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THE ROLE OF MICRODOSIMETRY IN HEAVY CHARGED PARTICLE INDUCED THERMOLUMINESCENCE DOSE RESPONSE

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ABSTRACT

Microdosimetric phenomenae, not addressed by conventional kinetic calculations in the framework of "conduction band/valence band" atomic models, play an important role in the thermoluminescence (TL) dose response and the relative TL efficiency of various types of radiation fields of different microscopic patterns of ionization density (1). In this paper we discuss Track Interaction Model (TIM) calculations of the heavy charged particle (HCP) induced TL linearity and supralinearity of the various glow peaks of LiF:Mg,Ti,OH.

INTRODUCTION

The normalized TL dose response, f(D), shows in many TL materials, a linear, then supralinear, then sublinear behaviour with increasing dose. The details of the behaviour of f(D) in LiF:Mg,Ti,OH depend upon a large number of experimental and material dependent factors (2), and in addition, f(D) is known to exhibit a strong dependence on ionization density. For example, the maximum supralinearity for peak 5 ($\sim$190°C) begins to decrease with decreasing electron energy below $\sim$275 keV, reaching a value of only 1.2 for 5 keV electrons compared to $\sim$3.5 for Co-60 gamma rays at 1.25 MeV (3). Typical behaviour of f(D) as a function of incident gamma ray energy for peak 5 in LiF:Mg,Ti,OH is shown in Figure 1. For peak 7 ($\sim$275°C) this behaviour is even more pronounced and for 95 kV_p X-rays the supralinearity has almost completely disappeared (4). Even more dramatic is the disappearance of peak 5 supralinearity for low energy ($\sim$ 1 MeV/AMU) HCPs or fast neutrons. On the other hand, peaks 8 and 9 show strong supralinearity induced by low energy alpha particles (5). In general, therefore, the TL dose response in LiF:Mg,Ti,OH can be described by two dominant characteristics: a decrease in the supralinearity with increasing ionization density and an increase in the supralinearity with increasing glow peak temperature. This behaviour is illustrated in Figures 2 and 3.

Two models have been proposed which can explain the decreasing supralinearity with increasing ionization density as well as the linear-supralinear

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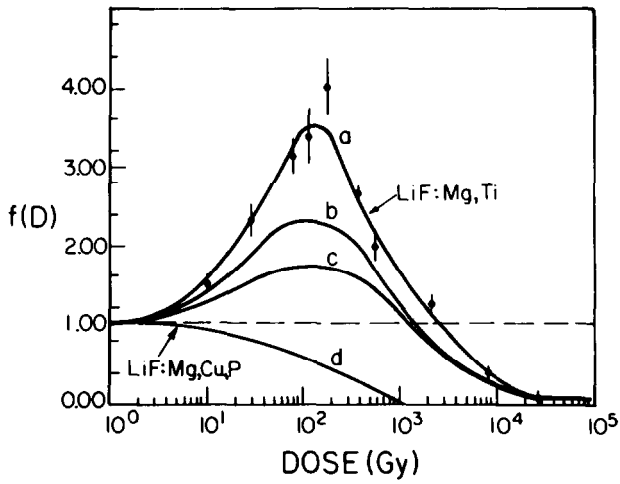

Figure 1. Normalized TL dose response of LiF:Mg,Ti following: a) Co-60 irradiation, b) 50 kV_p X ray irradiation, c) 20 kV_p X ray irradiation, and d) LiF:Mg,Cu,P following Co-60 irradiation.

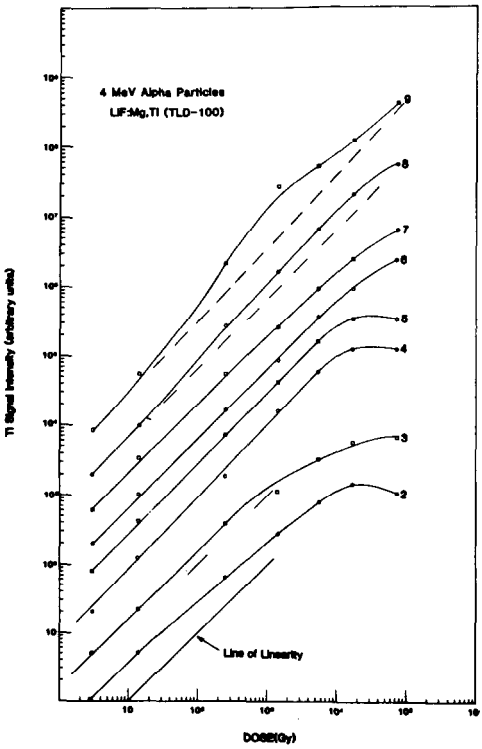

Figure 2. TL dose response curves for peaks 2 through 9 in LiF:Mg,Ti after 4 MeV alpha irradiation.

