Fluorescence yield for plastic scintillators after irradiation

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Abstract

The ratio of the fluorescence yield versus wavelength for plastic scintillators EJ-408 and EJ-260 before and after irradiation by a ^{60}Co source for doses of 50, 30, 10, 4, and 2 Mrad at various dose rates and for different concentrations of the primary and secondary dopant. While the nominal dopant concentration gives the highest light output prior to irradiation, a higher concentration is found to be optimal for irradiated plastics.

Keywords: plastic scintillator, fluorescence, radiation hardness

1. Introduction

Organic scintillators (such as toluene, polystyrene, and naphthalene) containing wave-length shifting additives in solution have long been popular elements in detectors used in particle physics, nuclear physics, radiation safety, and heath physics applications due to their high light output, low cost, fast response, and versatility of physical construction. Prolonged exposure of plastic scintillator to ionizing radiation, however, can result in damage: light self-absorption (yellowing) increases and initial light yield decreases. In this paper, we present measurements of ratio of the light output before and after irradiation for two different types of plastic scintillator manufactured by Eljen corporation, EJ-408

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and EJ-260, before and after irradiation by a ^{60}Co source for doses of 50, 30, 10, 4, and 2 Mrad at various dose rates and for different concentrations of the primary and secondary dopant. Dose rate effects are of interest because materials testing is typically done at much higher dose rates, because of the cost of reactor time, than the scintillator will experience in use.

Dose rate effects are well documented for radiation-induced yellowing, as the induced attentuation length in plastic scintillators has been the study of extensive studies [1], [2], [3], [4],[5],[6],[7]. Especially, the presense of oxygen plays an important role. As discussed in [6], the presense of oxygen increases the number of migration mechanisms for the radicals produced during irradiation. The diffusion of oxygen into the scintillator thus provides a mechanism for radiation damage to depend not only on dose, but also on time and on dose rate. Simulations based on oxygen diffusion have been shown to reproduce time dependence of the induced attentuation length in scintillators based on polystyrene and PMMA[2]. They show that the penetration depth of oxygen into the substrate depends on the dose rate: at lower dose rates, oxygen penetrates more deeply. Because of the importance of the interaction of oxygen with radicals produced from the substrate during irradiation, this can lead to dose rate effects for radiation damage. They also show that the recovery of the induced self absorption after irradiation (bleaching) is consistent with oxygen diffusion. They show that there is little bleaching without oxygen, and that a very large number of color centers form if there is no oxygen, although the permanent damage after bleaching (exposure to oxygen after the radiation) is slightly larger if there is oxygen.

Studies on the effect of radiation on the light yield are fewer than those on self-absorption. In an early study, Rosman and Zimmer[8] found that the light output for organic scintillators based on polystyrene versus dose is described, approximately and for relatively large dose rates, by a double exponential, with a small-dose component whose constant is approximately 100 Mrad. For a polystyrene scintillator doped with 1.5% TPB, they also used UV light to illuminate the samples with 1.5% TPB, and found that this showed less reduction

of light than excitation via charged particles. Since polystyrene is transparent to UV, this indicates that the TPB was not damaged, and instead the damage was either to the polystyrene or the migration of excitation from the polystyrene to the dopant.

In [2], decreased light output for a plastic scintillator from Kuraray, SCSN-38, which is based on polystyrene with b-PBD and BDB dopants, was seen. The main absorption wavelengths for polystyrene typically range between between 230 to 260 nm, for the primary dopant b-PBD between 270 to 330 nm, and for the wavelength shifting dopant BDB between 310 to 400 nm. They found that light loss was much stronger in the presence of oxygen. Note that while oxygen plays a beneficial role in regards to annealing of induced absorption length at the end of radiation, it plays a detrimental role in regards to light output. They also found the light output loss was independent of the wavelength of the light that was used to excite the scintillator when it was varied between 230 and 400 nm. From this they conclude that the damage is due to destruction of the second flour. This is different than what was found in the Rosman and Zimmer study, which indicated that damage to the dopants was small and that damage was mostly to the substrate, although different dopants were used in the studies. By looking at the damage as a function of the thickness of the scintillator, they concluded that the BDB molecules are mainly destroyed near the surface, which lends support to a mechanism involving oxygen diffusion.

If the damage is due to oxygen diffusion, a dose rate effect is expected. An interesting result is described in [9], in 1996. They look at light output reduction for two polystyrene-based scintillators (SCSN-38 and SCSN-81) and a polyvinyltoluene-based scintillator (Bicron-499-35). They find a reduction in light output that depends linearly on the log of the dose rate for dose rates ranging from 0.01 to 2 Mrad/hr. Note that the effect is not small: for a dose of 2 Mrad, the light loss is negligible for a dose rate of 2 Mrad/hr but 20% for a dose rate of 0.01 Mrad/hr for SCSN-81.

In order to understand the relative role of destruction of the dopants versus damage to the substrate for modern scintilating plastics, we have studied

the light output for two plastic scintillators, EJ-408 and EJ-260, varying the concentration of the dopants, for different total doses and dose rates.

2. Measurements

Both EJ-408 and EJ-260 use polyvinyltoluene as a substrate. EJ-408 has a light output that is 60% of anthracene and a wavelength of maximum emission of 435 nm. EJ-260 also has a light output that is 60% of anthracene but a wavelength of maximum emission of 490 nm. Eljen prepared scintillator bars with dimensions of 1x1x5cm. For the EJ-408, bars were made with concentration of the primary scintillation dopant at 0.5, 1.0, 1.5, and 2.0 that of the standard concentration. For the EJ-260, bars with made with concentrations of the primary (x) and secondary (p) dopant of 1x1p, 2x1p, 1x2p, 2x2p, 4x The fluorescence output was measured

3. Interpretation

If this dose rate effect is due to oxygen diffusion, then we expect it to be governed by the diffusion equation. Since the oxygen diffusion depth is greater at lower dose rates, we expect the damage for the same dose at different dose rates to increase up to the point where the dose rate is low enough that oxygen permeates the entire sample. The dose rate effect should plateau at this point. Specifically, we predict that the light output reduction should depend on both the dose and the dose rate as:

$$L(R, D) = 1 - [f(D)Z(R) + a(D)(1 - Z(R))]$$

where L is the % light yield, D is the dose, R is the dose rate, Z(R) is the fraction of the scintillator containing oxygen and is given by $min(\frac{2z_0(R)}{d}, 1)$ where d is the thickness of the scintillator and z_0 gives the depth of scintillator penetrated by oxygen, a(D) is related to the fraction of quenching in the part of the scintillator containing oxygen and is given by $1 - e^{-a_0 D}$, and f(D) is related to the fraction

of quenching in the part of the scintillator not containing oxygen and is given by $1 - e^{-f_0 D}$. The diffusion depth $z_0(R)$ is given by diffusion theory as

$$z_0(R) = \sqrt{\gamma / R}$$

where γ is a property of the substrate and the radicals that are dissolved in that substrate during the diffusion process. The value for γ depends on the material, oxygen pressure, radical concentration (which is proportional to the dose) and temperature. The minimization in Z(R) occurs because the fraction of scintillator containing oxygen can not exceed one. Note that this equation assumes the temperature and the surrounding atmosphere is held constant, as this can affect diffusion.

4. Conclusions

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