTE by spurious luminescence.

It shall be emphasized that our knowledge of the high-temperature emission in LiF:Mg,Ti is far from being complete and further studies need to be performed using both the HTE composite structure and deconvolution into individual glow peaks.

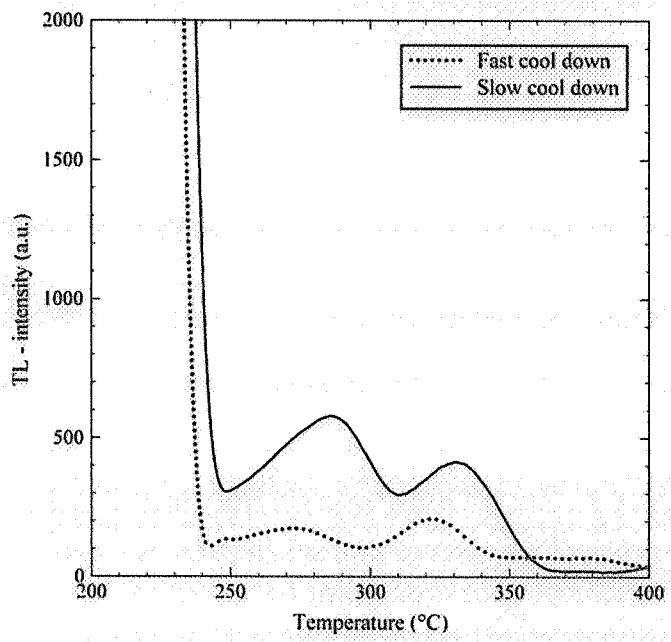

Fig. 12. HTE emission intercomparison for fast and slow cooled down TLD-700 detectors (normalized for better intercomparison on peak 5 height at 10,000 counts).

5. Conclusions

The paper reported on the linearity of the high-temperature emission from ^{7}LiF:Mg,Ti (TLD-700) phosphors. It was shown that for the applied instrumentation and procedures, particularly regarding detector batch and annealing, the HTE is linear with dose between 1 and 200 mGy for ^{60}Co gamma radiation. For the applied readout procedure (ATI standard protocol), the high-temperature structure is clearly visible already at doses around 1 mGy from both gamma rays and heavy ions, without being influenced by the technique of background subtraction. These conclusions do by no means claim to be universal: we strongly support the interpretation that the annealing procedure, especially the slow cooling of the TL detectors, is responsible to a great part for the HTE to be intensified compared to the situation following the usual fast cooling, therefore making a reliable background subtraction a crucial requisite. Further studies about the slope of the dose–response following both gamma as well as heavy-ion irradiations are currently undertaken.

Acknowledgments

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References

Berger, T., 2003. Dose assessment in mixed radiation fields—special emphasis on space dosimetry. Ph.D. Thesis, Vienna University of Technology.

Berger, T., Hajek, M., Fugger, M., Vana, N., 2006a. Efficiency corrected dose verification with thermoluminescence dosemeters in heavy ion beams. Radiat. Prot. Dosim. 120, 361–364.

Berger, T., Reitz, G., Hajek, M., Vana, N., 2006b. Comparison of various techniques for the exact determination of absorbed dose in heavy ion fields using passive detectors. Adv. Space Res. 37, 1716–1721.

Bilski, P., 2006. Response of various LiF thermoluminescent detectors to high energy ions—results of the ICCHIBAN experiment. Nucl. Instrum. Meth. Phys. Res. B 251, 121–126.

Bilski, P., 2007. Private communication.

Hajek, M., Berger, T., Fugger, M., Vana, N., Akatov, Y., Shurshakov, V., Arkhangelsky, V., 2006. Dose distribution in the Russian segment of the international space station. Radiat. Prot. Dosim. 120, 446–449.

Hoffmann, W., Prediger, B., 1984. Heavy particle dosimetry with high temperature peaks of CaF_2:Tm and ^{7}LiF phosphors. Radiat. Prot. Dosim. 6, 149–152.

Horowitz, Y.S., Satinger, D., Puks, E., Oster, L., Podgalov, 2003. On the use of LiF:Mg, Ti TLDs in space—a critical review. Radiat. Prot. Dosim. 106, 7–25.

Horowitz, Y.S., Oster, L., Datz, H., 2007. The thermoluminescence dose–response and other characteristics of the high-temperature TL in LiF:Mg, Ti (TLD-100). Radiat. Prot. Dosim. 124, 191–205.

Jähnert, B., 1972. The response of TLD-700 thermoluminescent dosemeters to protons and alpha particles. Health Phys. 23, 112–114.

Massillon-JL, G., Gamboa-deBuen, I., Brandan, M.E., 2006. Onset of supralinear response in TLD-100 exposed to ^{60}Co gamma-rays. J. Phys. D: Appl. Phys. 39, 262–268.

Pradhan, A.S., Rassow, J., Meissner, P., 1985. Dosimetry of d(14)+ Be neutrons with the two-peak method of LiF TLD-700. Phys. Med. Biol. 30, 1349–1354.

Shachar, B.B., Horowitz, Y.S., 1988. Dosimetric characterisation of the high temperature peaks of LiF:Mg,Ti and CaF_2:Tm using computerised glow curve deconvolution. Radiat. Prot. Dosim. 22, 87–96.

Uchihori, Y., Benton, E. (Eds.), 2004. Results from the First Two Intercomparison of Dosimetric Instruments for Cosmic Radiation With Heavy Ions Beams at NIRS (ICCHIBAN 1&2). NIRS, Chiba HIMAC-078.

Vana, N., Erlach, R., Fugger, M., Gratzl, W., Reichhalter, I., 1988. A computerised TL read out system for dating and phototransfer measurements. Int. J. Radiat. Appl. Instrum. D 14, 181–184.

Waligórski, M.P.R., Katz, R., 1980a. Supralinearity of peak 5 and 6 in TLD-700. Nucl. Instrum. Meth. 175, 48–50.

Waligórski, M.P.R., Katz, R., 1980b. Supralinearity of peak 5 and 6 in TLD-700. Nucl. Instrum. Meth. 172, 463–470.

Yasuda, N., Uchihori, Y., Benton, E.R., Kitamura, H., Fujitaka, K., 2006. The intercomparison of cosmic rays with heavy ion beams at NIRS (ICCHIBAN) project. Radiat. Prot. Dosim. 120, 414–420.

Ziegler, J.F., Biersack, J.P., Littmark, U., 1985. The Stopping and Range of Ions in Solids. Pergamon, New York, 321 pp.