EXTINCTION COEFFICIENT USED AS PARAMETER IN GAMMA-RAY DOSIMETRY

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Abstract. In this paper, the variation of the extinction coefficient as a result of the exposure to gamma-ray was studied. The material used in this study was BK-7 type glass. Several samples were exposed to gamma-ray (Co-60) in order to obtain different absorbed dose values. By using photo-spectrometric measurements, different extinction coefficient values as a function of the absorbed dose, were obtained. The results showed that the dependence of the extinction coefficient to the absorbed dose presents linear regions, which make it a quantity that can be used in gamma-ray dosimetry.

Key words: extinction coefficient, gamma-ray dosimetry, absorbed dose.

1. INTRODUCTION

The main optical phenomena producing when light reaches a material are transmission, reflection and absorption [1–4]. By measuring these three parameters using photo-spectrometric techniques, a quantification of other important secondary optical parameters can be obtained [5]. It was demonstrated that the propagation speed and the other characteristics of the electric field carried by an electromagnetic field depend to the properties of the passing thru materials [6–9].

In this paper, the variation of the extinction coefficient as a result of the exposure to gamma-ray was studied, starting from high quality photo-spectrometric measurements [10–14].

The extinction coefficient is an optical parameter which measures the absorption of light in a medium and it is represented by the imaginary part of the complex index of refraction. When the light is passing thru a medium, some part of it is attenuated, fact that can be expressed by defining a complex refractive index, Equation (1):

$$n = n + i \times k$$

(1)
In Equation (1) the real part \( n \) is the refractive index and indicates the phase velocity, while the imaginary part \( k \) is called the extinction coefficient and indicates the amount of attenuation when the electromagnetic wave propagates through the material [1]. The phase velocity of a wave is the rate at which the phase of the wave propagates in space. Both \( n \) and \( k \) are dependent on the frequency. In most cases \( k > 0 \) (light is absorbed) or \( k = 0 \) (light travels without loss). In some special cases, especially in the gain medium of lasers, it is also possible that \( k < 0 \), due to an amplification of the light. The real and imaginary parts of the complex refractive index are connected through the Kramers–Kronig equations [15–20].

The material used in this study was BK-7 type glass, several samples being exposed to gamma-ray in order to obtain different absorbed dose values. Different extinction coefficient values, as a function of the absorbed dose, were determined. The results showed that the dependence of the extinction coefficient to the absorbed dose presents linear regions, which make the extinction coefficient a quantity that can be used in gamma-ray dosimetry [21, 22].

2. MATERIALS AND METHODS

A number of ten BK-7 type glass samples of 10 mm thickness were exposed to a Co-60 gamma-ray source (mean energy of 1.25 MeV), inside an irradiation chamber, in order to obtain different absorbed dose values (Fig. 1).

![Absorbed doses in the exposed samples](image)

Fig. 1 – Absorbed doses in the exposed samples.
A constant dose debit of 6.2 kGy/h was used. The obtained doses values were placed between 0.04 kGy and 21.0 kGy. For the measurements of absorbed doses, an ECB (ethanol-chlorobenzene) dosimeter system with an average measurement uncertainty of 2.5 % (for a coverage factor $k = 2$) was used. After the exposure of the samples, high quality photo-spectrometric measurements were performed [23–27].

3. RESULTS AND DISCUSSIONS

The variation of transmitted light intensity thru the irradiated glass samples as a function of the absorbed dose is shown in Fig. 2. As it can be seen, the transmitted light intensity is decreasing with the increase of the absorbed value. The fact that transmitted light intensity is decreasing with the increase of the wavelength can be also seen, due to the fact that a higher wavelength means a lower frequency. A lower frequency means a lower energy transported by the involved electromagnetic wave, which leads to a higher absorption when traveling thru a volume of material.

![Graph showing transmitted light intensity as a function of absorbed dose.](image)

Fig. 2 – Transmitted light intensity ($I_{tr,i}$) as a function of absorbed dose.
Extinction coefficient values were determined using the following Equation (2):

\[ k_i = \frac{\lambda_i}{4\pi x} \times \ln \frac{I_0}{I_{tr,i}}, \]  

(2)

where: \( \lambda_i \) – used wavelength;  
\( I_{tr,i} \) – transmitted light intensity (thru exposed glass samples) for the specific \( \lambda_i \) wavelength;  
\( I_0 \) – initial intensity of the light source;  
\( x \) – sample thickness (10 mm).

The analytical expression of the variation of extinction coefficient as a function of the absorbed dose has the following form (3):

\[ k(D)_i = \frac{\alpha(D)_i \times \lambda_i}{4\pi}, \]  

(3)

where: \( \lambda_i \) – used wavelength;  
\( k(D)_i \) – the extinction coefficient for an absorbed dose value \( D \), for the specific \( \lambda_i \) wavelength;  
\( \alpha(D)_i \) – absorption coefficient for an absorbed dose value \( D \), for the specific \( \lambda_i \) wavelength.

The absorption coefficient was determined using Equation (4):

\[ \alpha(D)_i \cong \frac{1}{x} \times \ln \left( \frac{I_0}{I_{tr,i}} \right), \]  

(4)

where: \( \lambda_i \) – used wavelength;  
\( I_{tr,i} \) – transmitted light intensity (thru exposed glass samples) for the specific \( \lambda_i \) wavelength;  
\( I_0 \) – initial intensity of the light source;  
\( x \) – sample thickness (10 mm).

