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The effect of an external electric field on radiation transmission and Compton scattering in plexiglass

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Abstract

The effect of an external electric field on radiation transmission of a plexiglass sample has been studied by using an extremely narrow-collimated-beam transmission method. Also, the photon scattering properties of the charge centers have been determined by changing the charge density distributions of the plexiglass sample with an external electric field having an intensity in the range 0–1000 V/cm. The plexiglass sample was bombarded by 59.5 keV gamma rays emitted from an Am-241 point source. The transmitted and Compton scattered photons were detected by a Si(Li) detector. Appreciable variations were observed in the transmission factors of the plexiglass sample as a function of applied field. The results show that the electrical properties of the plexiglass sample changes with the applied electric field and the gamma ray irradiations although it is a dielectric material. Furthermore, the negatively charged scattering centers are slightly more effective than the positively charged scattering centers in the Compton scattering of gamma rays from an insulator sample, similar to result found for conductor and semiconductors.

1. Introduction

A narrow beam of monoenergetic photons with incident intensity I_0, penetrating a layer of material with mass thickness x (mass per unit area) and density ρ emerges with intensity I given by the exponential attenuation law

$$\frac{I}{I_0} = \exp[-(\mu/\rho)x], \tag{1}$$

where I/I_0 is the transmission factor and (μ/ρ) is the mass attenuation coefficient. (μ/ρ) can be obtained from measured values of I/I_0 and x. The photon attenuation coefficient is an important parameter for characterizing the penetration and diffusion of X- and gamma rays in multi-element materials. The mass attenuation coefficients depend on the chemical composition of the absorbing material and the energy of the gamma rays. Abdel-Rahman et al. [1] investigated the effect of the sample thickness on the measured mass attenuation coefficients of the plexiglass (perspex) for 59.54, 661.6 and 1332.5 keV gamma rays.

Compton scattering is one of the methods giving information about the electronic structure, electronic momentum distribution and the wave functions of atoms, molecules and solids. Compton scattering is the scattering of a photon of high energy from an electron considered being free and stationary or from an atomic electron whose binding energy is small compared with the incident photon energy. In the Compton scattering, the incident photon imparts some of its energy to the electron, and the energy of scattered photon is given by the equation

$$E_s = \frac{E_i}{1 + \frac{E_i}{m_0c^2}(1 - \cos\theta)}, \tag{2}$$

where m_0 is the mass of an electron at rest, c is the velocity of light, θ is the angle between the directions of the incident and the scattered photons, E_i and E_s are the energies of the incident and scattered photons, respectively. The intensity of Compton scattered photons is proportional to the electron density of material under investigation (n_e);

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$$I_{\text{Compton}} \propto n_e \quad (3)$$

and

$$n_e = \rho N_a (Z/A), \quad (4)$$

where ρ is the density of the material, N_a the Avagadro number, Z the atomic number and A the atomic weight of the scatterer [2]. Mazarakiotis et al. [3] examined the electronic momentum density of polyethylene, one of the simplest polymers, with Compton scattering experiments.

Dielectrics differ from conductors in that they have no free charges that can move through the material. Although all the electrons are bound in dielectrics, a minute displacement of positive and negative charges are possible in opposite directions in the presence of an electric field. The displacement is usually small compared to atomic dimensions.

Plexiglass, which is dielectric, thermoplastic and transparent, is the name given to polymethyl-2-methylpropanoate the polymer of methyl methacrylate. When the electron or X-ray beam interacts with a polymer material, the energy is absorbed by the polymer material by producing the ionization and excitation of the polymer molecules. Important properties of polymer materials, such as their electrical and mechanical properties, thermal stability, chemical resistance, melt flow and surface properties can be significantly improved by radiation processing. High energy irradiation of polymers can convert them from dielectric materials to materials having electrical conductivity and this creates opportunities for the use of radiation in producing specialty materials for electronic applications.

