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The development of a novel technique to evaluate the CR-39 track response to alpha particles

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Abstract: A novel technique is presented for the assessment of the track response of the detector CR-39 to alpha particles by photothermal deflection spectroscopy and image analysis. The 2 new techniques can be implemented to CR-39 as in situ measurements. The proposed techniques offer the possibility of monitoring nuclear radiation directly. Photothermal deflection is described to detect the change in the thermal and optical properties of the track nuclear detector CR-39 when irradiated to alpha particles. In situ image analysis of the photothermal deflection spot is presented to assess the detection of the CR-39 of any nuclear particle or radiation instantaneously.

Key words: Nuclear track detector CR-39, photothermal deflection spectroscopy, alpha particles, image analysis

1. Introduction

Photothermal deflection spectroscopy (PDS) is an attractive optical contactless method for determining both the thermal and optical parameters of a tested material. The system operates on the pump-probe technique, with a pump laser for initiation of the surface thermal deformation that is chopped mechanically and a probe laser for deflection by passing through the thermal lens. PDS is nondestructive and provides a higher sensitivity than transmission measurements because, rather than observing small changes in a large quantity, absorption-induced heating is detected directly [1]. The physical properties of the nuclear track detector CR-39 will be evaluated with PDS. When traversing a plastic material such as CR-39, charged particles create along their ionization track a region that is more sensitive to chemical etching than the rest of the bulk [2]. CR-39 is convenient for the detection of alpha particles and fast neutrons because of high detection efficiency, high sensitivity, and short etching time [3]. After treatment with an etching agent, tracks remain as holes or pits, which can be seen with the aid of an optical microscope [4].

The size, depth of penetration, and shape of these tracks provide information about the mass, charge, energy, and direction of motion of the particles [5]. It had been found that there is a complete relationship between the track diameter and the alpha energy in the energy range from 0.2 to 8.8 MeV [6]. The commercially available CR-39 with a thickness of 100 μm can be etched in 1 N NaOH/ethanol at 40 °C to below 20 μm [7]. The detector CR-39 is of high sensitivity, but it is not reusable and it requires long processing time and extensive chemical etching [8]. A method based on surface profilometry is proposed to determine the track lengths in CR-39 detectors through measurements of their replicas [9]. Another method using a computer program called TRACK-TEST for the calculations of alpha particle ranges, determination of the distance along the particle

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trajectory penetrated by the chemical etchant, calculations of track coordinates, determination of the lengths of the major and minor axes, and determination of the contour of the track opening was also proposed [10].

In this article, 2 new proposed methods are suggested for the evaluation of radiation dose as alternatives to chemical etching. PDS can detect any small variations in the thermal and optical properties of the track nuclear detector CR-39 when irradiated to alpha particles. Image analysis can monitor, in situ, the photothermal deflection spot for the detection of the CR-39 of any nuclear particle or radiation instantaneously.

2. Experimental

The experimental setup is shown in Figure 1 for photothermal deflection spectroscopy. The pump beam was a continuous-wave (300 mW) diode-pumped solid state Nd:YAG laser and at the second harmonic wavelength (532 nm). The laser output power was modulated at a low frequency (40 Hz) by a mechanical optical chopper (Thorlabs Model MC 1000) and then focused on the sample surface. The probe beam was a He-Ne laser (632.8 nm) of power output (1 mW). A position sensor (bi-cell photodiode) was used to determine the amplitude and phase of the probe beam deflection. The output of the position sensor was fed into the lock-in amplifier (EG & G Princeton Applied Research Model 5209) via a differential detecting and amplifying circuit. A reference frequency from the mechanical chopper was connected to the lock-in amplifier. The sample holder for CR-39 (200 μm thick) was mounted on a 3-axes inclination micropositioning device. The signal was then recorded by the digital storage oscilloscope (UT 2102 C) with repeated measurements accomplished in order to minimize the noise. Lenses were used to focus the beams in an accurate manner after choosing the appropriate focal lengths and to adjust the focal waist of the beams.