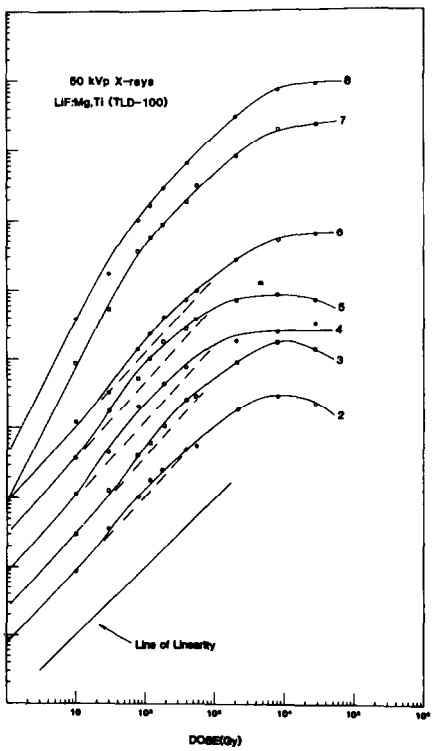

Figure 3. TL dose response for peaks 2 through 8 in LiF:Mg,Ti after 50 kV_p irradiation.

dose response. The first one is the absorption stage, deep trap competition model (6), the kinetics of which have been treated both analytically and numerically by Chen and colleagues (7,8). Horowitz (9), however, has argued against all radiation absorption stage models on the basis of the experimentally observed non-supralinear growth of all the radiation-created optical absorption bands in LiF:Mg,Ti,OH (eg., (10,11)). Other arguments against absorption stage models have recently been reviewed by McKeever and Horowitz (12). The Track Interaction Model was first suggested by Claffy et al (13), elaborated on by Attix (14) and analytically formulated for HCPs by Horowitz et al (15-18). In the following we shall see how the TIM requires a competitive mechanism in the luminescence recombination stage in order to explain all the features of TL supralinearity in LiF:Mg,Ti,OH.

THE TRACK INTERACTION MODEL

The TIM postulates that electrons and holes are trapped near the track of the ionizing particle and that some of these activate centers which serve as TL trapping and recombination centers. The distances between the tracks at low doses are large enough for the recombination, during glow curve heating, to occur between charge carriers and the activated luminescence centers in the same track only. The TL dose response is linear in this region. In order for inter-track migration not to occur at low dose levels, the unirradiated regions between the tracks must be inhabited by non-radiative, competing centers which can localize electrons without producing luminescence. At higher doses, when the distances between the tracks become comparable with the average separation of the activated centers along each track, the probability that a charge carrier generated in one track will recombine with a luminescence recombination center produced along another track increases and the TL dose response rises more rapidly than linearly. As the incident gamma irradiation energy decreases, or if the irradiation is via HCPs, the tracks are even more localized, requiring even greater dose levels to initiate track interaction. Thus, the TIM naturally accomodates the ionization density dependence of TL supralinearity. Since the capture cross-section for Coulombic attractive traps and recombination centers is believed to follow a T^{-n} dependence (19). the effectiveness of the competing centers may decrease with increasing glow peak temperature. The TIM thus naturally accomodates the generally observed increasing supralinearity with increasing glow peak temperature.

We have used to advantage the fact that HCP tracks define a straight line track axis around which a nearly cylindrical volume of ionization creates, on the average, an amenable geometry for the calculation of inter-track effects.

APPLICATION TO HEAVY CHARGED PARTICLES

In the TIM applied to HCPs the probability of a released charge carrier migrating from one track to its nearest neighbour, at distance r, is approximated by a two dimensional solid angle factor multiplied by an exponential attenuation factor, $\exp(-\alpha r)$, representing the probability of the migrating charge carrier not being captured by the competing centers. This probability is then multiplied by the first nearest neighbour probability function and integrated over all values of r from r_0 to ∞, where r_0 is the effective radius of the HCP irradiated volume and is $\sim$200 Å for 4 MeV alpha particles in LiF. The resulting expression for f(n), where n is the HCP fluence, is:

$$f(n) = 1 + 2\pi n^{1/2} r_0 \, \mathrm{erfc}\{(\pi n)^{1/2} r_0 + (\alpha/2)(\pi n)^{-1/2}\} \qquad (1)$$