Electrical conductivity of the polymers has attracted considerable scientific and technological attention in recent years. The influence of radiation on physical and chemical properties of conducting polymers was investigated by Wolszczak and Kroh [4]. The radiation induced discoloration of polymers was studied by Clough et al. [5]. When external forces are applied to macromolecules, the electrical and optical properties of the polymer change, as manifested by electric birefringence and dielectric dispersion. Navarro et al. [6] studied the electric and optical properties of polymer chains under the external forces or electric fields by combining theory with numerical simulation. Chernov et al. [7] reviewed the experimental studies and the changes of the electrical properties of dielectric materials under irradiation. Golovin et al. [8] investigated the influence of a weak magnetic field on the radiation induced conductivity of C_{60} single crystals. Maeda et al. [9] measured radiation induced conduction in polyethylene-terephthalate (PET) under high electric field. The radiation induced conductivity of some polymers under pulse irradiation conditions in vacuum at room temperature was studied by Tyutnev et al. [10].

In the present work, radiation transmission of the plexiglass sample was measured with 59.5 keV photons in the external electric field having an intensity in the range 0–1000 V/cm. The effect of the external electric field and irradiation on the electrical properties of the plexiglass sample was discussed in detail, also.

2. Experimental procedure

The geometry and shielding of the experimental setup used for radiation transmission and Compton scattering is shown in Figs. 1 and 2, respectively. The sample used was a cylinder of plexiglass, 15 mm in diameter and 20 mm in length. The characteristic properties of the plexiglass sample are given in Table 1. Gamma rays of 59.5 keV from a filtered point source (Am-241) of intensity 3.7×10^9 Bq were used for experiments. The Am-241 gamma source was housed at the center of a cylindrical lead shield of 10 mm diameter and 36 mm depth. The Compton scattered gamma photons from the target were detected at a scattering angle 100°. Two Al plates measuring $270 \times 270 \times 0.7\ \text{mm}^3$ in size were used to obtain the electric field. The distance between plates was set to 30 mm. The plates were connected to a variable power supply capable of producing the potential of 0–3000 V. The potential difference between the plates was continuously controlled with a voltmeter. The sample was mounted on a dielectric sample holder placed in between the plates. The transmitted and Compton scattered photons from the target were detected by a Si(Li) detector shielded by a cylindrical plastic cap of 9 mm diameter circular aperture, 25 mm length and 2.3 mm wall thickness to protect it from the external electrical discharge or conduction. The detector has a resolution of 180 eV full width at half maximum at 5.9 keV, sensitive crystal depth of 5 mm, active area 30 mm^2 and a Be window of 0.008 mm thickness. To obtain a thin beam of photons emitted from the target and to absorb undesirable radiation (environmental background and background arising from the scattering sample holder and Al plates), a lead collimator of 8 mm diameter circular

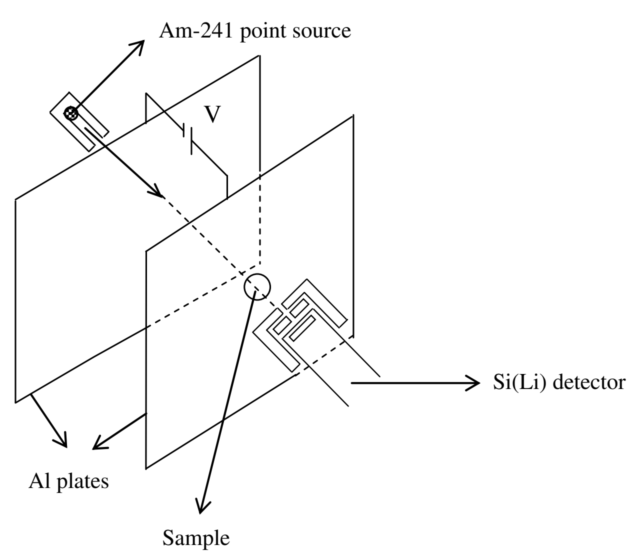

Fig. 1. Experimental geometry for radiation transmission through the plexiglass sample in an external electric field.