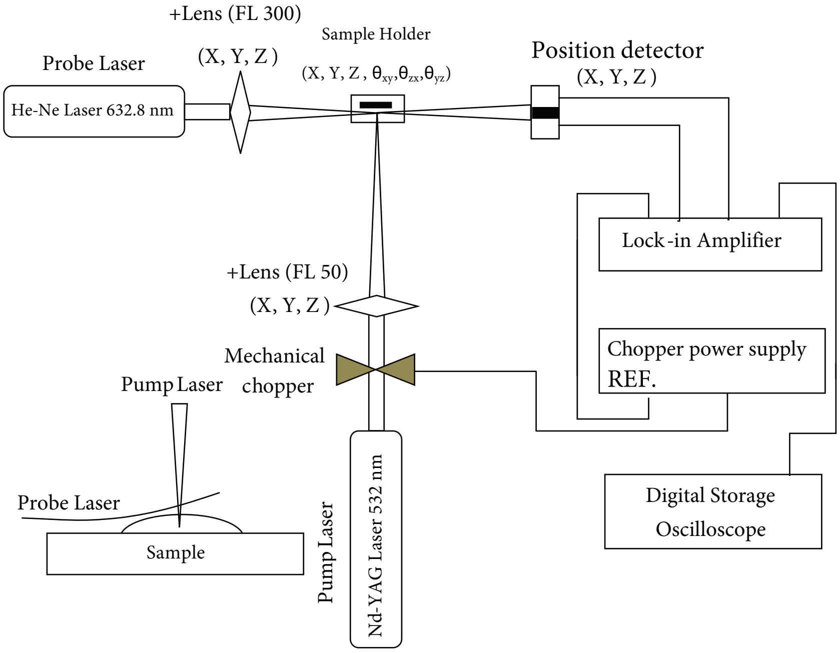

Figure 1. Experimental setup and optical alignment for photothermal deflection method.

The source of α-particles for irradiation of CR-39 was a pellet of Americium-241 with energy 1.5 MeV, which will definitely leave a track in the detector. Each piece of CR-39 detector was placed above the Americium source and exposed normally. The energy loss of alpha particles in air was calculated as follows [11]:

$$E_\alpha = E_o \left(1 - \frac{x}{R}\right)^{2/3}, \tag{1}$$

where E_α is the α-particle energy at distance x, $E_o = 5.485$ MeV is the maximum energy from the source Am^{241}, and $R = 4.16$ cm is the range of α-particles in air. The energy of an α-particle as a function of distance from the source is shown in Figure 2. The energy decreases with distance, and at a specific distance the energy can be calculated.

To ensure the homogeneity of the irradiation on the surface of the CR-39 by α-particles from the source Am^{241}, Figure 3 shows the image of the detector after irradiation. The image shows the tracks of α-particles in the detector all over the surface.

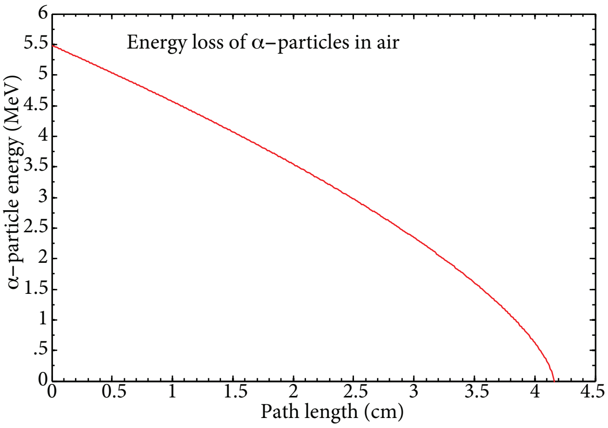

Figure 2. The energy loss of α-particles in air.

