TECHNICAL REPORT

Attenuation of electromagnetic radiation in Nuclear Track Detectors

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Abstract: A systematic study of the attenuation (absorption) of electromagnetic radiation in Nuclear Track Detectors (NTDs) is carried out. The attenuation of gamma rays, X-rays, UV and visible radiations in NTDs are investigated using NaI(Tl) detector, Gas Electron Multiplier (GEM) detector and UV-Vis spectrophotometer respectively. The values of some important parameters (e.g., mass attenuation coefficient, optical depth) of three commercially available NTDs (PET, Makrofol\textsuperscript{®} and CR-39\textsuperscript{®}), at the relevant regions of the electromagnetic spectrum, are determined. The details of the experimental techniques and the results are also presented in this report.

Keywords: Interaction of radiation with matter; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Particle tracking detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

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1 Introduction

Nuclear Track Detectors (NTDs) comprise one of the detector types of choice for detecting highly ionizing rare particles (strangelet, magnetic monopole) in cosmic rays [1, 2] or in accelerators [3, 4]. Some of the most important advantages of NTDs are low cost, ease of use, and the existence of natural thresholds of detection [5]. NTDs offer excellent charge resolution in the relativistic regime (≈ 0.4 e corresponding to energy ≈ 158 GeV/nucleon [6]) as well as in the non-relativistic regime (≈ 1 e corresponding to energy ≈ 2.8 MeV/nucleon [7]), where e is the electronic charge. They offer good position resolution (≈ 1 μm) also. In addition, being passive in the nature of action (as they do not require electrical power during their operation), NTDs are often one of the best choices for the experiments which require detector arrays to be set-up in remote locations for cosmic ray observation [1, 8].

Heavy charged particles create narrow trails while passing through the NTDs. Their tracks are revealed later through chemical etching. Previous studies show that the etching rate (and hence the sensitivity) are largely affected by the exposure due to electromagnetic radiations [9–13]. To investigate this particular issue, we pursued a systematic study on the attenuation of electromagnetic radiation over a wide range of energies for three commercially available NTDs, namely - PET (Desmat, India), Makrofol® (Covestro AG, Germany) and CR-39® (TASL, England). In this report, by attenuation is meant absorption of electromagnetic radiation, as the effect of loss of intensity due to scattering of radiation has not been determined. The attenuation of gamma rays, X-rays and UV-visible radiations in NTDs are studied using NaI(Tl) detector, Gas Electron Multiplier (GEM) detector and UV-Vis spectrophotometer respectively. The values of some important parameters (e.g., mass attenuation coefficient, optical depth, etc.) of different NTDs at the relevant regions of the electromagnetic spectrum are determined. The details of the measurement techniques, experimental set-up, and the results are presented in this paper.

Electromagnetic radiation interacts with matter through different processes: (i) excitation of atoms, (ii) Rayleigh and other types of scattering, (iii) photoelectric effect, (iv) Compton scattering,
and (v) pair production. While passing through the material, the number of transmitted photons get reduced by scattering and absorption due to the processes mentioned above. It can be shown that the intensity of the photons $I_0$, after passing through a distance $x$ inside the absorber of mass density $\rho$ reduces to

$$I(x) = I_0 e^{-\mu x}$$  \hspace{1cm} (1.1)

Here $\mu/\rho$, called the mass attenuation coefficient (actually, the mass absorption coefficient in the present experiment), is a characteristic of the absorbing material and the energy of the photon [14]. Hereafter, we shall use the term attenuation to imply absorption as the effect of scattering could not be taken into account.

Experimental procedure and results of the study of the attenuation of electromagnetic radiation (gamma rays, X-rays, UV rays and visible rays) while passing through the NTDs, are presented in the next few sections.

2 Experimental arrangement

Nuclear Track Detectors (NTDs) are optically transparent, dielectric solids comprising of long polymer chains. The chemical composition [15] and thickness of the different plastic NTDs used in these experiments are given in table 1.

The detailed experimental procedures in different electromagnetic regions are described below.

| NTD material          | Chemical composition | Thickness $x$ (μm) | Density $\rho$ (kg/m$^3$) |
|-----------------------|----------------------|--------------------|---------------------------|
| PET (Poly-ethylene terephthalate) | (C$_{10}$H$_{8}$O$_{4}$)$_n$ | 90             | 1.39 × 10$^3$           |
| Makrofol® (Bisphenol-A polycarbonate) | (C$_{16}$H$_{14}$O$_{3}$)$_n$ | 480          | 1.20 × 10$^3$           |
| CR-39® (Poly-allyl diglycol carbonate) | (C$_{12}$H$_{18}$O$_{7}$)$_n$ | 630        | 1.32 × 10$^3$           |