Equation (1) is capable of quantitatively predicting the alpha-particle-induced supralinearity of glow peak 8, (Figure 4) as well as the linear behaviour of the low temperature glow peaks. The supralinearity arises from an average

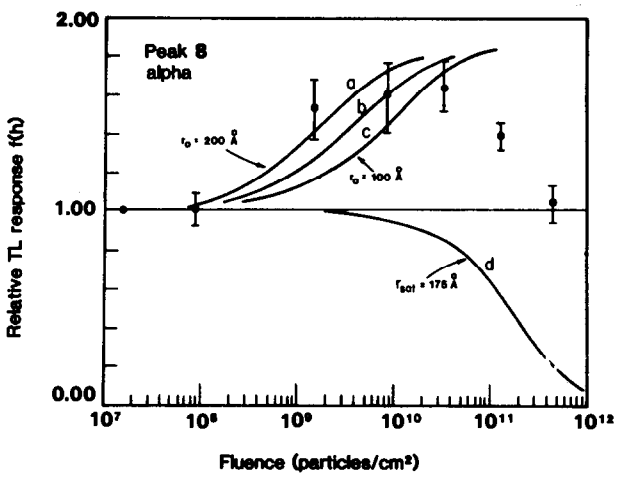

Figure 4. The relative TL response f(n) for peak 8 plotted against alpha particle fluence. Curve d shows how the saturation in the TL response can be phenomenologically understood using r_{sat} = 175 A (15). Curves a-c are the calculated results using equation (1) and illustrate how increased charge carrier migration distances between nearest neighbour tracks accurately predicts TL supralinearity.

charge carrier migration distance of $\sim$5000 Å at the temperature of peak 8 ($\sim$290°C) bringing about significant nearest neighbour track interactions at a fluence of $\sim 10^8$ particles cm^{-2}. The linear behaviour of all the low temperature peaks up to n = 10^{10} particles cm^{-2} yields an average charge carrier migration distance of $\sim$250 Å. This is consistent with the premise that at low

sample temperatures there is negligible inter-track migration of the charge carriers.

The dependence of the supralinearity on ionization density and the success of the TIM described herein suggests that the wave packet of the thermally freed electron maintains a high degree of localization around the HCP track. This appears to conflict with the conduction band/valence band kinetic interpretation which assumes that the electron wavefunction is delocalized once the electron is raised to the conduction band and can recombine anywhere within the crystal and not just within the track. McKeever and Horowitz (12), however, have pointed out that the HCP track represents a region of high defect density and the potential distribution in the vicinity of the track will be markedly different from the 'perfect' crystal outside the track. Thus, solutions to the Schrodinger equation inside the track will predict a different energy gap to that outside the track. In this sense, the freed electron will be 'delocalized' but will be confined to the track volume and will have to overcome potential barriers before it can move between the tracks.

Kinetic models which assume a constant energy gap throughout the crystal volume may be inappropriate for describing charge migration and recombination over regions greater than the track volume. However, they will be good approximations of the situation within the track and may provide good descriptions of the recombination processes taking place inside the track volume. For this reason kinetic analyses retain their general validity.

In summary, the TIM, incorporating greatly increased charge carrier diffusion lengths in the luminescence recombination stage with increasing sample temperature, correctly describes the details of the alpha particle-induced linearity and supralinearity in LiF:Mg,Ti. It is reasonable to believe that the same mechanism underlies the increase in supralinearity in the gamma ray-induced TL dose response curves as a function of glow peak temperature. It appears, therefore, that the track interaction model should be viewed as the model providing the microdosimetric framework which, when coupled with other appropriate physical mechanisms (spatial localization of traps and recombination centers, competing centers, variation in the capture cross-section with temperature) can be used to describe all the dominant features of the linear/supralinear behaviour of LiF:Mg,Ti.

In other areas of interest as well, for example the relative response of X-rays and HCPs, microdosimetry plays a crucial role (12). On the other hand, it has very little to say concerning TL signal stability, where the physics of the trapping centers themselves is of major importance. Finally, as we have mentioned, it is also necessary to reconcile the dual validity of

the microdosimetric interpretation and the conduction/valence band kinetic interpretation since the former requires that the charge carriers are delocalized in the region of the track and not throughout the crystal. Exact modelling of these processes is an extremely formidable problem.

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