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A Monte Carlo study of the extrinsic and intrinsic efficiencies detection of the CR-39 detector for alpha particles emitted by uranium and thorium series in geological samples

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ABSTRACT
A Monte Carlo method for determining the intrinsic and extrinsic efficiencies detection of a CR-39 solid-state nuclear track detector (SSNTD) was developed. This method is based on the simulation of the trajectory of alpha particles with energy $E\alpha i$ *emitted by the uranium and thorium series inside a natural material samples (for example phosphate), placed in a cylindrical capsule in contact with the SSNTD. The study of the convergence of the Monte Carlo approach shows that for* 10^7 *histories. The influence of the radius of the detector CR-39 and the cylindrical capsule on these efficiencies has been studied. The variation of these efficiencies as a function of the alpha particles initial energy* $E\alpha i$ *was also investigated. The impact of the critical angle* θc *of etching of the CR-39 SSNTD on these efficiencies was also been taken into consideration.*
Keywords: *Monte Carlo, CR-39 Detector, intrinsic efficiency, extrinsic efficiency, phosphate*

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I. INTRODUCTION

Since the discovery of fission in 1938 by Otto Hahn and Fritz Strassmann [1], the demand for the uranium element has steadily increased, which led scientists to develop several physical [2, 3], and chemical methods for the prospection and dosage of this element because once he is enriched in uranium-235, it is used as a fuel in nuclear fission reactors [4, 5]. The chemical methods have two major disadvantages: they are destructive and need long and often complex preparation periods. Physical methods have the disadvantage of requiring the sophisticated expensive equipment such irradiation techniques [6] or gamma spectrometry [7, 8]. The field of application of Solid State Nuclear Track Detectors (SSNTDs) has extended to various fields such as geology [9-11], archeology [12], dosimetry [13-15] , medicine and technology [16, 17] and environmental sciences [18, 19]. Therefore, SSNTDs are used as an effective means for measurement of alpha activity due to uranium, thorium and their progenies. However, the quantitative analysis of the uranium and thorium content in different samples based on the measurement of their alpha-activity using SSNTDs till remains difficult except that their extrinsic efficiency is determined. Therefore, we have developed a calculation method adapted to the experimental conditions using the Monte-Carlo method for the determination of the extrinsic and intrinsic efficiencies for CR-39 SSNTD exposed to the different geological samples (for example phosphates). The CR-39 SSNTD called polycarbonate of allyldiglycol ($C_{12}H_{18}O_7$); it is the newest SSNTD. It is well transparent, amorphous, isotropic and highly sensitive to ionizing radiation damage.

II. METHODOLOGY

2.1. Experimental procedure

The CR-39 SSNTD placed in direct contact with the studied sample (phosphate) in a cylindrical plastic capsule of radius R and height H (Figure-1) for one month. During this exposure time, the alpha particles emitted by the uranium-238 and thorium-232 series contained in the sample, bombard the CR-39 SSNTD. After its irradiation, the CR-39 detector undergoes an appropriate chemical treatment of NaOH solution (Normality is 6.25 N at a temperature of 70 °C during 7 h). After this chemical treatment, the latent traces developed on this detector for each exposure are determined using an optical microscope.

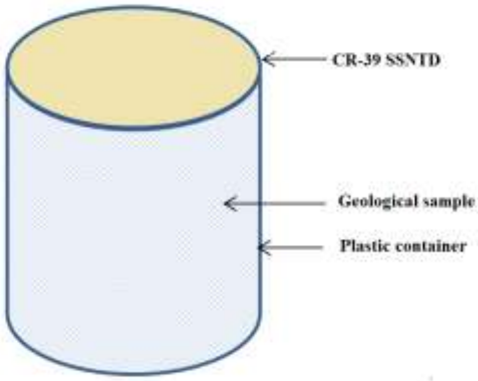


Figure 1. Arrangement of CR-39 SSNTD placed on a geological sample in a cylindrical plastic container