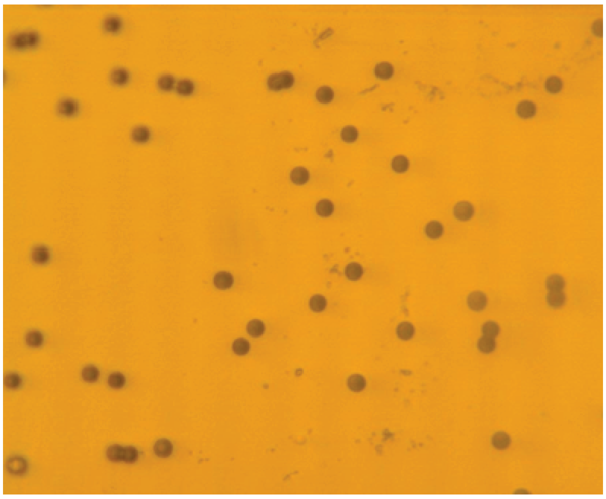

Figure 3. Image shows the damage created by α-particles of energy 1.5 MeV on the surface of the detector CR-39.

The absorption spectrum of CR-39 (UV-IR) is shown in Figure 4. This spectrum is for an unirradiated sample. The absorbance of the detector shows a pronounced peak around the 532 nm wavelength of the pump laser.

The α-particle irradiation of CR-39 can lead to the increased scissions of the polymer chains and additional formation of hydroxyl groups in the track region, which in turn enhances the solubility into the etchant [12]. The relation between detector sensitivity and track diameter and depth can be established for α-particle irradiation of CR-39. The damaged tracks may be revealed by proper treatment of chemical reagent with less rapid removal of the surrounding undamaged matrix to enlarge the etched holes [13]. For further reading on tracks and etching, see [14] and [15].

The time of exposure was taken from 0 to 6 min with a 20 s minimum step to increase the penetration depth or the damaged track in the detector due to α-particle fluence. The fluence of α-particles was estimated as 4.47×10^5 particles cm^{-2} min^{-1}. The exposure time of irradiation of α-particles to the CR-39 is related to the fluence after keeping the particle flux constant.

After exposure, no etching process was carried out. Each piece of CR-39 of a definite time of exposure was then placed in the setup for PDS measurements and image analysis. In this investigation, the track properties of CR-39 will be revealed without the need for etching, but by PDS and image analysis as a possible technique for direct determination of nuclear radiation and dose.

3. Results and discussion

The effect of α-particles on the recorded deflection of the lock-in amplifier is illustrated in Figure 5. The influence of α-particles on detector CR-39 through the deflection is obvious and decreased with increasing time of exposure. On the other hand, besides the reduction in the deflection, the behavior still remained the same, i.e. increasing the deflection with pump power. The unexposed CR-39 had shown a sharp increase in the deflection above a pump power of 220 mW. The detector CR-39 had shown a pronounced peak in the absorption spectrum around the wavelength of the pump laser when visible infrared (VIS-IR) absorption spectroscopy was carried out. Two exposed samples are shown in Figure 5 in order to present the effect. All irradiated samples of time (0–6 min) show the same behavior.

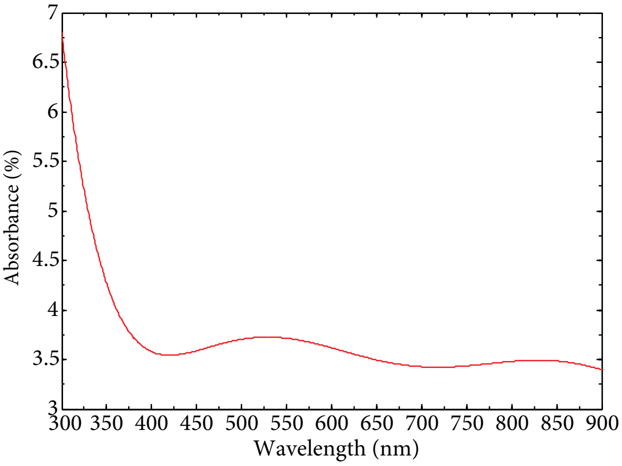

Figure 4. The absorption spectrum of unirradiated CR-39. Absorbance of 3.722% at laser pump wavelength of 532 nm.