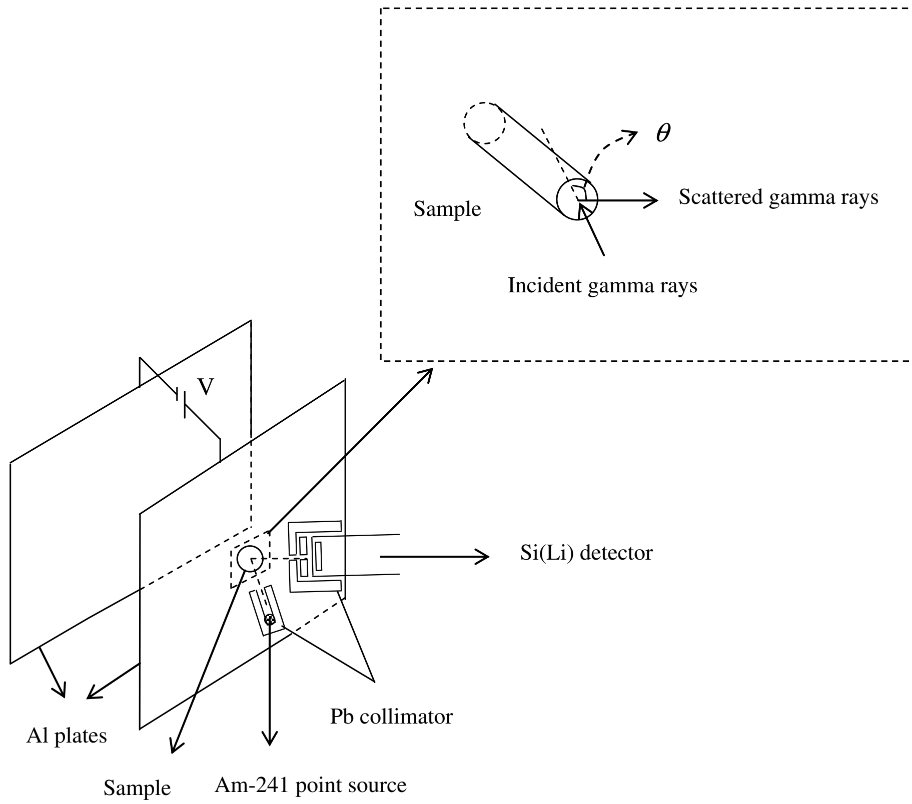

Fig. 2. Experimental geometry for Compton scattering from the plexiglass sample in an external electric field.

Table 1
The characteristics properties of the plexiglass sample

Mean excitation energy	74 eV
Density	1.19 g/cm^3
Refractive index	1.492
Resistivity	10^{15} Ω cm
Transmission of light	0.93
Dielectric constant	2.6

aperture and 6.5 mm in thickness was housed into the plastic cap.

The potential differences between the Al plates were increased in 300 V increments from 0 V to 3000 V. The data were collected into 1024 channels of a digital spectrum analyzer (DSA-1000), which is a full featured multichannel analyzer incorporating digital signal processing (DSP) techniques. The DSA-1000 is operates using the Genie-2000 gamma spectroscopy software which has many features including; peak searching, peak evaluation, energy/efficiency calculation, nuclide identification, etc. For the radiation transmission, the spectra were obtained for a period of 600 s at each stable value of potential. The pulse height spectra of scattered gamma rays were acquired for a period of 1200 s to obtain a good statistics in the evaluation of each Compton peak. To obtain the experimental Compton scattering peak from the raw data, the latter was processed through several corrections. A weak background arose mainly from electronic noise, scattering from sample holder and Al plates, stray cosmic background, etc., was determined by running the system without any sample. It was then subtracted from the measurement point by point after scaling it to the actual counting time. Thereafter, the measured spectrum was corrected for absorption in the sample and energy dependence of the Compton cross section. Peak determination was accomplished using a demo version of the Microcal Origin 7.5 software. All the peak areas were evaluated from the same channel interval at the representative background level of each spectrum. A typical spectrum of 59.5 keV gamma rays transmitted though the plexiglass sample in an external electric field with an intensity of +500 V/cm is shown in Fig. 3. A representative spectrum of photons scattered by the plexiglass sample in an external electric field is shown in Fig. 4.