2.2. Monte Carlo calculation

The disk CR-39 SSNTD of radius R_D is placed in close contact with the studied sample, which is placed in a cylindrical plastic capsule of radius R and height H. The Monte Carlo code developed here is a simulation of the path of alpha particles, one by one, using random numbers. The position point P of alpha particle produced with energy $E_{\alpha i}$ inside the sample is chosen randomly is identified by P (r, z) (Figure-2). The emission direction of alpha particle with energy $E_{\alpha i}$ in the sample is also chosen using random number. She is spotted by the angle θ (figure-2).
With:

$$\begin{cases} r = R_i \times \zeta_1 \\ z = R_i \times \zeta_2 \\ \theta = R_i \times \zeta_3 \end{cases} \quad (1)$$

R : capsule radius
R_i: range of alpha particle of energy $E_{\alpha i}$ in the considered sample
ξ_i: random number between 0 and 1

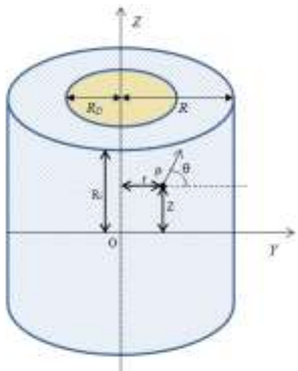


Figure 2: The Alpha particle is generated with random numbers at point P

The limiting angles θ_{L1} and θ_{L2} (Figure-3) under which the alpha particle energy $E_{\alpha i}$ produced in the point P will emitted and can be reach the CR-39 are given by the following relationships:

$$\theta_{L1} = Arc\sin\left(\frac{R_i - z}{L_1}\right) \text{ With } L_1^2 = (Ri - z)^2 + (R_D - r)^2 \quad (2)$$

and

$$\theta_{L2} = Arc\sin\left(\frac{R_i - z}{L_2}\right) \text{ With } L_2^2 = (Ri - z)^2 + (R_D + r)^2 \quad (3)$$

So if $\theta<\theta_{L1}$ and $\theta>\theta_{L2}$ then alpha particle, of energy $E_{\alpha i}$, emitted at this angle θ does not arrive at CR-39 detector and therefore it will not be detected.

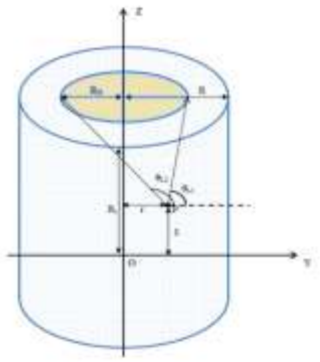


Figure 3: the emission of the alpha particles with $E_{\alpha i}$ from the point P under the limiting angles θ_{L1} and θ_{L2}

Therefore, the alpha particle with energy $E_{\alpha i}$ can eventually reach the CR-39; it must be emitted under an angle θ such that: $\theta_{L1} \leq \theta \leq \theta_{L2}$. In that case; the likely distance that can be traveled by the alpha particle of energy $E_{\alpha i}$ in the sample so that it can reach the CR-39 SSNTD, is given by:

$$l_i = \frac{R_i - z}{\sin\theta} \qquad (3)$$

If $l_i \geq R_i$, the alpha particle will be absorbed inside the sample and it will not reach and not be detected by the CR-39 SSNTD.

If $l_i < R_i$, the alpha particle reaches the CR-39 SSNTD with a residual energy $E_{\alpha i}^{Res}$ which will be the energy required to travel the distance (R_i - l_i) in the sample, that is determined from the range-energy curve corresponding to the studied sample (figure-4) obtained using the SRIM program [20] which is itself used to calculate the range R_i^D corresponding to the input energy $E_{\alpha i}^{Res}$ in the CR-39 SSNTD (figure-5).