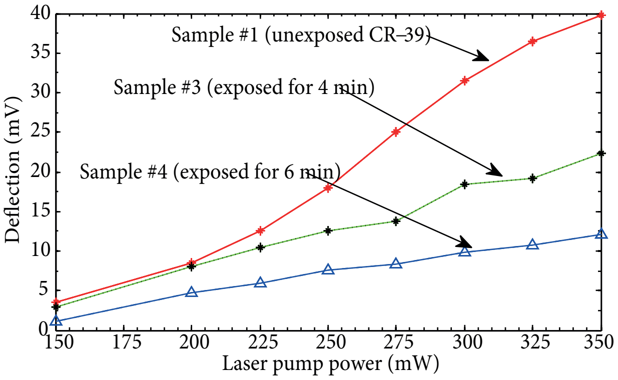

Figure 5. Photothermal deflection recorded by lock-in amplifier of the detector CR-39 with samples exposed to α-particles and unexposed.

The fluence particle rate is incident on the sample, i.e. the number of particles per unit area per unit time, and so if more particles are going through this area per unit time, the beam is going to be more intense than if we have fewer particles per unit time. However, if the beam is kept on for a longer period of time with a lower fluence rate, then the fluence could be the same and ultimately the dose will be the same. Nevertheless, here we are talking about fluence rate, which ultimately will convert to dose rate.

The recorded data of deflection were then fed to a PC for analysis and performing of first derivatives on the data of the above. The derivatives show how the functions change as their input changes. The values of laser pump power for which the deflection is stationary (that is, for which the derivative is zero) are critical values for the function. The relative maxima and relative minima can be found from the first derivative, provided that the function is differential and continuous in that interval. The derivatives of the data given above are provided in Figure 6 for unexposed and exposed samples. The unexposed sample showed a maximum at a pumping power of 270 mW from the Nd:YAG laser. The exposed samples show a minimum around this pump power. This is shown as a dip in the plots of the exposed samples. The dip can be interpreted as occurring because of extra heat absorption in the damaged zones by α-particles of the CR-39 and lowering of the deflection in the lock-in amplifier. The PDS signal amplitude depends on the sample light absorption while the signal phase depends on the localization of the effective "center" of absorption within the sample [16].

The track detector CR-39 showed a different behavior when the pump power was kept at 220 mW. This behavior is presented in Figure 7. The manner of CR-39 at this pump power and its derivative suggest that this pump power is sufficient for creating the thermal lens that is responsible for the PDS. The minimum in the first derivative at a time of exposure of around 120–140 s will be studied thoroughly with image analysis. The amplitude of photothermal deflection recorded by the lock-in amplifier relies on the conversion of absorbed pump power by the detector into heat.

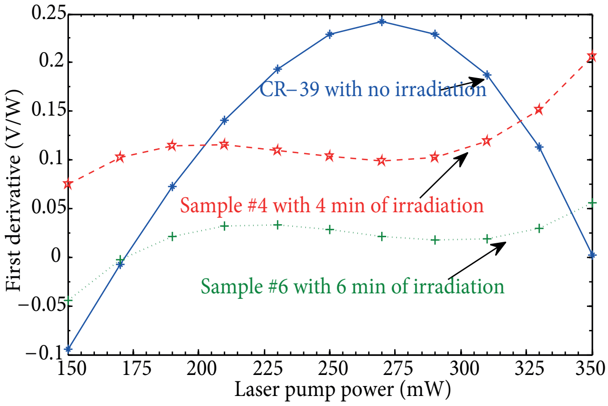

Figure 6. The first derivative of the data of unexposed sample #1, exposed sample #3, and exposed sample #4.