Compton scattering experiment were repeated 10 times for both positive and negative polarities for only one potential value selected. The *t*-test was applied to check the difference between the Compton scattered counts obtained with the collection of the negative and positive charge carriers on the bombarded surface of the sample.

3. Results and discussion

The activity of the excitation source is 3.7×10^9 Bq and charge concentration of the sample under investigation is about 10^{13} cm^{-3}. Therefore, the charge concentration produced by photon excitation is ignorable. The electrical conductivity caused by ionization of the air in the region of the applied electric field is not measurable in this experimental.

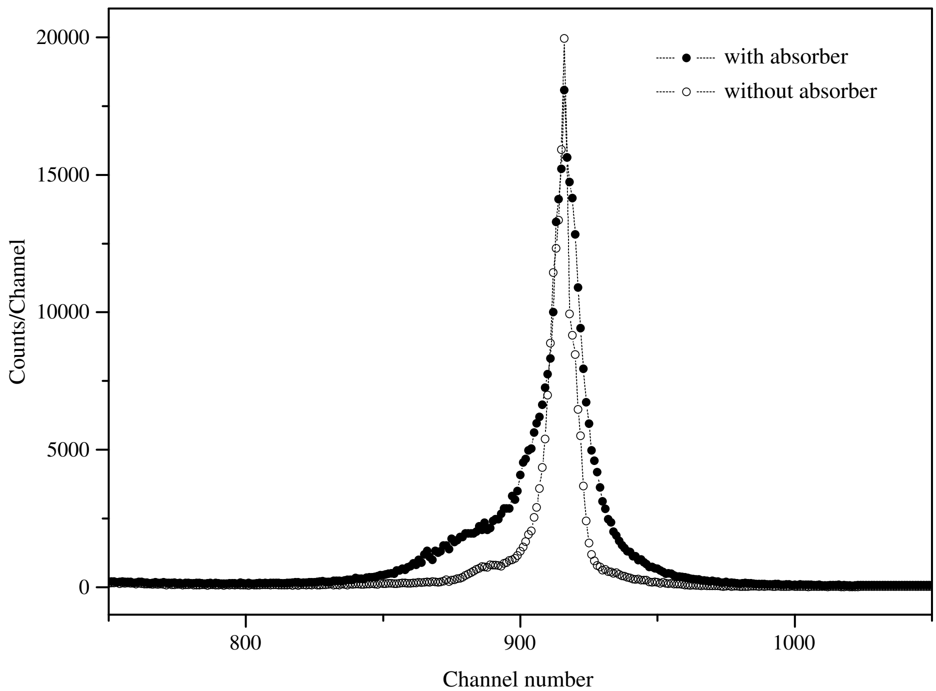

Fig. 3. A typical spectrum of 59.5 keV gamma rays obtained with and without absorber (plexiglass) in an external electric field with an intensity of +500 V/cm.

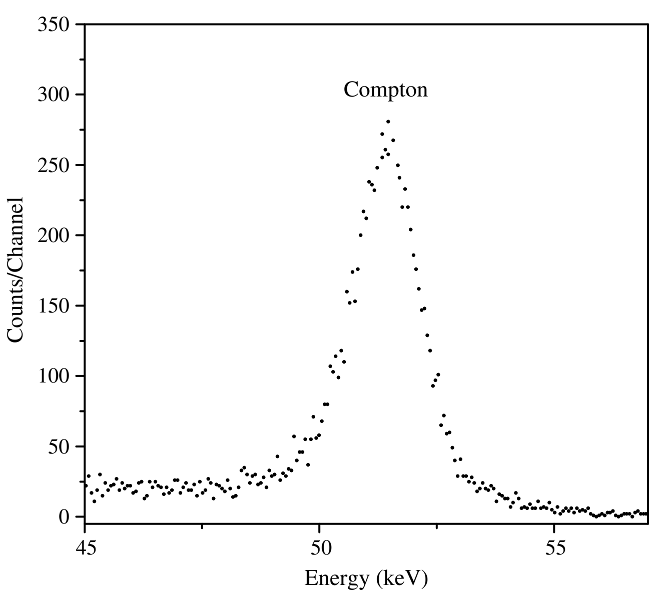

Fig. 4. A representative spectrum of photons scattered by the plexiglass sample at 100° scattering angle in an external electric field with an intensity of +500 V/cm.

