Note

Response of Thermoluminescence Dosimeter CaF₂ : Tm to Low-Level Proton Beams Using Rutherford Backscattering

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Low-level proton beams from a van de Graaff accelerator operated at 1–3 MeV with proton dose from 1.48 to 94.56 mGy using the Rutherford backscattering method were used to study the response of thermoluminescence dosimeter CaF₂ : Tm. The glow curves, TL output and sensitivity obtained were analyzed with respect to proton energy, dose and dose rate. The experimental results indicate that TLD CaF₂ : Tm may also be used as a proton dosimeter in the low energy range.

KEY WORDS : proton beam, TLD, glow curve

I INTRODUCTION

In the early 1990s one of the authors carried out the basic study of CaF₂ : Tm (TLD-300) exposed to protons with reference to the kinetic order of the fifth peak (P_5) of the glow curve.¹⁾ Over the past we have also investigated the response of thermoluminescence dosimeter (TLD) CaF₂ : Tm with a commercial name of TLD-300 to high-level proton beams.²⁾ They were drawn from a van de Graaff accelerator operated at 1–3 MeV. From the glow curve analysis it was shown that the glow curve thus obtained was similar to that of 5–5.5 MeV alpha particles or 5.9 keV X-ray. However, both the peak height (P) ratio of the third to the second (P_3/P_2) and that of the third to the fifth (P_3/P_5) were dependent on the proton energy and dose,

particularly the fifth peak (P_5) which was strongly dependent on the proton dose.

On the contrary this investigation was to study the response of CaF₂ : Tm to low-level proton beams using the same van de Graaff accelerator but equipped with a Rutherford backscattering (RBS) device to keep the proton level low.

The Rutherford backscattering technique has long been used in spectrometry to take advantage of its analytical power. Other applications such as crystalline lattice study, ion implantation and semiconductor industry are also available. However, the Rutherford backscattering presented here is referred to classical scattering of protons by the electrostatic coulomb field of a gold nucleus. It is a common practice for small accelerators such as a 3 MV van de Graaff as ours. Both charged particles of proton and alpha are the main particles to be accelerated in this case. This kind of device is good for nuclear reaction studies in the low energy range for charged particles. In this work it was to investi-

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gate the feasibility of using TLD as a proton dosimeter which may be applied to the environmental monitoring for a proton therapy facility.

II MATERIALS AND METHODS

1. Thermoluminescence dosimetry

The TLD used is of the ribbon type made by Harshaw, U.S.A. under the commercial name TLD-300. The dimensions of TLD-300 are $3.2 \times 3.2 \times 0.9$ mm (thick) with a density of $3.25 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$. The effective atomic number is 16.3.

The TLD reader used is a Harshaw 2000C equipped with a Model 2080 analyzer. The system can record TL output, glow curves, peak heights and peak locations. The heating planchet used is made of a special material named A-P with dimensions of $6.35 \times 6.35 \text{ mm}^2$. The heating rate was 21°C s^{-1} , and the maximum temperature used was 300°C . The stability of the photomultiplier output is within $\pm 1\%$.

The oven used is a Thermolyne Model 10500, U.S.A. A range of temperature control is from room temperature to $1,200^\circ\text{C}$. The variation of temperature control is within $\pm 1^\circ\text{C}$. The annealings were performed in air. The TLDs were annealed at 400°C for 90 min prior to normal use.³⁾

2. Rutherford backscattering method

The van de Graaff accelerator used for this study is operated by National Tsing Hua University. It has the useful property of producing monoenergetic particles. The voltage is stabilized to within a few kV of the set value of 3 MV. Three types of particles such as protons, deuterons and alpha particles can be accelerated.

The energy range of the proton beam is from 1 to 3 MeV with a very narrow full width at half maximum. The uncertainty of the proton energy is within $\pm 1\%$. The irradiations were performed in a vacuum chamber at 1×10^{-6} torr. The current ranged from 4 to 30 nA. The dose of protons irradiated was from 1.48 to 94.56 mGy.

Traditional Rutherford backscattering method was used with the aid of a surface barrier detector made by Canberra, U.S.A., Model PD25-12-100 AM operated at 40 V. The proton spectrum and number can thus be obtained through a pream-

Fig. 1 Schematic diagram of Rutherford back-scattering device.

plifier, an amplifier, an analog-to-digital converter (ADC) and a multichannel analyzer (MCA).