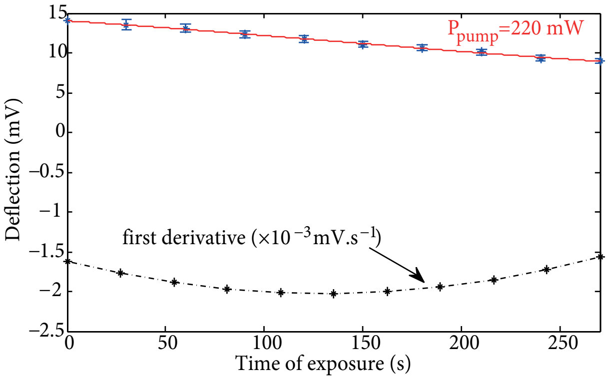

Figure 7. The reaction of the detector CR-39 at pump power of 220 mW as a function of time of exposure and its first derivative.

This conversion process implies a temperature rise in the CR-39 film. The temperature distribution inside the film would be altered in the case of irradiated samples due to the damaged zones. These zones can lead to localized changes in the temperature distribution. Such change is correlated with recorded photothermal deflection.

The measured deflection is proportional to the nuclear irradiation dose. The deflection decreased with the increasing time of exposure to alpha particles, and this can be interpreted as that the absorbance of the CR-39 had decreased with the increasing time of exposure. When an ionizing particle crosses the nuclear track detector, it produces damages at the level of polymeric bonds on its trajectory, forming the so-called "latent track", and the damage depends on the ratio Z/β [11], where Z is the particle charge and β is the velocity of the particle. As illustrated in Figure 7, the pump power can be implemented as low as possible for the correlation between the photothermal deflection and the irradiation dose for the required measurements. This linear relation is the preferable manner of correlation in this application, in order to replace the etching procedure with photothermal deflection. More pump power, as will be discussed later, would induce or act as a stimulus for nonlinear correlation in the absorption mechanism of irradiated CR-39 to α-particles.

The reaction of sample #2 (irradiated to α-particles for 120 s) to pump power in the range of 0–360 mW is presented in Figure 8. The normalization in the deflection was obtained as a reference to the maximum deflection of the lock-in amplifier at a specific laser pump power (300 mW). The same specified circumstances of recording the PDS were applied to this sample. The situation for this sample is of some physical importance due to the damages that were created by the nuclear radiation. As can be seen from the graph, after a pump power of 220 mW of the pump laser, the deflection undergoes a decrease (a dip) in its manner. This confirms the suggested power for studying the photothermal deflection of damaged CR-39 as a result of nuclear radiation to be in this range of power; otherwise, excess pump power will induce nonlinearities in the characteristics of CR-39. The aim of this research is to find an alternative way, instead of etching, to assess the radiation dose by PDS. This situation will be studied further, i.e. the optimum pump power was 220 mW by image processing when the laser spot was analyzed.

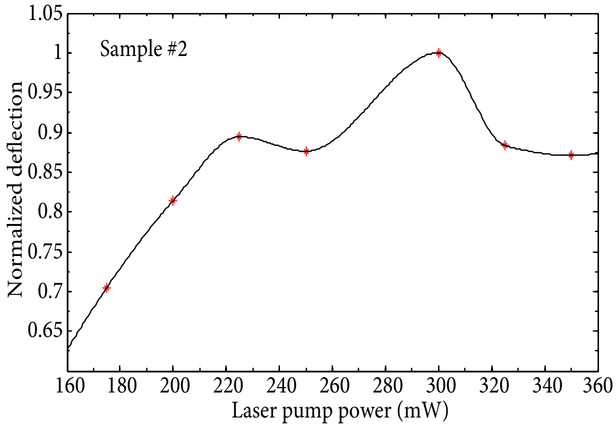

Figure 8. The influence of Nd:YAG laser as a pump power on the photothermal deflection of irradiated CR-39. The solid line presents the numerical fit. Irradiation time was 120 s.