2.1 Gamma ray region using NaI(Tl) scintillation detector

A NaI(Tl) scintillator detector [16] coupled with a Photo Multiplier Tube (PMT) is used to detect the gamma radiation from a $^{60}$Co source. A high voltage of 600 V is applied to the PMT. The signal from the PMT is fed to a charge sensitive pre-amplifier which is integrated with the base of the PMT. The pre-amplifier signal is fed to a spectroscopy amplifier (ORTEC-671) with a coarse gain of 500. The amplified signal is then connected to a PC controlled Multi Channel Analyser (MCA) (Ortec EASY-MCA-8k) to obtain the energy spectrum. The attenuation of $\gamma$ rays is studied by placing the NTDs (size 5 cm × 5 cm) in-between the source and the detector, as shown in figure 1(a). The energy spectrum $^{60}$Co radioactive source in the given range of the ADC channel number 300 – 3000 (corresponding to the energy interval 0.1 – 1.5 MeV) is plotted in figure 1(b).

The NTDs are placed on top of the scintillation counter and below the $^{60}$Co radioactive source one by one. Total number of counts for the $^{60}$Co source alone (i.e. without any absorber) and placing
different NTDs just below the source in NaI(Tl) detector, is plotted in a histogram (figure 2(a)). From this figure the effective mass attenuation coefficient of different NTDs for the energy range from 0.1 MeV to 1.5 MeV are calculated and the values are presented in table 2.

2.2 X-ray region using Gas Electron Multiplier (GEM) detector

In this experimental set-up, X-ray radiation is detected by a Gas Electron Multiplier (GEM) detector [17–19]. Triple GEM detector is a gaseous ionization detector; it consists of three GEM foils cascaded inside a chamber filled with gas. A pre-mixed gas mixture of Ar:CO₂ in 70:30 volume ratio is used at a flow rate of 3.5 l/h. Each GEM foil (10 cm×10 cm) is made up of a polymer (Kapton) foil of thickness 50 μm sandwiched between two copper foils of thickness 5 μm. Relatively low voltages (~ 400 V) are applied between the copper planes of each foil. There are a large number of holes (~ 80 mm⁻²) of diameter 70 μm etched on the GEM foil at a pitch of 140 μm. Thus a high electric field (~ 80 kV cm⁻¹) is created inside the holes. A negative high voltage of ~4175 V is distributed across the GEM foils and the electrodes using a passive resistive chain. Ionizing radiation, on passing through the gas, creates electron-ion pairs. An electron, while moving along the large electric field inside those holes, initiates an avalanche of electrons. They
are then collected from the readout anode pad placed after the third GEM foil. The experimental arrangement is shown in figure 3(a). X-rays from $^{55}$Fe source get partially absorbed by the NTDs (size $5 \text{ cm} \times 5 \text{ cm}$) placed in-between the source and the detector. The signal from the GEM detector is fed to a charge sensitive pre-amplifier (VV50-2) [20]. The analog signal is then fed to a four output linear Fan-in-Fan-out (linear FIFO) module in a NIM based data acquisition system. One of the outputs is connected to a MCA to obtain the energy spectrum. One such spectrum of $^{55}$Fe on GEM detector is shown in figure 3(b) where the noise peak (below channel number 150), argon escape peak (channel number 570, energy 2.9 keV), and main 5.9 keV X-ray peak (channel number 1190) from $^{55}$Fe source are clearly visible. Another output from the linear FIFO is fed to a Single Channel Analyzer (SCA), the threshold of which is set at 0.1 V to reject the noise. The total count of the incident particles is measured by a NIM scaler, which is connected to the SCA via a TTL-NIM adapter. The findings of this study are presented in the results and discussions section.

2.3 Visible to ultraviolet region using UV-Vis spectrophotometer

To check the transmittance of different NTD samples (table 1) in Ultra-Violet (UV) and visible radiation, they are scanned by a Perkin-Elmer Lambda 25 UV/Vis spectrometer (figure 4(a)), covering wavelength ranging from 200 nm to 1000 nm with a resolution of 1 nm. Figure 4(b) shows the transmission profile of different NTDs in the visible and UV region of electromagnetic radiation.

3 Results and discussions

From figure 2, the typical values of the effective mass attenuation coefficient of different NTDs for gamma rays in the energy region 0.1 – 1.5 MeV using $^{60}$Co radioactive source and for the X-rays in the energy region 1 – 7 keV using $^{55}$Fe radioactive source, are calculated and the corresponding values are presented in table 2. It should be noted that, as the distance between NTD and the NaI(Tl) detector is small in the present experimental set-up, the solid angle acceptance of the NaI(Tl) is high. Hence, most of the gamma ray photons, after Compton scattering from the NTD, managed to reach the NaI(Tl) crystal of the scintillation spectrometer. So, what has been measured in this case is the effective mass absorption coefficient, associated with photoelectric effect and pair production.
Figure 4. Left panel (a): instrument for the study of attenuation of UV and visible radiation in NTDs. Right panel (b): percent transmittance of photons in ultra-violet and visible regions by NTDs.