The experimental setup is shown in Fig. 1. The TLD $\text{CaF}_2 : \text{Tm}$ and the surface barrier detector were placed at $+150^\circ$ and -150° respectively with respect to the incident direction of protons. The TLD irradiated area was kept at $2.5 \text{ mm} \times 3.2 \text{ mm}$. An approximate thick of $0.2 \mu\text{m}$ gold foil was placed at the center of the vacuum chamber. When the incident protons bombarded the gold foil, equal amounts of protons would scatter back and reach the TLD and the surface barrier detector separately. The energy of backscattered protons from the gold foil was calculated as Eq.(1).⁴⁾

$$E_1 = E_0 \frac{M_1^2}{(M_1 + M_2)^2} \left\{ \cos \psi + \left[\left(\frac{M_2}{M_1} \right)^2 - \sin^2 \psi \right]^{1/2} \right\}^2 \quad (1)$$

where

E_1 = energy of backscattered protons (MeV)

E_0 = energy of incident protons (MeV)

M_1 = mass number of incident protons

M_2 = mass number of target atom

ψ = backscattered angle

The energy loss of protons due to passing through a $0.2 \mu\text{m}$ gold foil was about 30 keV.⁵⁾ The 1–3 MeV proton beams that bombarded the $0.2 \mu\text{m}$ gold foil would have the backscattered protons with energies controlled at 0.98–2.94 MeV within an accuracy of 2%.

The number of backscattered protons that reached the surface barrier detector or TLD can be calculated by Eqs.(2) and (3) as below:⁵⁾

$$Y = I n_t \Delta x \sigma d \Omega \quad (2)$$

and

$$\sigma = \left(\frac{Z_1 Z_2 e^2}{4E_0} \right)^2 \left[\sin^{-4} \frac{\psi}{2} - 2 \left(\frac{M_1}{M_2} \right)^2 + 1 \right] \quad (3)$$

where

Y = number of protons reaching TLD or the surface barrier detector

I = number of incident protons

n_t = target nucleus density

Δx = target thickness (cm)

$n_t \Delta x$ = target thickness (atoms/cm²)

σ = scattering cross section

$d\Omega$ = the differential solid angle extended at ψ from the target

Z_1 = atomic number of proton

Z_2 = atomic number of target nucleus

e = electric charge

By the following Eqs.(2) and (3), one can control the number of protons that would irradiate the TLD or the surface barrier detector.

The conversion of proton number into absorbed dose (D) in Gy is carried out as the following the equation:

$$D = \frac{1.6 \times 10^{-13} En}{Atd} \quad (4)$$

where

E = energy of protons at the target (MeV)

n = number of protons

A = irradiated area of TLD

t = proton range in the irradiated TLD

d = density of TLD used

1.6×10^{-13} = energy conversion factor (J/MeV)

By using the SRIM Monte-Carlo simulation code,⁵⁾ all parameters calculated in this way are listed in **Table 1** as shown below:

III RESULTS AND DISCUSSION

Several parameters such as proton energy, dose

Table 1 Parameters related to proton irradiation.

Proton energy E (MeV)	0.98	1.47	1.96	2.45	2.94
Proton range (μm)	11	20.2	31.8	45.5	61.2
Number of protons	2×10^4	2×10^4	2×10^4	2×10^4	2×10^4
Absorbed dose (mGy)	10.96	8.96	7.59	6.63	5.91

Fig. 2 Glow curves of $\text{CaF}_2 : \text{Tm}$ irradiated with various proton energies.

and dose rate were investigated to study the relationship among those parameters and the response of $\text{CaF}_2 : \text{Tm}$.

1. Proton energy effect

The response of $\text{CaF}_2 : \text{Tm}$ to 0.9–2.94 MeV protons is shown in **Fig. 2** while the proton dose rate and dose both were kept constant. In the glow curve thus obtained, there are three main peaks as those obtained from ^{137}Cs photon irradiation. The second peak (P_2) is located at 110°C, the third peak (P_3) at 130°C, and the fifth peak (P_5) at 230°C. The temperature differences between these peaks were identified as $P_3 - P_2 = 20^\circ\text{C}$ and $P_5 - P_3 = 100^\circ\text{C}$. A new peak can be observed between P_3 and P_5 over 2.45 MeV as shown in **Fig. 2**.

Fig. 3 Peak height ratios of $\text{CaF}_2:\text{Tm}$ glow curves irradiated with various proton energies.

Fig. 4 Sensitivity response of $\text{CaF}_2:\text{Tm}$ to various proton energies.

As far as α particles and 5.9 keV photons are concerned, all glow curves including proton irradiated also looked similar. The peak height is $P_2 > P_3 > P_5$ in order. The peak height ratios (P_2/P_5)

Fig. 5 Glow curves of $\text{CaF}_2:\text{Tm}$ irradiated with various doses.