The image analysis of the photothermal deflected laser spot will be the next step of the proposal for irradiated CR-39. This technique can be implemented without the need for the position sensor detector and the lock-in amplifier. In comparison with the above procedure, image analysis will provide a fast, in situ way to record the variation in the optical properties of the CR-39 when exposed to ionized nuclear particles. Eventually, photothermal deflection recorded by lock-in amplifier or image can be used for the assessment of the CR-39 as a function of alpha dose or irradiation time.

The deflected probe laser beam spot, as shown in Figure 9a, was fed to the computer for image processing using MATLAB programming that was written for this purpose. Our MATLAB software, as illustrated in Figure 9b, then processes this spot. The image analyses have the ability to acquire data rapidly and allow as many as possible to be averaged with excellent repeatability. Moreover, computer programming takes a very short time compared to any other technique. The next step is to determine what changes have been found in the transformed image compared to the stored data for the unexposed CR-39 and to evaluate its variation with the energy of the nuclear particles or with the time of exposure. Many parameters were found in this study when the data were analyzed; one of them is the variation of laser intensity full width of the beam at half its maximum (FWHM; referred to as laser spot radius in pixels) with time of exposure and the shift of the spot with different times of exposures. The converted images in one dimension are shown in Figure 9c without pumping and Figure 9d with pumping.

The shift in the location of the peak intensity of the laser spot with time of exposure is shown in Figure 10. The written MATLAB software has the ability to convert an image into any kind of data. The converted image was in one dimension in terms of pixels and was then converted to position. This procedure was used to estimate the FWHM of the curve and the shift of the location of the spot when varied with pump power or time of exposure. This estimation will be treated as an overall effect of photothermal deflection analysis for the detector CR-39 rather than using the usual manner of calculations of deflections in terms of the stimulus. The spot was transferred to an image taking into account the contrast of the light intensity and then converted into a gray-scale image and stored into the computer. After that, the image is filtered and trunk limited through the software.

