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Properties of plastic scintillators after irradiation ☆

Zhao Li[a,b,*], Wu Chong[b], Heng Yuekun[b], Zhao Xiaojian[b], Shi Feng[b], Sun Zhijia[b], Wu Jinjie[b], An Zhenghua[b], Zhao Yuda[b,c], Zhang Ziping[a], Wang Yifang[b]

[a]*Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*
[b]*Institute of High Energy Physics, CAS, Beijing 100049, China*
[c]*Department of Physics, Nanjing University, Nanjing 210093, China*

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Abstract

The radiation damage characteristics of three types of plastic scintillators, BC-408, EJ-200 and BC-404, are experimentally studied. The results show that after irradiation, the light yield and light transmission of these scintillators decrease and the shapes of the excitation and emission spectra remain unchanged. Recovery of light yield is not observed after weak irradiation.

Keywords: Plastic scintillator; Light transmission; Spectrum; Light yield; Radiation damage

1. Introduction

Scintillators are transparent materials that emit light upon excitation by energetic charged particles. There are in general three kinds of scintillators, inorganic, organic and gaseous. Plastic scintillators are based on organic fluors. They have many advantages such as fast rise and decay time, high optical transmission, ease of manufacturing, low cost and large available size. For these reasons they are widely used in Time-of-Flight (TOF) systems for particle identification. Since particle detectors usually are used in a radiation environment, the radiation resistance of plastic scintillators is of great importance. The radiation damage of scintillators, usually characterized by decreasing light yield and transmission as a function of total dose or dose rate, has been studied in the past [1–5].

Currently the upgrade of the Beijing Electron-Positron Spectrometer (BESIII) is underway [6], and its TOF system provides signals for particle identification and level 1 trigger. The study of commonly used PolyVinylToluene (PVT) plastic

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*Corresponding author. Institute of High Energy Physics, CAS, Beijing 100049, China. Tel.: +86 10 88236189.
E-mail address: zhaoli78@mail.ihep.ac.cn (Z. Li).

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scintillators, BC-404, BC-408 and EJ-200, and their properties after irradiation, is important for the BESIII detector and useful for the community. In this paper we report results for the radiation damage of these plastic scintillators, including light transmission, light output, excitation and emission spectra, etc.

2. Experimental setup

The main characteristic parameters provided by manufacturers [7,8] of plastic scintillators to be tested are listed in Table 1. Each sample was machined to be a cylinder with a length of 6 cm and a diameter of 3 cm. Their transverse sections are polished, and cleaned with lower alcohols before every measurement, but the side surfaces are left intact. Moreover, all the samples were stored, irradiated and measured in air.

Samples are irradiated by two ^{60}Co γ-rays sources, one with an activity of 1 Ci, and the other with an activity of 5 M Ci. Typically the samples are put at a distance of 19 cm (40 cm) from the weak (strong) source, hence the dose rate corresponds to 8.3×10^{-3} Gy/min (52.7 Gy/min). It was estimated that the total expected dose for the TOF counter at Beijing Electron Positron Collider II (BEPCII) is about 10 Gy per year at maximum [6]. The dose rate, duration time and the total irradiation dose of each exposure are listed in Table 2, in which the first three used the weak source, and the last two used the strong one.

The light yield of each sample of plastic scintillator is measured by using an ^{241}Am source which emits γ-rays with an energy of 0.0594 MeV. The scintillator sample is wrapped by Tyvek, except the transverse face which is coupled to the PMT without silicone greases. The PMT is a Philips XP2262B, supplied by a negative high voltage of 1950 V. The measurement setup is shown in Fig. 1(A), including a LeCroy 3001 QVT, 623Z discriminator, CAEN N109 attenuator, Phillips 752 logical unit, and a LeCroy 222 gate generator. The environment temperature of the lab is about 31–32 °C.

The transmission spectra were measured with a Shimadzu UV-240 Visible Recording spectrophotometer (Fig. 1B(1)), while the excitation and emission spectra with a Hitachi-850 fluorescence spectrophotometer.