P_5) and (P_3/P_5) depend on the proton energy as shown in Fig. 3. In the energy range 0.9–2.94 MeV mentioned above, the ratio P_2/P_5 was between 2.50 and 1.69, while the ratio P_3/P_5 was between 1.7 and 1.13.

The sensitivity defined as the total TL output (nanocoulomb) per unit dose calculated by Eq.(4) is shown in Fig. 4. The higher the energy, the higher the sensitivity is. The difference may reach a factor of 270 in the energy range 0.9–2.94 MeV.

2. Proton dose effect

When both the proton energy and dose rate were kept constant, the glow curves of $\text{CaF}_2:\text{Tm}$ irradiated at 2.94 MeV with various proton doses are shown in Fig. 5. From 1.48 to 94.56 mGy. The new peak can be observed between P_3 and P_5 over 11.82 mGy as shown in Fig. 5. The peak height ratio $P_2/P_5 = 1.73 \pm 0.10$ while $P_3/P_5 = 1.13 \pm 0.7$ as shown in Fig. 6.

The TL output expressed as the nanocoulomb (nC) versus dose expressed in mGy is shown in

Fig. 6 Peak height ratios of $\text{CaF}_2 : \text{Tm}$ glow curves irradiated with various doses.

Fig. 7 The TL output of $\text{CaF}_2 : \text{Tm}$ vs. doses.

Fig. 7. Between 1.48 and 94.56 mGy the TL output is increased as the proton dose exceeds 23 mGy. This reflects that the linear range of proton irradiated $\text{CaF}_2 : \text{Tm}$ can be extended to 23 mGy. As the

Fig. 8 Glow curves of $\text{CaF}_2 : \text{Tm}$ irradiated with variable beam current.

ranges of protons in $\text{CaF}_2 : \text{Tm}$ are rather short, the supralinear phenomenon illustrated in Fig. 7 can be explained as the surface irradiation, which is not similar to the bulk irradiation by γ radiations. The phenomenon of supralinearity in the radiation response of solid state systems is by no means unique; however, the dependence of TL supralinearity on ionization density is apparently unique to TL mechanisms.⁶⁾

3. Beam current effect

With fixed proton energy, the glow curves displayed for the proton irradiated $\text{CaF}_2 : \text{Tm}$ are shown in Fig. 8 while the beam current or dose rates were varied. Those curves are similar to Fig. 5, and no changes in glow curve are observed.

The peak height ratios, P_2/P_5 and P_3/P_5 , also remained unchanged regardless the changes in beam current as shown in Fig. 9 which is similar to Fig. 6. The ratios P_2/P_5 and P_3/P_5 are 1.59 ± 0.04 and 1.10 ± 0.04 , respectively.

Fig. 9 Peak height ratios of $\text{CaF}_2 : \text{Tm}$ glow curves irradiated with variable beam current.

Fig. 10 The TL output response of $\text{CaF}_2 : \text{Tm}$ vs. dose rates.

The TL output expressed as the nanocoulomb (nC) due to dose rate effect expressed in nano-ampere (nA) is shown in Fig. 10. It was decreased as indicated between beam current 4 and 30 nA, and the difference may reach a factor of 2.5.

In summary the experimental results may be concluded as:

1. Similar glow curves are presented for the proton irradiated, alpha irradiated, and 5.9 keV X-ray irradiated $\text{CaF}_2 : \text{Tm}$.
2. A new peak has been observed for glow curves for higher proton energies and doses.
3. Though the peak height ratios did not show any variation in various doses and dose rates, but were affected by the proton energy.
4. Strong dependence is shown by the sensitivity and TL output of $\text{CaF}_2 : \text{Tm}$ with respect to proton energy, dose and dose rate.

The ranges of protons in the energy range are limited in the order of micrometers as shown in Table 1; the response of TLD $\text{CaF}_2 : \text{Tm}$ is due to the surface irradiation in contrast with bulk irradiation due to γ radiation. This explains some of the effects studied that are different from photon irradiation.

If TLD $\text{CaF}_2 : \text{Tm}$ is to be used as a proton dosimeter in the low energy range, the parameters mentioned above should be studied. For the protons emanating from an accelerator, the energy, dose and dose rate are normally known, even those due to scattering, that would mitigate the energy and dose dependence effects.

IV CONCLUSION

In conclusion, the TLD $\text{CaF}_2 : \text{Tm}$ may be used as a proton dosimeter under certain circumstances. It can be served as an alternative when one comes to making choices.

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