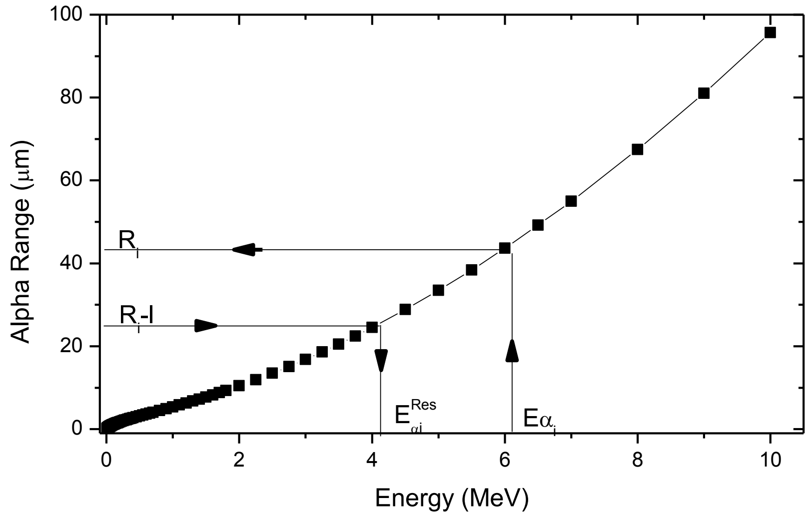


Figure 4: Alpha particle range-energy relation for phosphate samples

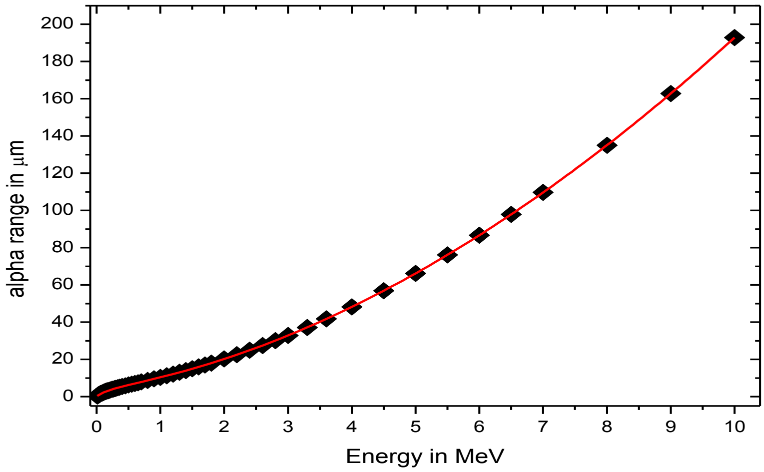


Figure-5: Alpha particle range-energy relationship for CR-39 SSNTD

This alpha particle of energy $E_{\alpha i}$ gives a latent track on the CR-39 SSNTD, but it will be observable using the optical microscope after the chemical treatment only, when, the incidence angle θ is greater than θ_c (where θ_c is called the critical angle of track registration; θ_c measured with the respect to the detector surface) which is defined by:

$$\theta_c = arcsin\frac{1}{V(R_i^D)} \quad (4)$$

Where

$$V(R_i^D) = \frac{V_T(R_i^D)}{V} \quad (5)$$

$V(R_i^D)$ called *response functions, with:*

V_B is the rate of removing layers of the undamaged surface of SSNTD.

$V_T(R_i^D)$ is the etching rate of the chemical solution along the latent track created during the passage of alpha particle with the residual energy $E_{\alpha i}^{Res}$ in the SSNTD.

For CR-39 SSNTD, the $V(R_i^D)$ is given by the following relationship [21]:

$$V(R_i^D) = 11.6\,\left(R_i^D\right)^{-0.464} \quad (6)$$

If $\theta \le \theta_c$ then the track latent created by this alpha particle with energy $E_{\alpha i}$ will not be observable using the optical microscope after chemical development.

If $\theta > \theta_c$, the latent track after chemically treatment is observable by the optical microscope.

This procedure is repeated for N_i alpha particles of energy $E_{\alpha i}$, therefore the extrinsic and intrinsic efficiencies for the CR-39 SSNTD are respectively defined by the following expressions:

$$\begin{cases} \varepsilon_{ex} = \dfrac{n_{iob}}{N_i} \\ \varepsilon_{in} = \dfrac{n_{iob}}{n_{id}} \end{cases} \quad (7)$$

With:

n_{iob}: number of tracks latent observed using the optical microscope after chemical development.

N_i: number of alpha particles for energy $E_{\alpha i}$ emitted initially in the sample.

n_{id}: number of alpha particles emitted initially in the sample with energy $E_{\alpha i}$ and reach the SSNTD detector with the residual energy $E_{\alpha i}^{Res}$ different from zero.

