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Review
Thermoluminescence dosimetric properties of beryllium oxide

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Beryllium oxide (BeO) displays strong thermoluminescence (TL) together with tissue-equivalent properties which underline its application as a TL dosimeter. In the dosimetry of X- and γ-rays some of the advantages of BeO over other TL materials are its commercial availability, low cost, chemical inertness, non-toxicity (as a ceramic), high sensitivity to ionizing radiations, good reproducibility of response, low fading, absence of low-temperature peaks and moderate energy dependence. Various authors have reported glow curves of BeO TL phosphor, whose dominant dosimetric peak lies between about 160 and 200 °C. The position of this peak, however, depends upon the type of the radiation used for exciting the phosphor. Although fading of TL is nominal when kept in the dark, the γ-exposed BeO phosphors fade faster when exposed to ambient light. When exposed to γ-radiation, these phosphors exhibit linearity from a minimum of about 1 mrad (1 rad = 10^{-2} gray) up to approximately 10 rad, above which there is supralinear behaviour, and the concentration of impurity ions in BeO is reported to expand the linearity region. Ceramic samples have been reported to exhibit a roughly flat response when exposed to X-rays of 30–115 keV and γ-rays of 60Co. Because their response to thermal neutrons is negligible compared to the γ-component, the use of BeO has been suggested to measure the γ-component in the (n, γ) mixed fields.

1. Introduction
High melting point (2570 °C) beryllium oxide (BeO) ceramics are refractory materials having high electrical resistivity ( > 10^{13} Ωcm), high thermal conductivity (as high as that of aluminium), a wide band gap of about 10.6 eV [1], and a low thermal neutron cross-section (10 mb). These properties render them suitable for use in refractory ware, as heat sinks for electronic devices and as high-efficiency moderators and reflectors in nuclear reactors. BeO also displays strong TL together with tissue-equivalent (Z_{eff} = 7.1) properties which underline its application as a TL dosimeter.

In the dosimetry of X- and γ-rays, some of the advantages of BeO over other TL materials are their commercial availability, low cost, chemical inertness, non-toxicity (as a ceramic), resistance to mechanical shocks, low fading, the absence of low-temperature peaks and moderate energy dependence. The low neutron sensitivity makes the application of BeO promising in mixed γ-neutron radiation fields, primarily as an inexpensive nuclear accident dosimeter [2].

However, these phosphors have some disadvantages, i.e. they emit a small amount of tribo-TL and possess a characteristic light-stimulated fading which can be overcome by precautions when handling preferably in red or yellow light. BeO is highly toxic when used in powder form but, on the other hand, completely harmless when used in the form of sintered pellets and chips. This paper reviews the various TL and dosimetric properties of BeO phosphors leading to their applications in radiation dosimetry.

2. Preparation methods
BeO is commercially available in the undoped form under the commercial name “Thermalox 995” manufactured by Brush Beryllium Co., Elmore, OH, USA, with a total content of impurities not exceeding 0.5% [3], the major impurities being, 2150 p.p.m. Si, 945 p.p.m. Mg, 100 p.p.m. Fe, 60 p.p.m. Ca and 55 p.p.m. Al. After igniting a mixture with a proper mineralizer, the amorphous BeO is transferred into a micro-crystalline state (hexagonal wurtzite structure) which is further sintered under high temperature and pressure. Tomita and Tsutsumi [4] used BeO ceramics (obtained from NGK Insulator Ltd, Japan) with impurities of silicon and calcium (100 p.p.m.), sodium (50 p.p.m.), magnesium, iron and nickel (20 p.p.m.).

Yamashita et al. [5] prepared lithium and sodium-doped BeO, i.e. BeO (Li 0.5 mol %) and BeO (Na 0.5 mol %). Purified BeO powder and a small quantity of dopant powder were mixed in proper ratio. The dopant materials used were SiO_2, GeO_2, Al_2(SO_4)_3 and Na_2SO_4. The mixture was press-formed into rod
and disc shapes, sintered at a temperature of more than 1500°C and cooled slowly. As a dosimeter sample, glass-encapsulated ampoules were prepared, because ceramic samples without surface treatment were often soiled by dust or repeated use. The ceramics were ground into small grains, 100–300 μm in diameter, and sealed into a glass ampoule.