The sequence of the above measurements is the following: the transmission and emission spectra were measured both before and about 30 min after irradiation. This step took about an hour, and then the light output was measured.

Table 1
Main parameters of the plastic scintillators provided by manufacturers

Scintillator (type)	Decay time (ns)	Light attenuation length (cm)	Wavelength of max. emission (nm)	Relative light output (anthracene = 100) (%)
BC-408 [7]	2.1	380	425	64
BC-404 [7]	1.8	160	408	68
EJ-200 [8]	2.1	380	425	64

Table 2
Irradiation data for all the samples

No. irradiation	Dose rate (Gy/min)	Time (min)	Total irradiation dose (Gy)
1	3.7×10^{-4}	1540.2	0.57 ± 0.04
2	8.3×10^{-3}	2722.8	22.6 ± 0.1
3	8.3×10^{-2}	865.2	71.8 ± 0.9
4	12.5	48	602 ± 24
5	52.7	273	14387 ± 104

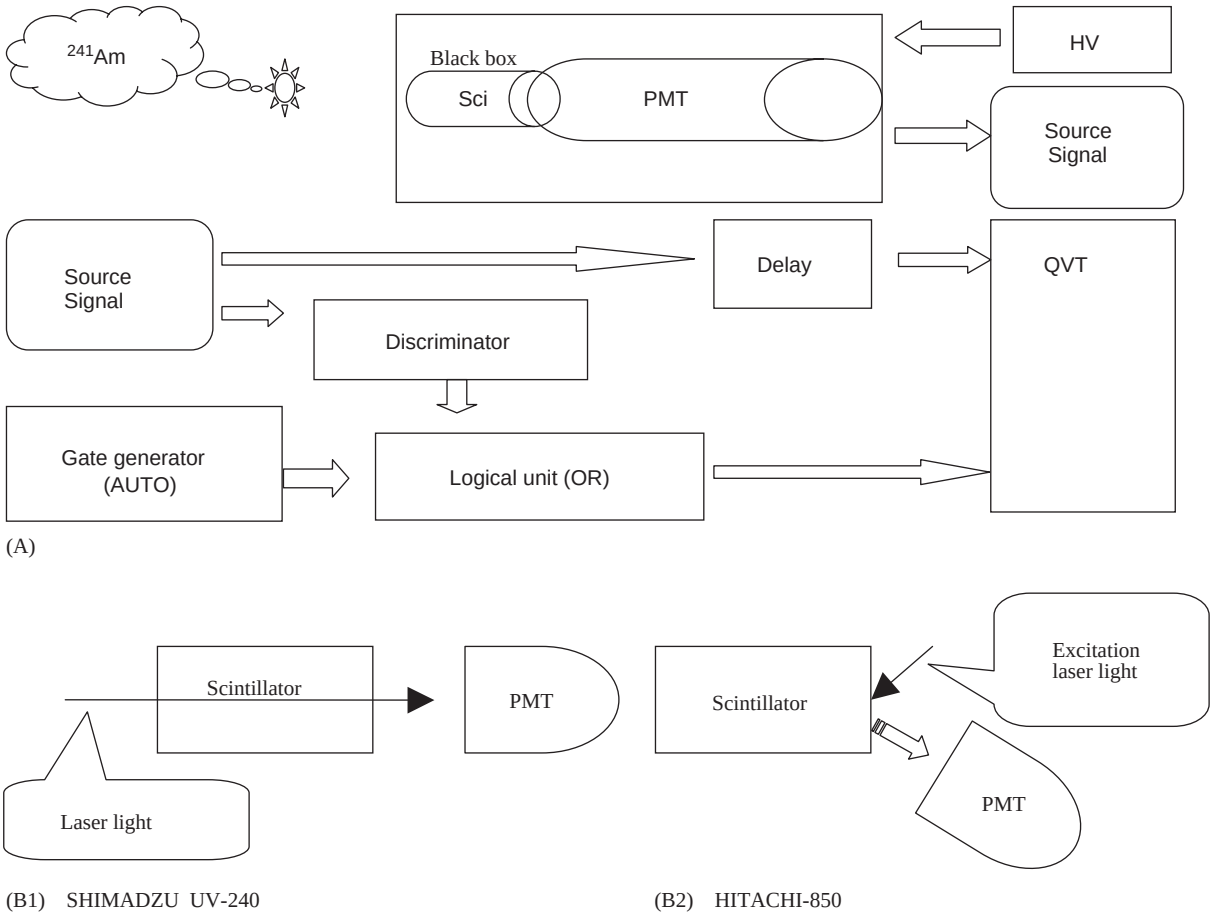


Fig. 1. (A) Setup for the light yield measurement. (B) Measurement principle of devices for transmission and excitation and emission spectra.

3. Transmission and emission spectrum

Results of transmittance of all the samples before and after irradiation are presented in Fig. 2. The absorption edge of BC-408 and EJ-200 is at about 400 nm, while that of BC-404 at about 390 nm. There is no