III. RESULTS AND DISCUSSION

After studying the convergence of the Monte Carlo method, we found that the results obtained on the extrinsic and intrinsic efficiencies converge from $N_i = 10^7$ iterations that we have adopted in our study. The study of the influence of the CR-39 SSNTD radius, R_D, on its extrinsic efficiency (Fig. 6) for different energies $E_{\alpha i}$ of alpha particles allows us to observe that this efficiency increases linearly with the radius R_D of the SSNTD and reaches its maximum value when $R_D = R$ (R is the radius of the capsule).

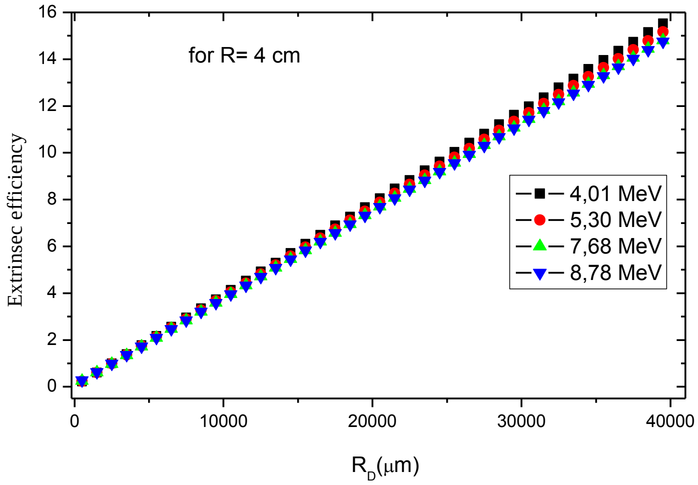
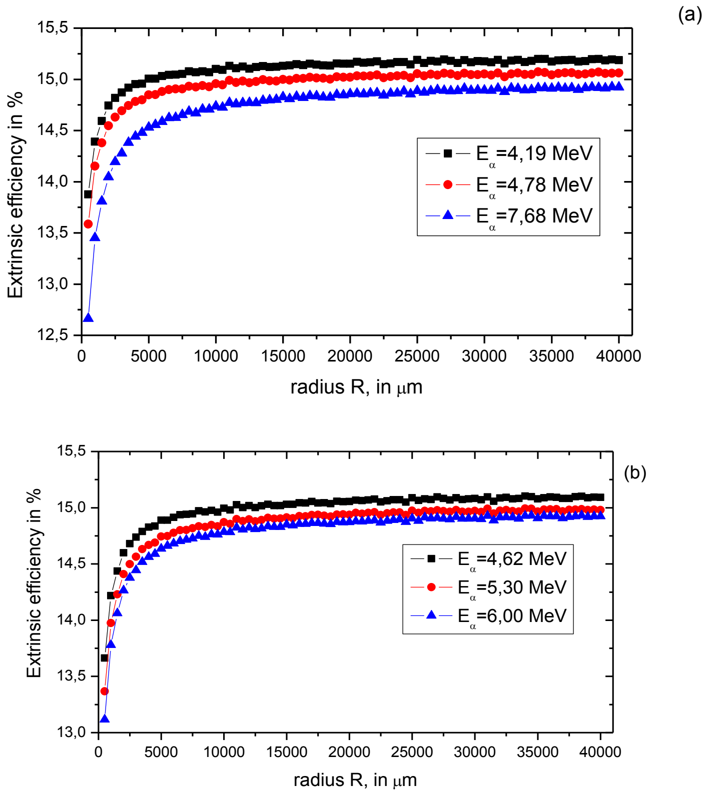


Figure 6: Variation of the extrinsic efficiency of the CR-39 SSNTD as a function of its radius (for R = 4 cm).

Similarly, we have studied the influence of the radius, R, of the capsule containing the studied sample on the extrinsic efficiency of the CR-39 SSNTD with $R_D = R$ for different values alpha energy particles $E_{\alpha i}$ (figure-7and 8). This study shows that the extrinsic efficiency increases when the radius R of the capsule increases. This extrinsic efficiency is almost constant from a threshold value of the radius of the capsule noted R_s that slightly varies with the energy $E_{\alpha i}$.



