A parameterization of nuclear track profiles in CR-39 detector

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ABSTRACT

In this work, the empirical parameterization describing the alpha particles’ track depth in CR-39 detectors is extended to describe longitudinal track profiles against etching time for protons and alpha particles. MATLAB based software is developed for this purpose. The software calculates and plots the depth, diameter, range, residual range, saturation time, and etch rate versus etching time. The software predictions are compared with other experimental data and with results of calculations using the original software, TRACK_TEST, developed for alpha track calculations. The software related to this work is freely downloadable and performs calculations for protons in addition to alpha particles.

Program summary

Program title: CR39
Catalog identifier: AENA_v1_0
Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AENA_v1_0.html
Program obtainable from: CPC Program Library, Queen’s University, Belfast, N. Ireland

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No. of lines in distributed program, including test data, etc.: 15598
No. of bytes in distributed program, including test data, etc.: 3933244
Distribution format: tar.gz
Programming language: MATLAB.
Computer: Any Desktop or Laptop.
Operating system: Windows 1998 or above (with MATLAB R13 or above installed).
RAM: 512 Megabytes or higher
Classification: 17.5.
Nature of problem:

∗ This paper and its associated computer program are available via the Computer Physics Communication homepage on ScienceDirect (http://www.sciencedirect.com/science/journal/00104655).
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A new semispherical parameterization of charged particle tracks in CR-39 SSNTD is carried out in a previous paper. This parameterization is developed here into a MATLAB-based code software to calculate the track length and track profile for any proton or alpha particle energy or etching time. This software is intended to compete with the TRACK_TEST [1] and TRACK_VISION [2] software currently in use by all people working in the field of SSNTD.

**Solution method:**

Based on fitting of experimental results of protons and alpha particles track lengths for various energies and etching times to a new semispherical formula with four free fitting parameters, the best set of energy independent parameters were found. These parameters are introduced into the software and the software is programmed to solve the set of equations to calculate the track depth, track etching rate as a function of both time and residual range for particles of normal and oblique incidence, the track longitudinal profile at both normal and oblique incidence, and the three-dimensional track profile at normal incidence.

**Running time:**

1–8 s on Pentium (4) 2 GHz CPU, 3 GB of RAM depending on the etching time value

**References:**

[1] ADWVT_v1.0 Track_Test


[2] AEAF_v1.0 TRACK_VISION


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1. Introduction

Solid state nuclear track detectors (SSNTD) are widely used for assessment of charged particles radiation levels. The operation of these detectors is based on the fact that regions within the bulk of the detector material damaged along the charged particle track can be made visible by etching processes using alkaline solutions. The chemical and physical phenomena associated with the damage a charged particle creates in a polymer type SSNTD and the response of the damaged products to the etching materials and conditions are so complicated to the extent that leaves only little room for any theoretical assessment of the processes involved. Two aspects of three-dimensional track developments upon etching are usually considered. The first involves the use of atomic force microscopes [1–3] and confocal microscopy techniques [4–7] to reconstruct the etched track three-dimensional profile. The second involves the construction of geometrical equations describing the track shape profile for different incident particle type, energy, inclination and etching times [8–11]. Many aspects of SSNTD theory and applications are discussed in the review article by Nikezic and Yu [12]. However, the authors point out that there is not a single complete theory that satisfactorily explains track formation and development. A widely used FORTRAN based computer code that has the flexibility to switch between three different empirical mathematical equations for the alpha particles track depth development is described in Ref. [13]. This code has been around for about five years now and has well served most people in the field. Even so, it is generally assumed that there is some room for improvement. One such improvement is related to the mathematical formulation of the track etching velocity \( v_T \). It may be thus useful from the instrumentation point of view, to try to build a new generation of this type of software. It is the purpose here to present new software based on completely alternative mathematical modeling introduced previously by the authors [14] for describing track depth, and etching rate versus alpha particle energy and etching time. The modeling is extended to describe proton tracks in addition to alpha particles. Furthermore, the software based on this modeling is written in MATLAB and is designed to produce both numerical and graphical outputs of results related to track depth, diameter, etc., in addition to two and three-dimensional plots of track profile.

