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Semi-automated, Three-dimensional Measurement of Etched Tracks in
Solid-State Nuclear Track Detectors

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Abstract

We describe a new method for measuring the shapes and sizes of etched tracks in plastic or glass detectors, using a commercial digital image processing system. The method exploits the fact that in transmitted light any portion of the microscopic image of the track is in best focus when it is darkest. A minimization algorithm is used to produce a two-dimensional projected image of the three-dimensional etched track. The locus of points of maximum gradients in the image leads to a closed contour of the projected image. From this gradient image the profile, length and width of the conical etched track are automatically determined. The method is also applicable (a) to a track that penetrates a detector and has been etched until the cones from opposite surfaces are connected and (b) to a track with a curved profile due to a strongly slowing particle. The method is illustrated with measurements of tracks of 1 A GeV uranium ions in Tuffak polycarbonate and in CR-73 polycarbonate and of cosmic ray tracks in a CR-39 detector.

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1. Introduction

Nuclear track-recording solids, in which the tracks are revealed by a preferential etching treatment [1], are now being used in the precise determination of charge Z and velocity $v = \beta c$ of charged particles in a variety of applications [2], in some cases with resolution sufficient to look for nuclei with nonintegral charge [3]. A number of current problems in nuclear physics and in astrophysics require the measurement of such a large number of events that some degree of automation is essential.

Figure 1 shows examples of the geometry of etched tracks of particles passing through a track-recording solid. All exposed surfaces of a solid immersed in an etching reagent at controlled concentration and temperature are removed at a rate v_G for a time t at the same time as the etchant proceeds along the track at a rate v_T . The latter rate is a monotonic function of the restricted energy loss (or, more simply, of Z/β) of the particle. Depending on the etch time and the rate of change of Z/β along the particle's trajectory, the competition between the two rates leads to a pair of (a) separated or (b) connected conical etch pits of half-angle $\varphi = \arcsin (v_G / v_T)$, or (c) to cones with curved sides. The ratio $s \equiv v_T / v_G$, called the sharpness of the cone, is the tangent to the curved side, and may vary along the particle's trajectory. Measurements of s at two points sufficiently well separated along the trajectory to observe or set limits on the rate of change of velocity (requiring, for high-energy particles, a stack of many detectors) permit both Z and β to be determined.

To determine s , there are, in principle, three approaches that can be taken. One can measure the cone mouth dimensions and

zenith angle; the cone length and zenith angle; or the complete profile of the cone, which determines s as a function of position along the trajectory.

It is far easier to develop more or less automated methods for measuring ellipse dimensions than for measuring etched cone lengths or profiles, because reasonably good results can be obtained by measurements in a single plane of gray values above or below a preset threshold for a digitized image [4-7]. Heinrich and his coworkers have developed a fully automated, microprocessor-based picture analysis system for rapidly measuring all the etchpit areas in a large plastic sheet [7]. Their system is well-suited for the study of particles at known angles of entry such as is common in accelerator experiments [8]. For particles at unknown angles, their system can roughly determine the angles from the ratio of major to minor axes of the elliptical etchpits.

For etched tracks with large s , the sensitivity of cone mouth dimensions to s becomes vanishingly small, and one must measure either cone lengths or profiles. In this paper we will describe a new method for determining the profile, minor axis, and length of a three-dimensional etched track with large s , using a commercial digital image-processing system. We will present some results of measurements of 1 A GeV uranium ion tracks in two different kinds of detectors which show that s can be determined at least as accurately with the image-analysis method as with the traditional, more laborious method that uses an eyepiece micrometer. Being largely automatic, it greatly reduces the elements of fatigue and subjectivity that restrict the range of problems to which manually made length measurements can

be applied.