Table 2. Typical values of effective mass attenuation coefficient of different NTDs in the gamma ray region 0.1 – 1.5 MeV using $^{55}$Fe radioactive source and in the X-ray region 1 – 7 keV using $^{55}$Fe radioactive source. Experimental uncertainties for the measurements using gamma rays and X-rays are < 1% [18, 22]. The values of mass attenuation coefficient of different NTDs for UV-rays of 5 eV energy and for visible ray of 3 eV energy have also been presented in column 3.

| Name     | Effective Mass attenuation coefficient $\mu/\rho$ (m$^2$kg$^{-1}$) | Mass attenuation coefficient $\mu/\rho$ (m$^2$kg$^{-1}$) |
|----------|---------------------------------------------------------------|--------------------------------------------------------|
|          | $\gamma$-ray (0.1–1.5 MeV) X-ray (1–7 keV) UV-ray (5 eV) | visible ray (3 eV)                                     |
| PET      | 0.89                                                         | 6.3                                                    | 73.38 | 1.49   |
| Makrofol®| 0.64                                                         | 6.7                                                    | 6.37  | 0.13   |
| CR-39®  | 0.18                                                         | 6.1                                                    | 15.66 | 0.21   |

Likewise, in the case of X-rays, the effective mass attenuation (actually, absorption) coefficient has been measured where the contribution is mainly from photo-electric effect (as in this energy range pair production is not possible and contribution from Compton scattering is negligibly small).

Figure 4(b) shows that the transmittance near the visible region of electromagnetic radiation is more than 85% for all NTDs, which is helpful to use them in transmitted light optical microscopy. Optical depths ($\tau$) corresponding to the wavelength 560 nm (yellow light) are calculated using the relation

$$\tau = \ln \frac{\phi_i}{\phi_t}$$

(3.1)

where $\phi_i$ and $\phi_t$ are the radiant flux incident and transmitted by the material at that wavelength.

For PET, Makrofol® and CR-39® the values of $\tau$ (at wavelength 560 nm) are given in table 3. The optical energy gap ($E_g$) is related to the absorption coefficient ($\alpha$) through the relation [23],

$$\alpha(h\nu) = \frac{B(h\nu - E_g)^{1/2}}{h\nu}$$

(3.2)
where $\alpha$ is calculated from $\alpha = 2.303 \times A/t$ ($A$ and $t$ are the absorbance and thickness of the material respectively); $B$ is a constant. By plotting $(ahv)^2$ as a function of photon energy ($hv$) [figure 5] and extrapolating the linear part of the curve to $hv$-axis at zero absorption, optical energy gap for different NTDs are computed ([10]) and the corresponding values are given in table 3. Figure 4(b) shows that the value of transmittance is negligibly small ($\approx 0$) below the wavelengths 310 nm,
Table 3. Physical parameters of different NTDs corresponding to ultraviolet and visible region of electromagnetic wavelength.

| NTD name | Optical depth $\tau$ | Wavelength cut-off (nm) | Direct band-gap energy $E_g$ (eV) |
|----------|----------------------|-------------------------|----------------------------------|
| PET      | 1.03                 | 310                     | 3.82                             |
| Makrofol® | 1.02                 | 280                     | 3.94                             |
| CR-39®   | 1.02                 | 230                     | 3.98                             |

280 nm, and 230 nm for PET, Makrofol® and CR-39® respectively (table 3). Figure 6 gives the values of mass attenuation coefficient over entire range from visible to UV radiation. These figures (figure 4(b), figure 6) also show that PET film blocks UV radiation more effectively than the other two. Thus, while using stacks of NTDs, keeping PET film in the top layer during open-air exposures, the effect of UV rays on altering the etch-rate may be prevented in the lower layers of NTDs [11]. The fact that PET can block UV radiation can have other practical uses as well. For example, UV radiation is effective in disinfecting SARS-CoV-2 surface contamination [24]. But prolonged exposure to UV can pose a health hazard to humans. So PET films can offer a cost-effective way to shield humans from the harmful effects of UV.

4 Conclusion

We have estimated some of the relevant physical quantities (e.g. the mass attenuation coefficient) of previously unexposed NTDs over a wide range of wavelengths of electromagnetic radiation. These results (i.e., mass attenuation coefficient, optical depth of unexposed NTDs) will serve as a reference in the study of the response (i.e., etch-rate, sensitivity) of NTDs which are exposed to electromagnetic radiation over a long period of time. In this work, it is also shown that a single PET film of thickness 90 $\mu$m can block the UV radiation almost completely. So, when a stack of PET films is given open-air exposure, the topmost PET film can prevent the change of etch-rate due to UV related damage in all subsequent layers. The ability of PET to block UV rays can find applications in other fields of research and industry.

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