2. Experimental data

2.1. Alpha particles data

The experimental method used for obtaining experimental alpha particles track longitudinal profiles as a function of energy and etching time is described in detail in Ref. [14]. 1 × 1 cm CR-39 detectors were laterally exposed to narrow collimated alpha radiation from an Am\(^{241}\) for about ten minutes. Distances between the source and detector corresponding to alpha particle energies of 1.5, 2.26, 3.2, 4, and 4.85 MeV are used. Tracks are etched in 6.25 N NaOH solutions, at 70 °C over successive fifteen minute periods of times and digitally photographed under a 25 × magnification calibrated optical “Microscope Series Biological XSZ-H” attached to a high-resolution digital camera. A set of digital pictures of the longitudinal development of each particular track is thus obtained. The track boundaries in each picture are converted to digital, micron units’ x-y data using a special MATLAB image processing program [15]. Several hundred numerical data points are obtained from each track longitudinal profile. Experimental track depth and radius are automatically obtained by the software. These are crosschecked by visual traveling microscope measurements. No major discrepancies were observed and the computer data were taken as the bases for the following analysis. Furthermore, results of repeated track depth measurements showed a standard deviation from the mean values by about 6%.

2.2. Proton data

In an attempt to extend this modeling to be able to handle protons as well as alpha particles in CR39 detectors, proton tracks depth versus etching time experimental data published by Dörschel et al. [16] are used to perform the empirical modeling. Five proton energy track data are selected. These are 1.27, 1.87, 2.25, 2.65, and 2.95 MeV. The data were retrieved from the scanned digital picture of track depth plots using the image processing technique described in Ref. [15]. This procedure can be assumed to be associated with up to 10% errors.
3. Empirical parameterization

The alpha particle data are used to perform the empirical parameterization of track depth against etching time and energy. The detailed empirical modeling procedure is described in Ref. [14]. The empirical equations for the track depth obtained are

\[ L(t) = A_1 \tanh(U) \]  
\[ U = \exp\left(\frac{t - A_2}{A_3}\right) \]  

where \( L(t) \) is the track depth after etching for a period of time \( t \) (hours).

The dependence of the four parameters \( A_1, A_2, A_3, \) and \( A_4 \) upon alpha particle energy are deduced as

\[ A_1 = a_1E - 1.4 \]  
\[ A_2 = a_2E^{0.5} \]  
\[ A_3 = a_3E^{b_1} \]  
\[ A_4 = \frac{1}{A_1A_2A_3} \]

The parameters \( a_1, a_2, a_3, a_4, b_1 \) and \( b_2 \) are scaled parameters which should have the same scaled values for all energies. Details of the modeling used, and the deduced values of these scaled parameters for alpha particles are presented in Ref. [14].

Eqs. (1)–(6) are used here to parameterize proton tracks. The results of such fitting are shown in Fig. 1(a). The dots in this figure represent the retrieved data. The solid lines are results of fitting the data to Eq. (2). It is clear here that not only good agreement between experimental data and model fits are obtained for all five energies but the energy independence of the four free fitting parameters is well achieved. This is demonstrated by the scaled fitting parameter values presented in Table 1.

The only slightly higher standard error value is that associated with the free parameter \( a_1 \) with a standard error of 10%. This is within the experimental errors associated with the data extraction method.

Using the above mean value of the fitted parameters, the track etching velocity \( V_T \) is calculated. The results are shown in Fig. 1(b). The results for the Bragg peak obtained from calculations using the
Fig. 3. Examples of graphical outputs produced by the software CR39 for 5 MeV alpha particle after etching time of 3 h with bulk etching rate of 1.32 µm/h. This example represents the conditions of Fig. 3 in Ref. [19].

Fig. 4. Comparison of results of the energy range in CR-39 from the present software with those of the SRIM software.

Fig. 5. Model predictions of track etching rate for 2.95 MeV protons and antiprotons in CR-39 with bulk etching rate of 1.43 µm/h.
proposed model are in good agreement with those estimated in Ref. [16] obtained using other fitting techniques.