obvious difference in the absorption edge for all the samples before and after irradiation. Their transmission spectra show that EJ-200 has a slightly better behavior of its optical transmission. Fig. 3 shows the transmission at a typical wavelength (emission peak) for different samples as a function of absorbed dose. Irradiation has no effect on the transmittance for a dose less than 600 Gy, at least at these dose rates. When the irradiation dose reaches 1.4×10^4 Gy at a dose rate of 52.7 Gy/min, the samples are obviously destroyed. They become yellow as can be seen by eye and their transmittance decreases substantially. However, the yellow color tends to disappear with time, fading from the outside towards the inside.

The emission spectra of all the samples before and after irradiation are normalized to their peak position as shown in Fig. 4. There is an emission peak at around 425 nm for samples of BC-408 and EJ-200, 407 nm for BC404, all consistent with data provided by the manufacturers. After irradiation, the shapes of the emission spectra of all the samples are unchanged even after the samples are

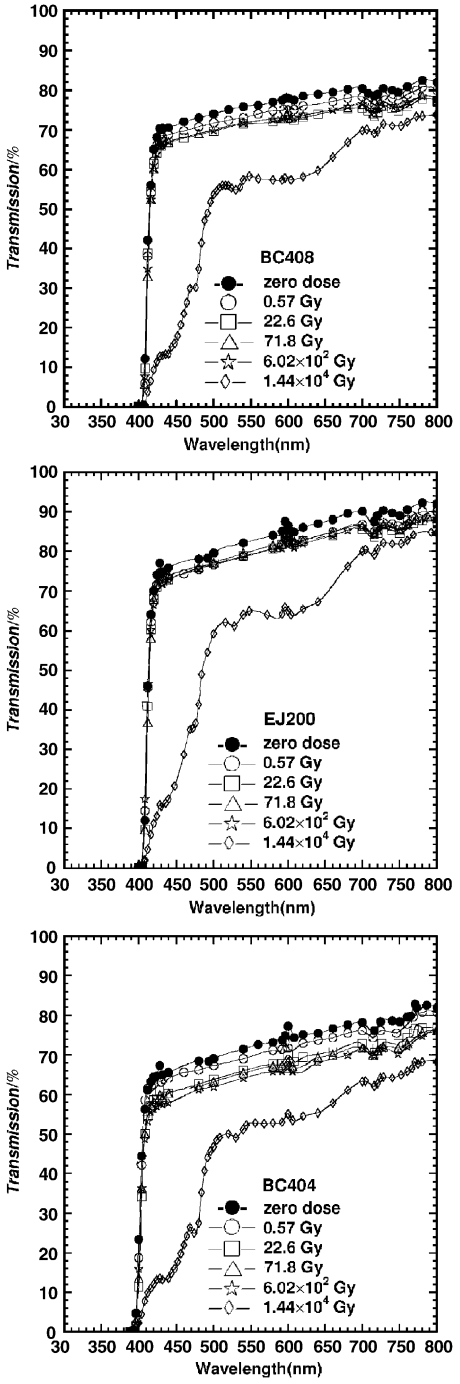


Fig. 2. Transmission spectrum before and after irradiation.