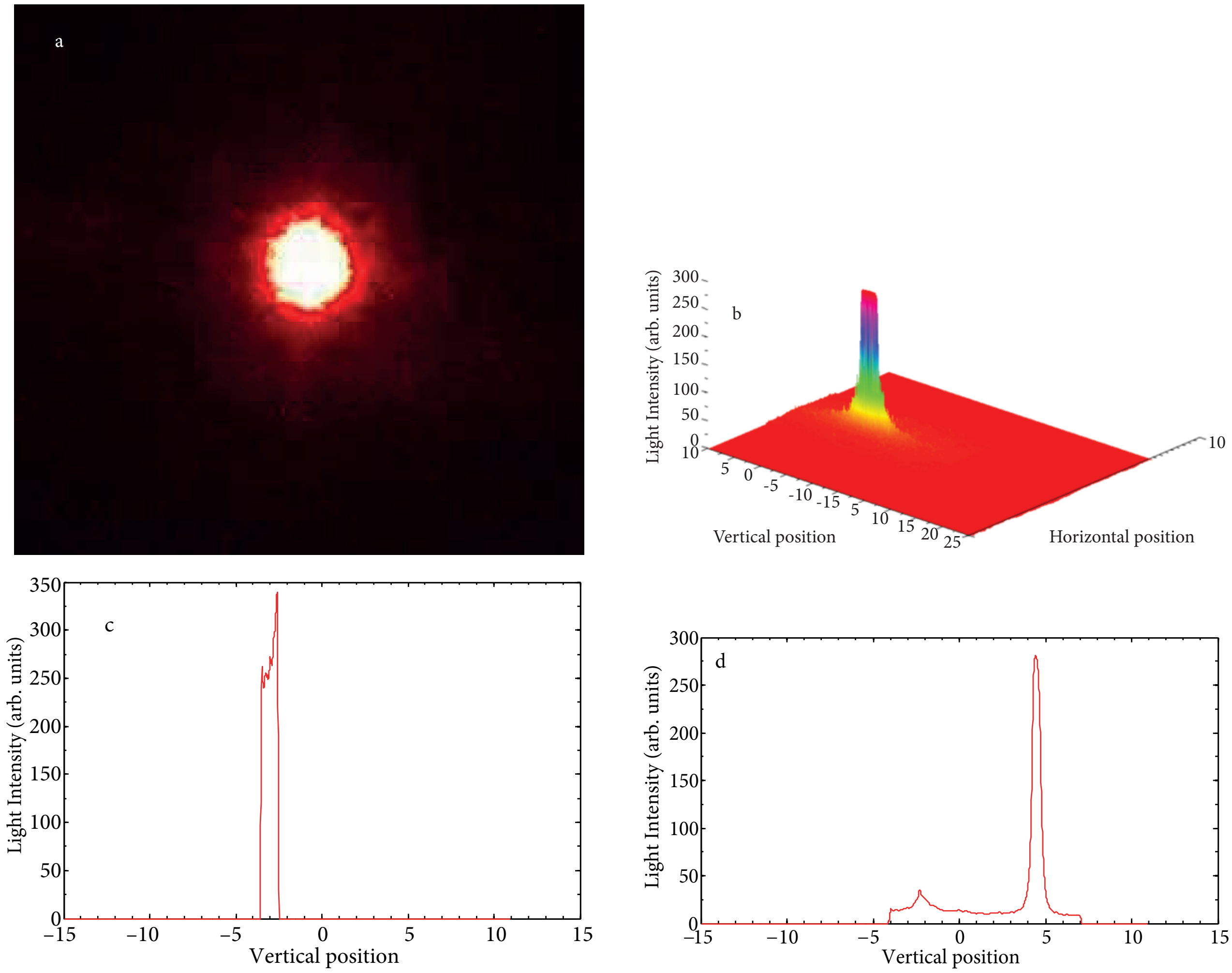

Figure 9. (a) The image spot, (b) the spot after having been processed by MATLAB software. (c) The converted image in one dimension without pumping and (d) with pumping.

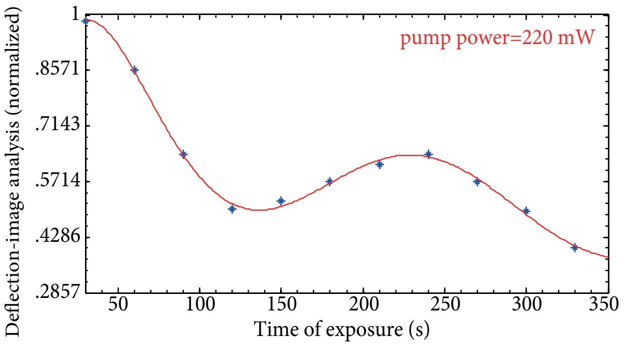

Figure 10. The calculated deflection from image processing in terms of time of exposure of CR-39 to nuclear radiation when the pump power was kept constant at 220 mW.

The laser pump power was kept at 220 mW to prevent any induced nonlinearities in the characteristics of CR-39. Figure 10 shows a decrease in the deflection with increased time of exposure of α-particles, but with a polynomial dependence of deflection on the time of exposure. The image analysis is more accurate since it records any tiny variation in the location or in the laser intensity. The interpretation of such behavior can be explained as with the damage in the solid-state detector CR-39 when irradiated by α-particles, the penetration of nuclear particles was shallow and the damaged bonds at this time of exposure (120 s) will cause laser-induced absorption in the film. This argument will be further investigated and the etching process may be carried out on these irradiated samples.

4. Conclusion

Photothermal deflection is a promising technique that can replace the chemical etching of the detector CR-39 in order to estimate the dose of radiation. Etching is time-consuming and troublesome. Photothermal deflections can be related to the dose and the time of exposure. Image analysis of the probe laser deflected spot was able to detect laser-induced absorption of localized clusters of α-particle–irradiated CR-39 when the pump power was raised above 220 mW. Time of exposure of around 120 s to α-particles with Americium-241 with energy 1.5 MeV of the CR-39 showed some peculiar results. This phenomenon needs more attention and further investigations are ongoing. Etching and UV-VIS absorption spectroscopy are the next steps.

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