4. Modeling track profile

Being able to model the track etching velocity represents a key step towards modeling the track profile. The bulk etching velocity can be reasonably assumed as a constant value for a particular detector type. This is conditional that the etching times are not so excessive as to change the detector material properties. It can thus be assumed that for normal incidence, the etching processes will proceed in two directions. The first is along the track axis $z$ with etching velocity component $V_T$. The second is along the track diameter $R$ with etching velocity component of $V_B$ perpendicular to the track boundary at any point. For any particular etching time $T$, the track depth can be written as

$$L = \int_0^T V_T dt - V_B \times T.$$  \hfill (7)

The second term on the right hand side of Eq. (7) represents the thickness of the layer removed from the detector surface through the etching process. The track radius at any section perpendicular to the track axis is the product of the bulk etching velocity component of $V_B$ perpendicular to the track boundary times the period of time $(t')$ the particular position along the track axis has been subjected to the etching solution. This period of time is equal to $T$ at the detector surface before allowing for any material removal from the surface, and zero at the end of the etched track. We may thus write:

$$t' = T - t \quad 0 \leq t \leq T.$$  \hfill (8)
This etching process will continue up to the limit when $V_T$ becomes equal to $V_B$ (end of the actual particle range). As this point is reached, the etching process will continue in all directions with etching velocity $V_B$.

The results for track depth, diameter and profile obtained using this modeling are compared to those predicted by modeling presented in Fig. 3 in Ref. [18]. This figure shows the track depth and diameter development against etching time for 5.2 MeV alpha particles on a CR-39 track detector after 3 h etching. The bulk etching velocity stated is $1.32 \mu m/h$. The software is tested under these conditions. The results are presented in Fig. 2. Results in this figure are more consistent with the experimental data in Ref. [18] as compared to TRACK TEST software predictions presented in the same reference.

5. The software

All the above calculations are made possible through the use of MATLAB software written for this purpose. The software is in the form of a MATLAB M-file CR39($E$, $T$, $V_B$, theta, particle). It is written such that it uses the five input arguments $E$, $T$, $V_B$, theta, and particle type. These represent the incident particle energy in MeV, the etching time in hours, the bulk etching velocity in microns/hour, the incidence angle in degrees (measured from the normal to the detector surface) and the particle type respectively. The latter is limited to protons and alpha particles. These should be entered as string variables 'p' or 'a' respectively. The outputs of the program are plots for the track depth development, the track etching velocity, two and three dimensional track profile for
normal incidence and two dimensional track profiles for oblique incidence. In addition, the program produces numerical results for the track depth, radius, saturation time, the particle range, and the particle residual range. The software is designed to be user friendly. No prior detailed knowledge of MATLAB programming language is assumed. The only prerequisite for using the software in having matlab6.5 or higher version installed; the zip file for the software is freely available on the MATLAB file exchange website [17], and from this journal program library website [19]. The zip file is to be extracted into the MATLAB “work” directory (this is where MATLAB keeps the user’s data and programs by default). For example, and in order to produce results for a track produced by a 5 MeV normal incident alpha particle after etching for 3 h, with bulk etching velocity of 1.32 µm/h, (inputs for data in Fig. 2 in Ref. [18]), the software can be initiated by simply entering the statement:

\[
\text{CR39}(5, 3, 1.32, 0, 'a') \quad \text{or} \quad [A, C, D, E, F] = \text{CR39}(5, 3, 1.32, 0, 'a').
\]

Using the latter statement will output the numerical results for track depth, track diameter, range, residual range, and track saturation time to the dynamical variables \(A, B, C, D,\) and \(E\) respectively.

Either way, the program will produce the following outputs:

1- Plot of the track depth development with etching time for periods of time between zero and post track saturation. The plot under the above conditions is shown in Fig. 3(a).

2- Plot of the development of the track etching velocity \(V_T\) with etching time. This is shown in Fig. 3(b).

3- Two dimensional plot of the track profile under the energy, etching time, etc. entered above. This is shown in Fig. 3(c).

4- For normal incidence only, the graphical output will include a three dimensional representation of the track profile under the above conditions similar to that of Fig. 3(d). This facility will not be activated for oblique incidence.
As far as oblique incidence is concerned, results similar to those in Fig. 3(a, b) are not altered. However, results for Fig. 5(c) are replaced by the oblique two dimensional view of the track profile looked at from the direction perpendicular to the track opening minor axis. In addition, the elliptical track opening major and minor axes together with the track vertical depth are presented numerically. Results for the same above conditions but with 30° oblique incidence are presented in Fig. 3(e).

