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Determination of *LET* in PADC detectors through the measurement of track parameters

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ABSTRACT

SSNTDs (solid-state nuclear track detectors), primarily made from PADC (poly(allyl diglycol carbonate)), are attractive detectors for dosimetric purposes. SSNTDs are more similar to human tissue than other passive detectors and the measurement of the track parameters provides information about the energy deposition of the incident particle. This paper describes a method for *LET* measurement based on the measurements of the major and minor axes of the track opening. The method was experimentally tested using alpha particles with energies ranging from 4.2 MeV to 6 MeV. The experimental results show that PADC can measure the total energy lost by a particle along a path of length Δx divided by the length itself, a quantity strictly related to the *LET*.

1. Introduction

The capability of PADC (poly(allyl diglycol carbonate)) detectors (commercially known as CR39) to measure unrestricted linear energy transfer (herein denoted as *LET*) is described in several papers [1–5] and used in dosimetry for dose assessment, especially in complex fields such as those that can be found in space.

With reference to Fig. 1, the absorbed dose delivered by a charged particle impinging at an angle θ on the surface of a given material with density ρ is given by(1)

$$D=\frac{\varepsilon}{m}=\frac{\int_0^x \frac{dE}{dx'}dx'}{\rho A l}=\frac{<\frac{dE}{dx}>x}{\rho A l}=\frac{\frac{\Delta E}{\Delta x}\frac{l}{\cos\vartheta}}{\rho A l}=\frac{\overline{LET}}{\rho A\cos\vartheta} \quad (1)$$

where ε is the energy imparted to a mass m of the given material, A is the area of the material surface and x and l are the length of the particle track and the material thickness affected by the energy deposition, respectively (see Fig. 1). $<dE/dx>$ is the mean stopping power, averaged over the length of the particle track x. This quantity can be also written as $\Delta E/\Delta x$, which represents the total energy lost by the particle along a path of length Δx divided by the length itself. $\overline{LET}$ is the mean *LET* averaged over x. Eq. (1) considers the stopping power and the linear energy transfer to be numerically equivalent. These quantities are formally different, however, and the difference lies in the energy that the secondary electrons lose by bremsstrahlung. This amount of energy is usually negligible, especially for low atomic number materials, as in the case of PADC. Thus, the mean particle energy loss (the mean stopping power $\Delta E/\Delta x$) can be considered to be equal to the energy transferred to the target (the mean linear energy transfer $\overline{LET}$).

Assuming that n particles impinge on the unit area (1 cm^2), the dose (mGy) and the dose equivalent (mSv) can be calculated using

$$D=\frac{1}{\rho}\times 1.602\times 10^{-6}\sum_{i=1}^{n}\frac{\overline{LET}_i}{\cos\vartheta_i} \quad (2)$$

$$H=\frac{1}{\rho}\times 1.602\times 10^{-6}\sum_{i=1}^{n}\frac{\overline{LET}_i}{\cos\vartheta_i}Q(\overline{LET}_i) \quad (3)$$

where the $\overline{LET}$ is expressed in keV μm^{-1}, ρ is expressed in g cm^{-3} and $Q(\overline{LET})$ is the ICRP quality factor.

In Eq. (2), the *LET* can be measured in any material, while in Eq. (3), the *LET* must be measured in water because the quality factor is a function of the *LET* in water.

Eqs. (2) and (3) provide an effective derivation of the dosimetric quantities, provided that the measuring system is able to detect the mean stopping power $\Delta E/\Delta x$ and the angle θ.

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2. Theory and practical formulae

The quantities used to describe the track growth during the etching process are V_b and V_t, which correspond to the bulk and track etch rates, respectively. While V_b can be assumed to be constant, V_t is a function of the initial energy (E) of the particle impinging on the detector surface and varies along its track, according to the decrease in the energy of the particle. This relationship indicates that the track growth velocity depends on the duration of the etching process t, i.e.

$$V_t = V_t(E,t) \tag{4}$$

$V_t\,(E,t)$ is the track-etch rate at the etching time t for an ion with initial energy E.

The variable t in Eq. (4) can be substituted by the variable x, resulting in a depth-dependent track etch rate $V_t = V_t(E,\ x)$ [6,9]. Other authors [10] consider Eq. (4) as unconventional and express V_t as a function of residual range. The practical formulae described in this section are experimentally verified using monoenergetic alpha particles and calculating the particle penetration x in CR39. This is the reason why it is convenient, in this work, to use Eq. (4).

This relationship is useful because it allows the definition of a correlation between $V_t(E,x)$ and the restricted energy loss $REL(E,x)$. In this paper the following practical relation is used [6,9]:

$$\begin{aligned} V = V_{mean} = V_t/V_b = 0.93 + 3.14\times10^{-3}REL - 7.80\times10^{-6}REL^2 \\ +1.11\times10^{-8}REL^3 - 5.27\times10^{-12}\,REL^4 \text{for } 33\text{MeV cm}^{-1} \\ \le REL \le 560\text{ MeV cm}^{-1} V = V_{mean} = V_t/V_b = 1.30 + 3.80 \\ \times10^{-4}REL + 4.9\times10^{-7}REL^2 \text{for } REL \ge 560\text{MeV cm}^{-1} \end{aligned} \tag{5}$$

Expression (5) holds under the assumption that delta electrons with energy higher than 350 eV do not contribute to track formation because their energy is deposited too distant from the ionising particle trajectory. This assumption is written formally as $REL = REL_{350}$. REL is a function of the particle energy and of the penetration depth (x) of the particle inside the detector. $REL(E,x)$ was calculated with the StopPow code [7]. Fig. 2 shows the curves representing the LET and the REL for protons and alpha particles in PADC.