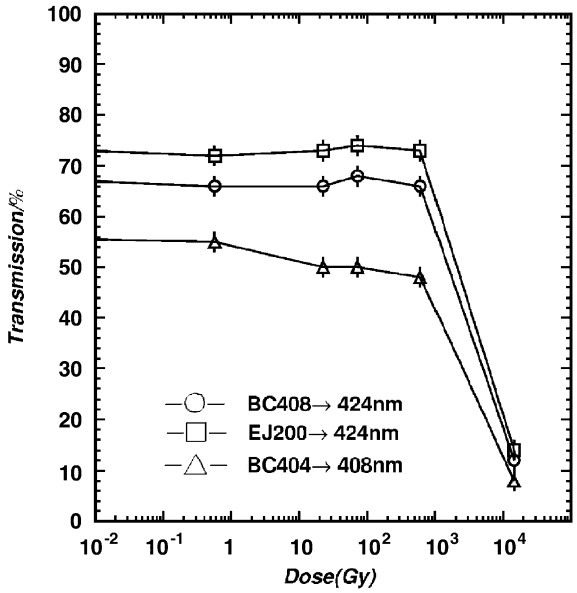


Fig. 3. Transmission as a function of dose at a typical wavelength (emission peak) for various scintillators.

significantly damaged. Hence the irradiation did not destroy the light emission mechanism of the fluorescent organic compounds at such an irradiation dose.

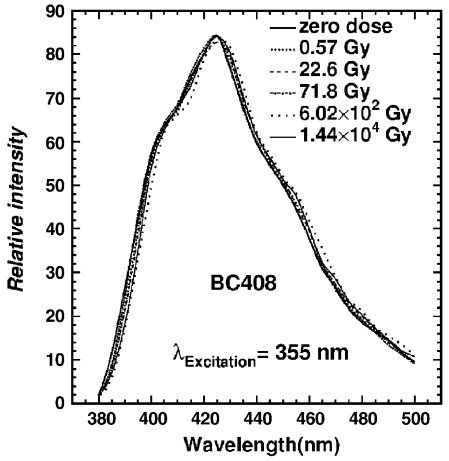
4. Light output

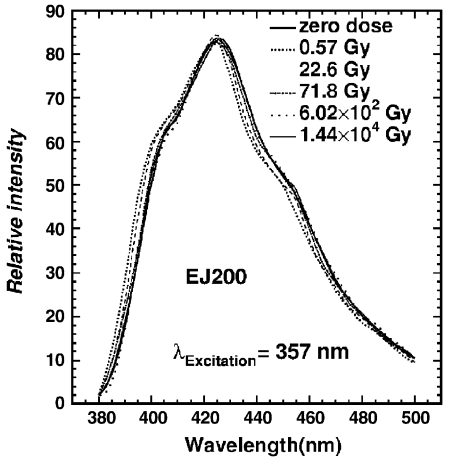
The light yield spectra [9,10] of all the samples are given by the average of three independent measurements, 4 min each, as shown in Fig. 5. The full energy peak can be clearly seen for all cases except for the case of a total dose of 1.4×10^4 Gy. In order to see clearly all the spectra in one plot, they are scaled with respect to the case no radiation with factors of 1.75, 1.3, 1.0, 0.8, 1.0 and 1.0.