2. Determination of s from Track Parameters

Using the symbols defined in Fig. 1, we give several relationships that allow s to be determined from measurements of the parameters of the projected image of an etched cone, together with a measurement of the sheet thickness at the etched cone. The values of s and θ can in principle be determined from measurements of the major and minor axes of the elliptical etchpits mouth, through the relations

$$s = [1 + (b/G)^2] \sec \theta / [1 - (b/G)^2] \quad (1)$$

$$\sec \theta = s a [G(s^2 - 1)^{\frac{1}{2}} - a] \quad (2)$$

provided the value of G , which depends only on the etchant and etching time, is known. For a given fractional error in b the fractional error in s becomes unacceptably large at large s , as can be seen from the relation

$$\sigma_b/b = \sigma_s \cos \theta / (s^2 \cos \theta - 1) \quad (3)$$

The value of s above which length measurements become more accurate than ellipse measurements depends both on the relative resolution of the systems used to measure cone mouth dimensions and cone lengths and on the roughness of the post-etched surface, which contributes to errors in mouth dimensions. The crossover value of s is typically in the vicinity of 3 to 6, as can be inferred from Fig. 2, which shows data for the plastic detector CR-39(DOF) calibrated by use of a variety of relativistic nuclei of known Z and β [9]. At the top of the figure is the measured dependence of $s - 1$ (which expresses the excess over the value in the absence of a particle track) on Z/β . The graphs at the bottom compare the fractional error in $s - 1$, determined from etchpits mouth diameters for beams at normal incidence, with the

same quantity assuming length measurements can be made with standard deviations of 1, 2, or 3 μm , and assuming etching conditions such that $G = 25 \mu\text{m}$. (A value $\sigma_L = 2 \mu\text{m}$ is attainable by an experienced microscopist using a 100X oil objective.) The curves intersect at values of Z/β corresponding to $s = 3, 4.6$, and 6.

To determine s from the projected cone length, y , the thickness, H , and the projected trajectory between the mouths of the pair of cones, p , one iterates the two relations

$$s = [(y-p/2)\csc\theta + (H+2G)/2\cos\theta]/G \quad (4)$$

$$\tan\theta = [p-2G\cos\varphi(1+\tan\varphi\tan\theta)/(\cos\theta + \sin\varphi)]/H \quad (5)$$

where $\varphi = \arccsc s$. If G is not known it can be found by measuring b and iterating eqs. (1), (4), and (5).

One can also determine s from the projected cone shape and a knowledge of G and θ . For the case where s is approximately constant along a cone one can measure the projected cone angle, α , and find s by iterating eq. (5) and

$$s = [\sin \arctan(\sin\theta \tan\alpha)]^{-1} \quad (6)$$

Again, if G is not known one measures b and includes eq. (1) in the iteration.

3. Picture Analysis of Digitized Images of Etched Tracks

We use a commercial digital image processing system (Gould - DeAnza IP6400) attached to a Vidicon camera at the focal plane of a Leitz Ortholux transmitted-light microscope. Figures 3 to 5 illustrate the method we have developed for extracting from the digitized image the values of y , b , and α for the pair of etch-pits along the trajectory of a charged particle. Looking in the microscope at an etched track, one sees a three-dimensional image that is in focus only in a narrow slice of depth ~ 1 to ~ 10 microns (Fig.3a), depending on the numerical aperture of the

objective used. The usual procedure in track measurements is for an operator to focus on different portions of the track and measure its projected length or width by moving the position of an eyepiece micrometer. The new method "integrates" slices at many different focus settings to produce a composite projected image (Fig. 3b). Then a gradient operation is performed on this image to produce a new image (Fig. 3c), from which the parameters y , b , and α are automatically extracted (Fig. 3d).

As one can see from the intensity profile in Fig. 4, the intensity of transmitted light is a minimum inside a cone, and the gradient is steepest at an edge that is in sharp focus. The basis of our method is the fact that in transmitted light any portion of the microscopic image of the etched cone is in best focus when it is darkest. The "integration" process consists of taking the pixelwise minimum of consecutive slices while the focus of the microscope is being moved manually or with a stepping motor from top to bottom of the plastic sheet.

The digital image-processing system (Fig. 5) starts by setting the result-memory B to the maximum gray-value 255. Then the program loops over the following two steps:

- 1) In one video frame time (30 ms) a new image of 512*512 pixels in 256 gray-levels is collected in image-memory A.
- 2) In 30 ms the digital video processor (DVP) finds the pixelwise minimum of the new image in A with the result image in B and stores the result back in B.

This loop is repeated (typically 20 to 100 times, depending on the numerical aperture of the objective and on the depth of the cone) until the entire three-dimensional image is vertically swept and a projected two-dimensional minimized image is pro-

duced.