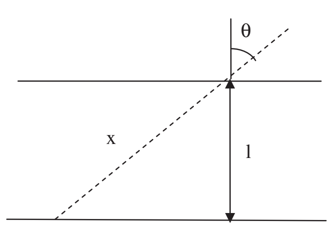

Fig. 1. Simple sketch to better understand the derivation of Eq. (1) (see text). x is the length of the particle track and l is material thickness affected by the energy deposition. It must be noted that $x \le R$ (R is range of the particle in the material). In case of perpendicular impact $l = R$.

Using a polynomial fit, it is possible to write an analytical relationship between LET and REL, which is written formally as $REL = f(LET)$. This function, together with Eq. (5), permits the expression of V as a function of LET, which is written formally as $V = g(LET)$. This function can be numerically inverted, and the result is the practical Eq. (6). Because of the fitting process needed to move from Eq. (5) to Eq. (6), data in the low LET region are better fitted by a 6-order polynomial, while in the higher LET region, a 3-order polynomial is sufficient. The relationship is split into three equations, each of which holds for a different V range. The low V range covers values that are typical of protons with energies below 10 MeV, the middle V range covers values that are typical of alpha particles below 6 MeV and the high V range covers values typical of ions with $Z > 2$:

$$\begin{aligned} LET_{nc}[\text{keV}/\mu\text{m}] = -6.627\text{E}+02V^6 + 6.338\text{E}+03V^5 - 2.488\text{E}+04V^4 \\ +5.124\text{E}+04V^3 - 5.825\text{E}+04V^2 + 3.469\text{E}+04V \\ -8.467\text{E}+03\text{Proton } 4 < LET_{nc} < 1001.04 < V \\ < 2.1LET_{nc}[\text{keV}/\mu\text{m}] = 1.4132V^3 - 22.453V^2 + 149.82V \\ -123.06\text{Alpha } 104 < LET_{nc} < 2862.1 < V \\ < 6.4LET_{nc}[\text{keV}/\mu\text{m}] = 0.0026V^3 - 0.3922V^2 + 29.997V \\ +116.81\text{Ions with } Z > 2286 < LET_{nc} < 9666.4 < V < 50.7 \end{aligned} \tag{6}$$

Eq. (6) must be regarded as a practical formulae valid within the specified V ranges. The index "nc" that appears in Eq. (6) was introduced to specify that this is a quantity measured with nuclear track detector CR39. In the "Results and discussion" section, the physical meaning of the quantity LET_{nc} will be clarified.

3. Experimental procedures

Two different PADC plastics were used: a set supplied by INTERCAST S.r.L in sheets with a sensitive area of 25×25 mm^2 and thickness of 1.4 mm as well as a set of PN3^{TM} detectors manufactured by Thermo Fisher Scientific in sheets with a sensitive area of 20×25 mm^2 and thickness of 1.5 mm.

The INTERCAST plastics were exposed to an electroplated ^{252}Cf source, an electroplated natural uranium source and a planar ^{241}Am source. The ^{252}Cf source has a diameter of 5 mm and is hosted on the bottom of a well that is 3 mm deep and 1 cm in diameter. This configuration causes the alpha particles to impinge on the detector surface with a maximum angle θ (angle defined by the particle trajectory and the normal to the detector surface) of approximately 60°. On the other hand, the natural uranium and ^{241}Am sources have an area wider than that of the PADC surface. For this reason, the exposures occurred by placing the detector in contact with the source. In this case, there is not an upper limit to θ. The exposure time was arranged to obtain a track density ranging from 1000 to 3000 tracks per cm^2. These values of track

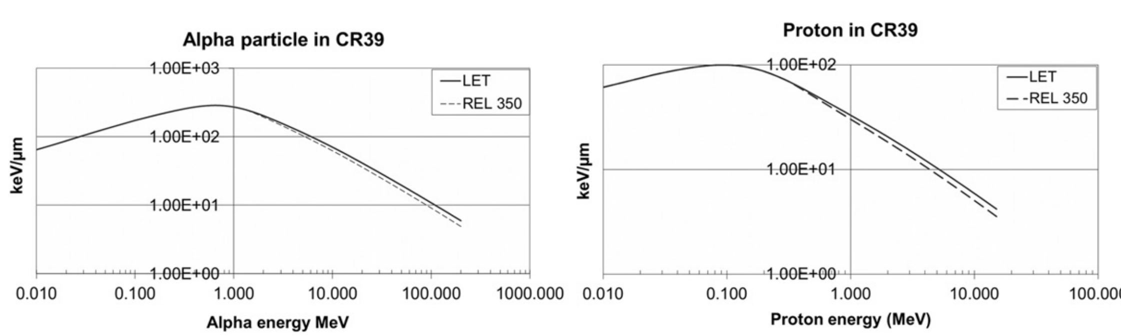

Fig. 2. LET and REL in PADC for protons and alpha particles calculated with StopPow.