The actual light yield defined as the number of observed photoelectrons per unit energy deposition (in MeV), is calculated by the following expression [11]:

$$\mathrm{LY} = \frac{P_{\mathrm{P}}}{P_{\mathrm{SPE}} \times E_{\gamma}} \tag{1}$$

where E_γ is the γ-ray energy released by ^{241}Am in units of MeV, P_{SPE} is the peak position of the





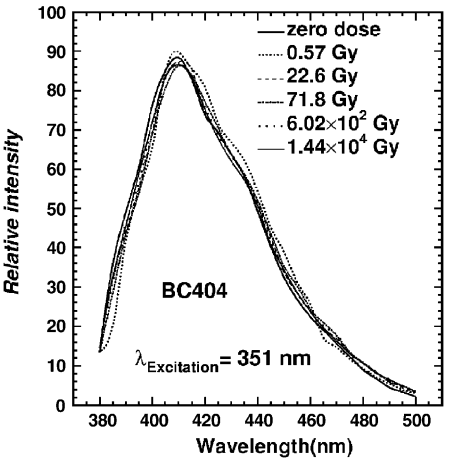
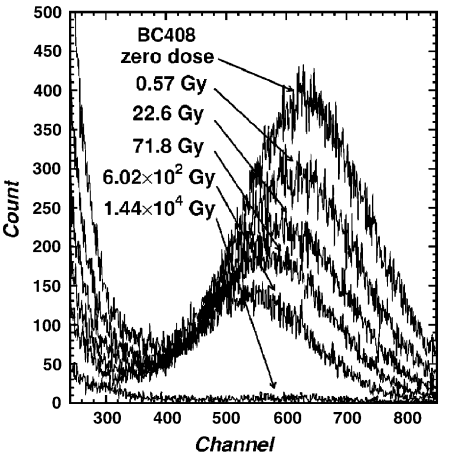
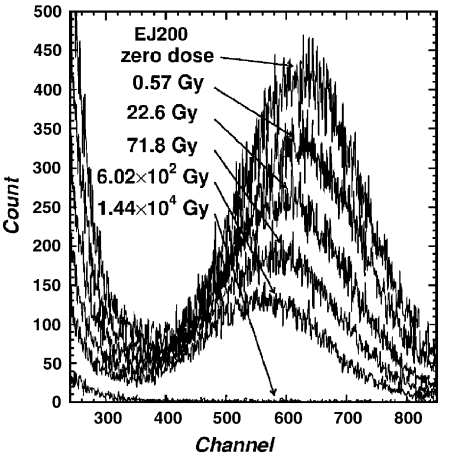


Fig. 4. Emission spectrum before and after irradiation.





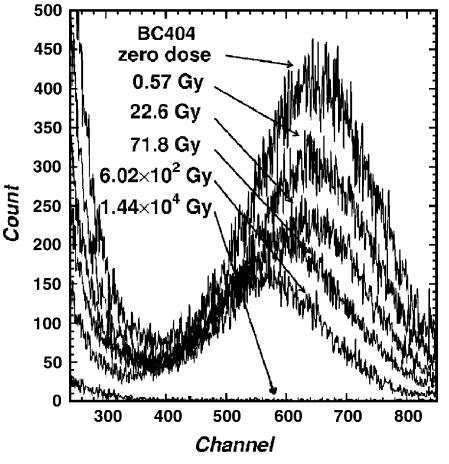


Fig. 5. Light yield spectrum before and after irradiation.

single photoelectron, obtained from a Gaussian fit to the thermal noise spectrum; and P_P is the position of the full energy peak, obtained from a Gaussian fit to the full energy spectrum. The effect of Compton scattering, which causes the full energy peak to be asymmetric, is taken into account by applying a proper cut to get a satisfactory value of χ^2/ndf during the fitting.