The experimental values of transmission factors versus the electric field intensities for the plexiglass sample were measured and graphically presented in Fig. 5. The experimental errors are in generally less than 0.01%. It is seen from Fig. 5 that radiation transmission of the plexiglass sample decreases with the increasing electric field intensity. The correlation theory is used to confirm the second-order polynomial relation between transmission factors and the electric field intensities. The correlation coefficient is $r^2 = 0.997$, which is significant according to the 5% confidence level. According to the results presented here, plexiglass located to an external electric field is a promising candidate material for gamma ray shielding.

The plot of counts acquired under the Compton peak versus the electric field intensities for the plexiglass sample is shown in Fig. 6. It is clear from Fig. 6 that scattering from the negative and positive charge centers in the plexiglass sample can be discerned. This is an expected result: there is polarization and a slight displacement of the negative and positive charges of the dielectrics atoms or molecules although there is no migration of charge when a dielectric is placed in the external electric field. Furthermore, the photon can interact with all charge centers (such as free electron, bound electron, ionized acceptor, ionized donor and hole) since it has both electrical and magnetic behaviour. This result shows that the dielectric material behaves like a conductor material when irradiation is conducted in the external electric field.

The standard deviation of 10 repeated measurements in the external electric field of intensity +500 V/cm is 1.04% of the arithmetic mean of these measurements. For −500 V/cm, this ratio is 2.12%. Small fluctuation of each measured value about the mean of each series or the smallness of the statistical counting errors mean that the replicate of each measurement is not necessary in the study. The t-test was applied to the Compton scattered intensities obtained for +500 V/cm and −500 V/cm. It was found that t_{expt} is 3.403. The critical t value is 2.101 at the 0.025 level of significance and 18 degrees of freedom. According to the

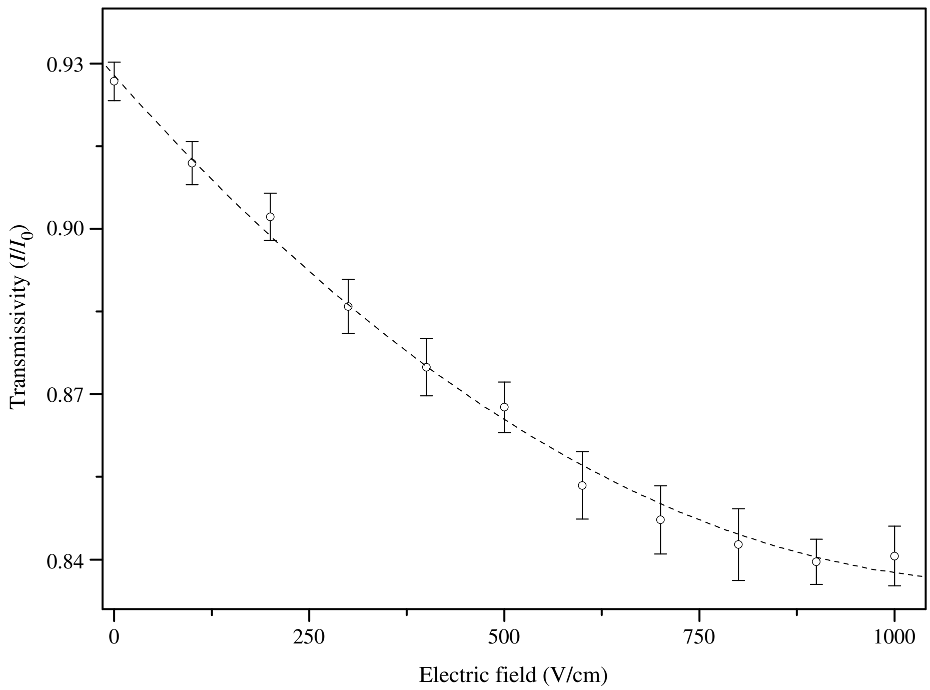

Fig. 5. The experimental transmission factors versus the external electric field intensities for the plexiglass sample.