The variation of the extinction coefficient as a function of the absorbed dose is presented in Fig. 3. An increase of the extinction coefficient value with the increase of the absorbed dose and with the decrease of wavelength can be seen. In Fig. 3 it can also be seen that the slope of the dependence between the extinction coefficient and the absorbed dose, showing the speed of change, is decreasing with the increase of the wavelength, meaning that by using a lower wavelength, the sensitivity of the method is increasing [28, 29].
Extinction coefficient used as parameter in gamma-ray dosimetry

Since the dependence of the extinction coefficient to the absorbed dose is linear on certain absorbed dose intervals ([0.16–21.0] kGy), as it can be seen in Fig. 3, it can be used successfully as a parameter in gamma-ray dosimetry.

The expression of the dependence between the extinction coefficient and the absorbed dose is obtained by fitting the experimental data, its general form being presented in Equation (5):

$$k_i = (a_k)_i + (b_k)_i \times \log(D),$$  \hspace{1cm} (5)

where: $k_i$ – extinction coefficient for an absorbed dose value $D$, for the specific $\lambda_i$ wavelength;

$i$ – index (1, 2, 3) corresponding to used wavelength (475 nm, 490 nm, 530 nm).

The general form of the Error Propagation Law [30–32] applied to Equation (5) is presented in Equation (6), as follows:
The general form of the Error Propagation Law applied to Equation (2) is presented in Equation (7), as follows:

\[
\sigma^2_h = \sigma^2_{(a_h)} + (\log(D))^2 \times \sigma^2_{(b_h)} + \left( \frac{(b_h)_i}{2.3 \times D} \right)^2 \times \sigma^2_D. \tag{7}
\]

By analytical calculus, the Equation (2) becomes Equation (8), as follows:

\[
D = 10^{\frac{k_i - (a_i)_i}{(b_i)_i}}. \tag{8}
\]

The Equation (8) is practically the general form of the dependence of the absorbed dose value to the value of the extinction coefficient. By using this expression, an unknown absorbed dose value can be determined, only by determining its corresponding extinction coefficient value.

The general form of the Error Propagation Law applied to Equation (8) is presented in Equation (9), as follows:

\[
\sigma^2_D = \left( \frac{\partial D}{\partial (k)_i} \right)^2 \times \sigma^2_k + \left( \frac{\partial D}{\partial (a)_i} \right)^2 \times \sigma^2_{(a_i)} + \left( \frac{\partial D}{\partial (b)_i} \right)^2 \times \sigma^2_{(b_i)}. \tag{9}
\]

The concrete form of the Error Propagation Law applied to Equation (8) is given by the Equation (10), as follows:

\[
\sigma^2_{D_i} = \left( \frac{2.3 \times D \times 10^{\frac{(a_i)_i - k_i}{(b_i)_i}}}{(b_i)_i \times \sqrt{D^2 - 10}} \right)^2 \times \left[ 2 \times \sigma^2_{(a_i)} + \left( \log(D)^2 + \left( \frac{k_i - (a_i)_i}{(b_i)_i} \right)^2 \right) \times \sigma^2_{(b_i)} \right]. \tag{10}
\]

All the quantities from Equation (10) are known, Table 1. The Equation (10) represents practically the uncertainty associated to the method presented in this paper.

By fitting the extinction coefficient as a function of the absorbed dose value, the calibration curves were obtained, as it can be seen in Table 2. By using them, an unknown absorbed dose value can be determined.
The fitting parameters and their associated uncertainties

<table>
<thead>
<tr>
<th>The absorbed dose range [kGy]</th>
<th>Wavelength [nm]</th>
<th>Fitting parameters</th>
<th>(a)</th>
<th>(b)</th>
<th>(\sigma_a)</th>
<th>(\sigma_b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16–21.0</td>
<td>475</td>
<td>(k_1 \times 10^{-7})</td>
<td>34</td>
<td>45</td>
<td>1.9</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>490</td>
<td>(k_2 \times 10^{-7})</td>
<td>32</td>
<td>44</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>530</td>
<td>(k_3 \times 10^{-7})</td>
<td>28</td>
<td>35</td>
<td>1.7</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 2
Absorbed dose value as a function of extinction coefficient for 475 nm, 490 nm and 530 nm wavelengths

\[
D_i = 10^{k_i \cdot \text{[nm]} - 4.5 \times 10^{-5}}
\]

Depending of what wavelength is used for determining the extinction coefficients, one of the three calibration curves from Table 2 can be used as follows: the first one is valid when a 475 nm light source is used, the second one when a 490 nm light source is used and the third one when a 530 nm wavelength is used. All three calibration curves from Table 2 are valid only on a dose range between 0.16 kGy and 21.0 kGy.

4. CONCLUSIONS

As it was shown in this paper, the exposure of optical glass to gamma-ray leads to modifications of its parameters, such is its extinction coefficient. The values of the extinction coefficient were determined for ten BK-7 glasses exposed to gamma-ray, by using photo-spectrometric measurements.

As it was shown, the extinction coefficient can be used as a dosimetry parameter, since its dependence to the increase of the absorbed dose is linear on certain intervals.
It was shown that the slope of the dependence between the extinction coefficient and the absorbed dose is decreasing with the increase of the wavelength, meaning that by using a lower wavelength, the sensitivity of the method is increasing.

The analytical expression of the variation of extinction coefficient as a function of the absorbed dose was obtained. The expressions obtained for the dependence of extinction coefficient to the absorbed dose represent the calibration curves, valid on a dose range between 0.16 kGy and 21.0 kGy. By using them, an unknown absorbed dose value can be determined. The useful doses range can be extended by using different types of glass, different samples thicknesses and different wavelengths.

Using the uncertainties propagation law, the uncertainty associated to the method was determined.

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