Several cross checks on the software’s ability to reproduce alpha particle data have been presented here, and in our previous paper. One additional such check as far as protons are concerned has been carried out using the well accepted energy-range results of the SRIM software [20]. The present software defines the range of a particle in the detector as the distance between the original detector’s surface and the position of the Bragg peak maximum. Fig. 4 shows the SRIM software results (dots) plotted with the present software results (solid line) for the energy range 1–7 MeV. It is clear that the present software is capable of reproducing the SRIM results with good accuracy.

### Table 1

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<th>Red Picture data</th>
<th>Blue Model</th>
<th>Black TRACK TEST software</th>
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</table>

Fig. 6. (continued)

### 6. Other charged particles tracks

The fact that the above modeling built on the basis of alpha particle data has succeeded in describing independent proton data reasonably well may encourage one to extend this modeling slightly further to describe other charged particle tracks. One such case is related to antiprotons. Published results on the nature of antiproton interactions with different materials suggest that the energy loss for antiprotons is much similar to that of protons apart from the fact that antiprotons produce a much larger Bragg peak [21–24]. This is due to the formation of a protonium atom followed by annihilation and the release of excess radiation energy. Sullivan [25] for example showed that the ionization produced by antiprotons in polyethylene at the Bragg peak is about twice that produced by protons. In addition, one published result on 5.9 MeV antiprotons track diameter in a CR-39 detector with bulk etching rate of 1.43 μm/h gives a value of 2.05 ± 0.45 μm after 185 min [23]. With the above results at hand, a tentative attempt was carried out to find suitable parameters for the model to be able
to accommodate antiprotons. The set of parameters obtained are: 22.2, 4.0, 2.1, and 0.14 for $a_1$, $a_2$, $a_3$ and $a_4$ respectively, to give a track diameter of 2.15 µm with the correct Bragg peak heights. Results of calculations of track etching rate plots for 2.95 MeV protons and antiprotons using these parameter values are shown in Fig. 5. It must be emphasized however that these parameter values are only tentative. They have been included in the software but they are not activated. They can be activated by simply removing the comment ‘%’ sign on line 22 in the software. Solid experimental data on antiproton track depth in CR-39 detectors are needed to perform robust fittings and obtain more accurate model parameter values.

7. Results and discussion

One of the main aims of the proposed software is to calculate charged particle track profiles in CR-39 detectors. Some concerns have been raised about the accuracies of predictions of the original TRACK_TEST and its updated version program TRACK_VISION [18]. The main concern here is related to the correct estimations of track diameter and track depth. However, and due to the relatively large experimental errors associated with these two track properties, the inclusion of track profile data in any comparison with a particular model will bring an added benefit. Our track profile experimental results are thus compared with both TRACK_TEST and current model predictions. The results of such comparisons are presented in Fig. 6. Three etching times corresponding to each of three stages of track development at each energy value are selected for presentation. Results at other etching times showed the same pattern. Each subfigure contains a digital picture of the track profile, and the numerical profile data plotted in red. The latter are compared on the same subfigure with the above model prediction plotted in blue and the TRACK_TEST software predictions using the third set of equations with the internal fitting parameters plotted in black.

The results from all five subfigures indicate that the original TRACK_TEST software always produces results that are systematically lower than those of the experimental data as far as
track depth is concerned. On the one hand, track diameter values obtained are higher than the experimental ones. The current model predictions on the other hand seem to be more consistent with experimental profiles. This fact is not only supported by our data but also by other independent experimental data discussed above.

8. Conclusions

A new empirical parameterization and the associated software of track depth and track profile development in CR-39 solid state nuclear track detectors are presented. The software is tested for both proton and alpha particle experimental data. The results of this modeling are in good agreement with experimental results as far as protons and alpha particles are concerned. This software, named CR39, has the added advantage over the original TRACK_TEST software in that it handles protons in addition to alpha particles. The software is made available for free download from both the MATLAB file exchange website and this journal program library website.

References