BeO discs were prepared by Scarpa [6] in three different grades: (i) slip cast (SC), (ii) hot-pressed (HP) and (iii) nuclear quality (NQ), depending upon their method of sintering, density and chemical purity. The SC grade was sintered without pressure and its normal density was 2.2 g cm\(^{-3}\). The density of HP and NQ types was higher, reaching 2.8 g cm\(^{-3}\). The main impurities were silicon, sodium, fluorine, sulphur and carbon, their typical impurity levels in SC and HP being 0.4% but only 25 p.p.m. for NQ.

Kortov et al. [7] have prepared and studied several types of commercial BeO ceramics with a view to their possible application in TL and/or ESR dosimetry. The best results were obtained with optically transparent high-density ceramics with little tendency to sputtering, simultaneously doped with lithium and neodymium ions and having no pyroelectric effects during heating and cooling. A mixed BeO:TiO\(_2\) ceramic, showing high electrical conductivity, has been subjected to preliminary investigation with regard to its application in thermally stimulated exoelectron emission (TSEE) and TL dosimetry [8]. The two oxides have been observed to construct independent substructures in the mixed ceramic. The TiO\(_2\) substructure provides electrical conductivity, and was passive from the TL and TSEE point of view, whereas the BeO substructure was found to be fully responsible for the dosimetric signals.

3. TL and dosimetric characteristics
The calculated effective atomic number, \(Z_{\text{eff}}\), of BeO is 7.1 compared to 7.5 for water and soft tissue [9].

3.1. Glow curves
BeO:Li (0.5 mol %) and BeO:Na (0.5 mol %), prepared by Yamashita et al. [5], show glow peaks at 180°C. The curve shape does not vary for exposure levels between 1 mrad (1 rad = 10\(^{-2}\) Gy) and several hundred rad. At more than 1000 rad, the glow curve changes and a new peak appears at about 210°C.

Hobzova [10] noticed three peaks in BeO at 50, 190 and 280°C when excited by β-rays and only two peaks at 190 and 280°C when excited by ultraviolet light (Fig. 1). Busuoli and Julius [11] also observed glow curves in BeO with two distinct maxima at \(\sim 180\) and \(\sim 280\)°C and the third at 60°C. Lakosi et al. [2] have shown that the glow curve of BeO displays two peaks; one at about 200°C and the other \(\sim 360\)°C. The position of the first peak depends on the dose value. For higher doses the first peak shifts to 260°C making it a dominant peak, whereas the peak at 360°C is reduced to a negligible value.

When excited by X-rays (\(\sim 1.5 \times 10^3\) rad dose), glow curves occur at 150 and 260°C [4] which are roughly in agreement with most of the reported results on various BeO samples. However, the structure of the glow curves depends upon the preparation parameters, such as concentration of impurities and the magnitude of the absorbed dose.

Scarpa [6] showed the effect of the physical form of the BeO dosimeter on its TL. High-temperature glow peaks at \(\sim 530\) and 630°C have also been observed in “Thermalox 995” tablets when irradiated by β-particles and X-rays (dose \(\sim 180\) Gy) [12]. TL of BeO has been reported to have two well-separated peaks at 222 and 369°C [13]. The activation energy values, found using different measurement methods, were in good agreement. A kinetic order of about two has been determined for the first peak, whereas the second peak follows first-order kinetics.

BeO exhibits TL emission from the blue region of the visible spectrum to the ultraviolet up to the lower limit of 200 nm [4, 5, 9, 11, 12, 14–16] (Fig. 2) which depends upon the nature of the glow curve. Different glow peaks show different TL emission spectra. This implies that to obtain maximum sensitivity, BeO must

\[\text{Figure 1 Glow curves of (1) BeO (Thermalox 995) irradiated to 700 rad of }\beta\text{-rays and (2) BeO exposed to ultraviolet light for 5 min [10].} \]

\[\text{Permission granted by Health Physics.}\]

\[\text{Figure 2 TL emission spectra of BeO (Li) and BeO(Na) observed after being exposed to }^{137}\text{Cs }\gamma\text{-rays at 1000 rad [5].} \]

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