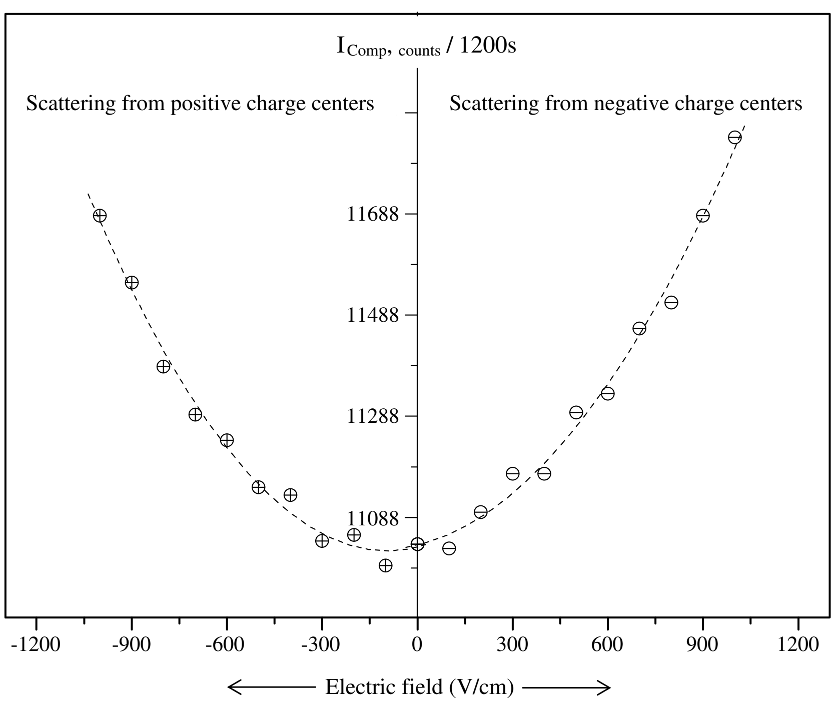

Fig. 6. The Compton scattered intensities versus the external electric field intensities for the plexiglass sample.

t-test result [$t_{expt} > t_{0.025}$ (for 18 degrees of freedom)], the difference is not significant between the Compton scattered intensities obtained for +500 V/cm and −500 V/cm. This means that the positive charge carriers behave like negative charge carriers in the Compton scattering of gamma rays. The counts acquired under the Compton peaks for the each positive electric field intensity are greater than acquired counts for each corresponding negative electric field intensity, as clearly seen from Fig. 6. This result shows that the negative charge centers are slightly more effective than positive charge centers in the Compton scattering of gamma rays.

As seen from Fig. 6, the Compton scattering intensity increased with the increasing magnitude of the electric field in both directions. This result arises from the surface charge densities increase with the increasing magnitude of the electric field according to Eq. (3). There is a good second-order polynomial relation between the Compton scattering intensity and the increasing (or decreasing) electric field intensity. The correlation coefficients are $r_+^2 = 0.998$ and $r_-^2 = 0.997$ for the positive and negative electric field intensities, respectively. Each correlation coefficient given above is significant according to the 5% confidence level.

4. Conclusions

Here, the photon scattering properties of the charge centers and the effect of the external electric field on radiation transmission in plexiglass are reported. The results show that the negatively charged scattering centers (free and bound electrons) are slightly more effective than the positively charged scattering centers (holes) in the Compton scattering of gamma rays from an insulator sample. Furthermore, the dielectric material behaves like a conductor material when irradiation is conducted in the external electric field. According to the results presented here, plexiglass located to the external electric field is a promising candidate material for gamma ray shielding. To obtain more definite conclusions on the external electric field dependency of the Compton scattering and transmission of gamma rays from an insulator sample, more experimental data are clearly needed.

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