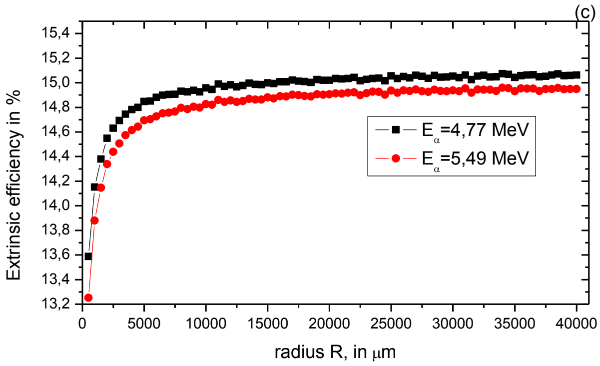


Figure 7: variation of the extrinsic efficiency of the CR-39 SSNTD as a function of radius plastic container for the uranium family alpha particles.

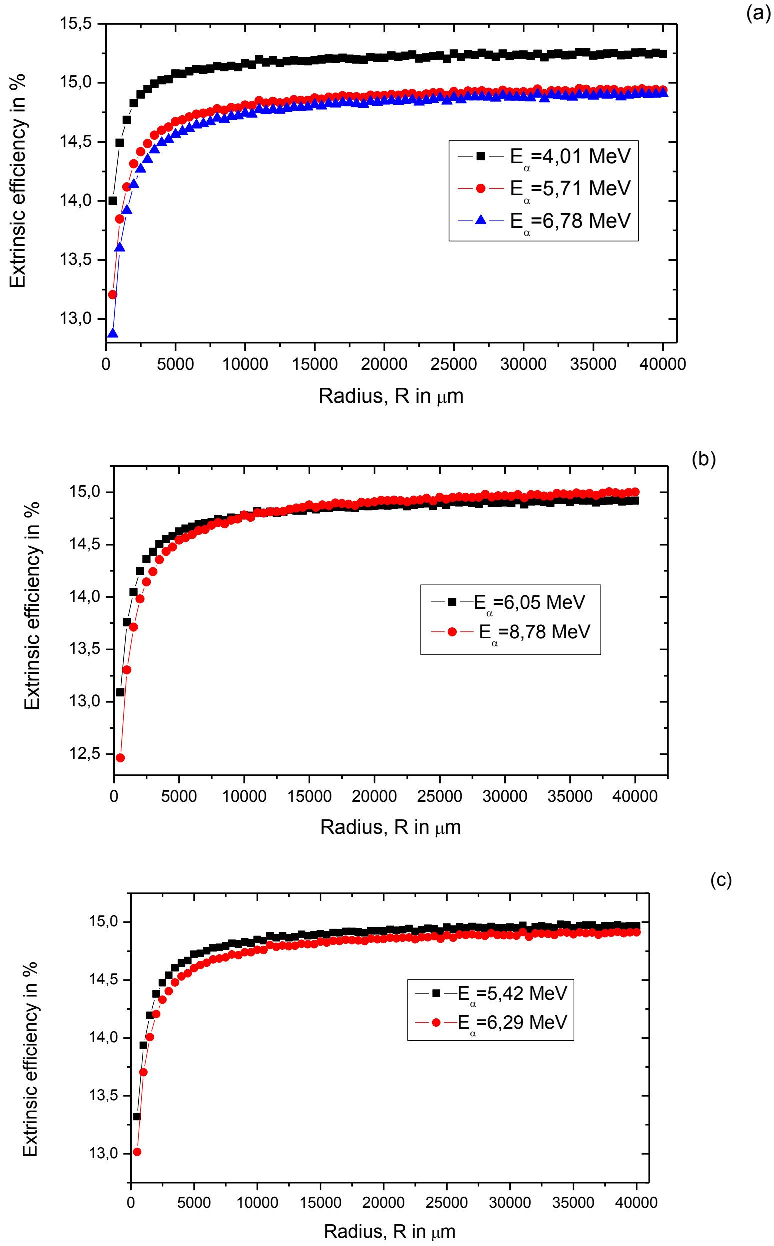


Figure 8: variation of the extrinsic efficiency of the CR-39 SSNTD as a function of radius plastic container for the thorium family alpha particles.