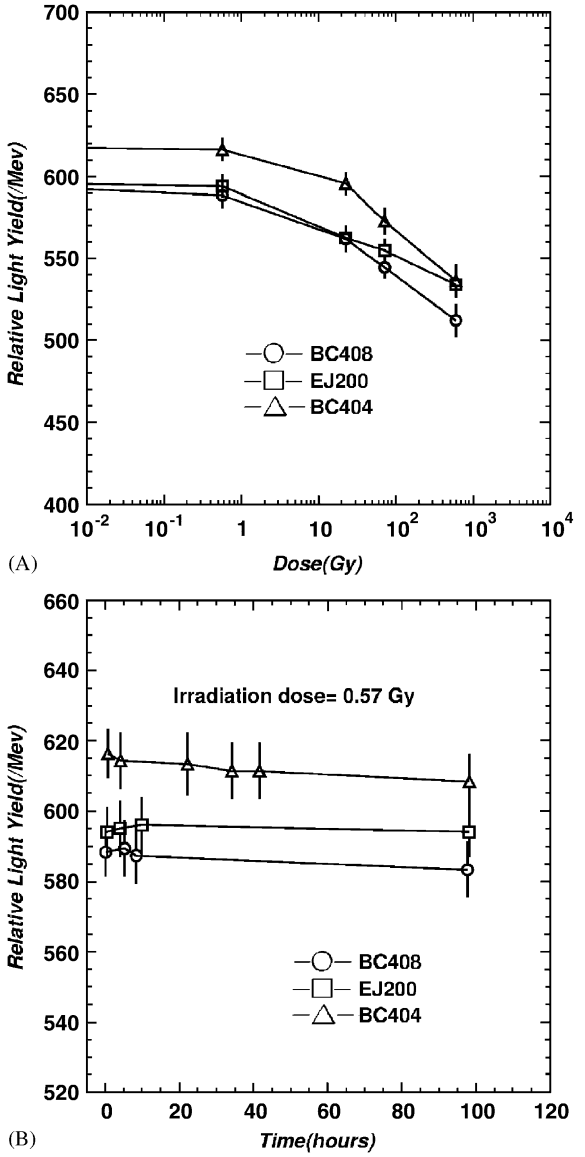


Fig. 6. (A) Light yield as a function of irradiation dose (B) The recovery of light yield over time.

Table 3
The light yield LY (photoelectrons/MeV), as defined in Eq. (1), of all the tested samples

Scintillator	Dose (Gy)				
	0	0.57±0.04	22.6±0.1	71.8±0.9	602±24
BC-408	596±6	588±8	562±8	545±7	512±10
EJ-200	597±7	594±8	562±7	555±7	534±8
BC-404	619±8	616±7	596±7	573±8	536±10

Fig. 6 shows that the position of the full energy peak decreases when the radiation dose increases, indicating a loss of light yield. The light yield of all the samples is listed in Table 3 that shows that the light yield of all the samples decreases when the dose increases. BC-404 has the maximum light yield, while the light yield of both BC-408 and EJ-200 are 4% lower.

The light yield as a function of radiation dose is presented in Fig. 6(A). All the samples lose their light yield at a very slow rate until the dose is more than 50 Gy. At 600 Gy, the light yield loss is 14.1% for BC-408, 13.4% for BC-404, and 10.6% for EJ-200. These results show that the irradiation effect in EJ-200 is the least, and that for BC-408 and BC-404 are almost the same.

The recovery of light yield after the first irradiation is shown in Fig. 6(B). There seems no evidence of recovery after 100 h.

5. Conclusions

The radiation damage to three types of fast scintillators for a time-of-flight system, BC-408, EJ-200 and BC-404, is studied by using γ-rays from a ^{60}Co source with a dose from 0.57 Gy up to 1.4×10^4 Gy. The following conclusions are drawn:

(1) For irradiation dose up to 600 Gy, the transmittance of the samples is almost unchanged. A substantial change was observed at a radiation dose of 1.4×10^4 Gy. EJ-200 shows the better optical transmission behavior.

(2) After irradiation, the shapes of the emission spectra of all the samples remain unchanged, even after the samples are significantly damaged as the irradiation dose reaches 1.4×10^4 Gy.
(3) The light yield of all the samples decreases when the radiation dose increases. BC-404 has the maximum light yield, while BC-408 has similar light yield compared with EJ-200. It shows that the irradiation effect for EJ-200 is the least, and that of BC-408 and BC-404 are almost the same.
(4) The results of 1 and 3 indicate that a certain fraction of fluorescent dyes were destroyed after irradiation.
(5) No evidence of recovery is observed after the first irradiation (0.57 Gy).

Since the estimated dose rate at BEPCII is about 10 Gy per year, all the samples tested can be used for the BESIII TOF counters.

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