The optimal threshold radius R_{sop} of the capsule, for which the extrinsic efficiency is almost constant for the different energies $E_{\alpha i}$ of the alpha particles emitted by uranium, thorium and their daughters is of the order of R_{sop} =1.1 cm. (Fig.7 and Fig.8). The study variation of the extrinsic efficiency of the detector CR-39 as a function of the energy $E_{\alpha i}$ shows that this efficiency decreases when the energy $E_{\alpha i}$ increases up to the value Eαi = 6.78 MeV. When this energy exceeds this value, the extrinsic efficiency begins to increase. (Fig.9).

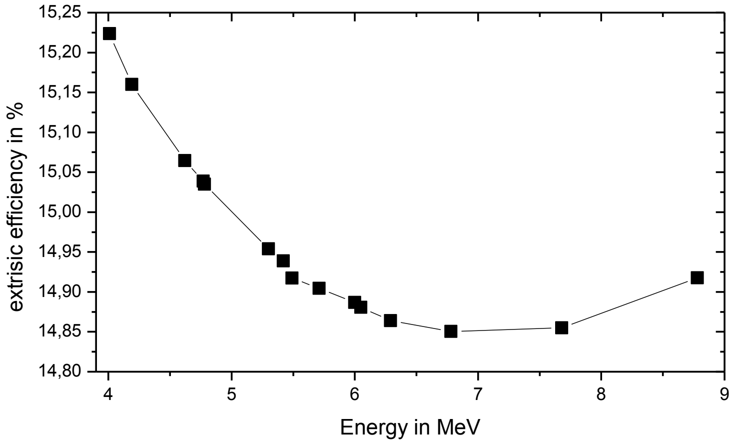


Figure 9: Extrinsic efficiency of the CR-39 SSNTD as a function of the initial energy Eαi for the emitted alpha particles

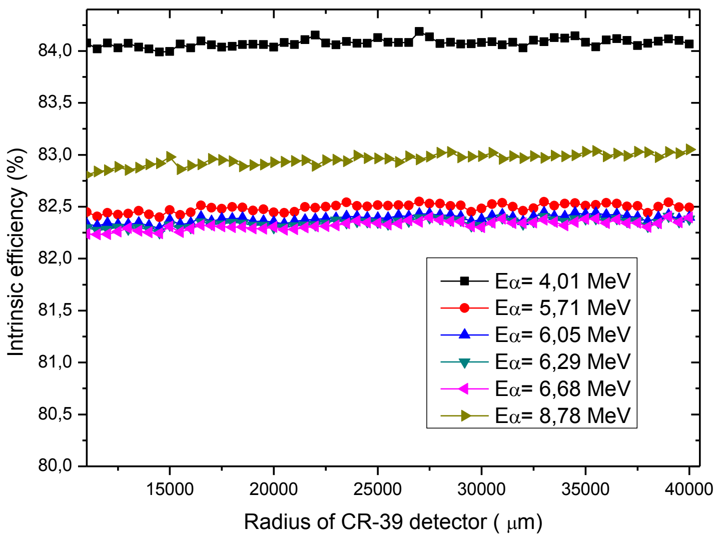


Figure 10: Variation of the intrinsic efficiency of the CR-39 SSNTD as a function of its radius for different alpha particles energy Eαi

The investigation of the variation of the intrinsic efficiency of the CR-39 detector as a function of its radius with (Rd = R> 1.1 cm) shows that this efficiency does not vary according to the radius of the CR-39. But, this efficiency vary according to the alpha particles energy emitted inside the geological sample (Fig. 10).

IV. CONCLUSION

A Monte Carlo method for calculating the intrinsic and extrinsic efficiencies of CR-39 SSNTDS for alpha particles emitted by uranium and thorium series inside a phosphate naturel sample in cylindrical plastic capsule is described in this work. The study of extrinsic efficiency has shown that it is maximal when the radius of CR-39 is equal to that of the cylindrical capsule (R = Rd)

This method is also used to calculate the optimal radii of the cylindrical capsule and the CR-39 detector whose extrinsic efficiency is maximal.

We have shown that the optimal radiuses R and Rd are of the order of 1.1 cm
On the other hand, we have found that the extrinsic efficiency of CR-39 decreases when the energy E_{ai} increases to the value E_{ai} = 6.78 MeV, then it increases from this value.
the CR-39 intrinsic efficiency does not vary according to the radius of the cylindrical capsule but it varies according to the energy E_{ai}

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