To determine the cone parameters a gradient image is produced of the minimized image, using a Prewitt mask. Then the local maxima -- the gradient peaks -- of this gradient image are found. Only those gradient peaks are kept that correspond to a gray-value below a predetermined threshold in the original minimized image. All of the preceding operations are performed with the digital image-processing system.

The gradient peaks are then read into the memory of the host computer (a VAX 11/780), and the cone parameters are determined by a computer program. We first use a simple track-following algorithm to find the two sides of the cone that converge on the cone tip. (In the present version of the program the location of the tip is temporarily given approximately by the operator; in the final version this will be done automatically.) The positions of all peaks are converted to polar coordinates and strung together if they are within ± 0.05 rad in θ and within 30 pixels in r .

The projected angle α between the two sides of the cone is computed by fitting straight lines through the straight sections of the two tracks in rotated coordinate systems. The fits are repeated if points have to be removed because of bad residuals. The width, $2b$, is defined as the maximum separation of points on the two sides of the cone at the same (to within two pixels) radial distance from the cone tip. A median filter is used to discard outliers. The projected length, y , is determined by finding the distance between the cone tip, given by the intersection of the two sides, and the position of the maximum gradient along the bisector. The projected trajectory, p , from the point

of entry at the top of the plastic sheet to the point of exit at the bottom is determined from the maximum gradients along the bisectors of the pair of cones.

Application of the technique to a pair of connected cones forming a constricted cylinder (Fig. 6) is straightforward.

Figures 7 to 9 show examples of minimized images of tracks in three different kinds of plastic detectors.

4. Tests of the Performance of the Picture-Analysis Method

Figures 10 and 11 and Tables 1 and 2 show the results of our measurements of etched tracks in two kinds of plastic detectors irradiated with 1 A GeV uranium ions at the Lawrence Berkeley Laboratory Bevalac. A 250- μm thick sheet of Tuffak polycarbonate was irradiated at zenith angles of $\sim 16^\circ$, $\sim 32^\circ$, and 48° and etched in 6.25 normal NaOH solution at 70°C for a time such that $G = 6.7\ \mu\text{m}$ and the cones were about $65\ \mu\text{m}$ long [10]. Figure 7 shows minimized images of cones at the three zenith angles; the middle and lower histograms in Fig. 10 show the distributions of values of s measured with a 45X dry objective and a 53X oil immersion objective; Fig. 11 compares measurements of projected track length, y , made on the minimized images with measurements made by eye using an eyepiece micrometer; and Table 1 compares mean values and fractional standard deviations of s , y and b at the three angles. A 1.1 mm sheet of CR-73 polycarbonate was irradiated at a zenith angle of 34° and etched in the same NaOH solution for a long time ($G = 70.0\ \mu\text{m}$) to produce very large cones [11]. Figure 8 shows a minimized image taken with a low-power (7X) objective, and Fig. 10 and Table 2 summarize our data for CR-73. Not having a digitized stepping motor for the focus, for both detectors we changed the focus manually during acquisition of the

minimized images and we determined the sheet thickness at each track from readings of the fine-focus knob. This would be done automatically in a permanent system.

From an inspection of the figures and tables we draw the following conclusions:

1) Mean values of s for cones at angles from $\sim 15^\circ$ to $\sim 48^\circ$ agree extremely well among themselves and with the mean value obtained with an eyepiece micrometer. Since tracks at larger zenith angles require less correction for their vertical component, measurements of s from minimized images should be practicable over essentially all zenith angles above $\sim 15^\circ$.

2) The fractional standard deviations of s and y obtained from minimized images and of y obtained with an eyepiece micrometer are all of comparable magnitude, about 3 to 4%. Salamon et al. [12] have shown that for 1 A GeV uranium ions in a plastic medium the statistical processes of pickup and stripping of atomic electrons lead to a fractional standard deviation of about 0.5% in ionic charge, which corresponds to $\sigma_s/s \approx 2.8\%$. Thus, most of the spread in values of s and y is due to fluctuations in energy deposition by the uranium ions rather than to measurement error.

3) The fractional standard deviation of b for the cones in Tuffak is $\sim 2\%$, which corresponds to 0.35 pixel or 0.12 μm . Using eq. (3) with $s \approx 13$, we find that the corresponding value of σ_s/s is $\sim 25\%$, which is far poorer than can be achieved using y or α . Assuming no change in σ_b with increasing etch time, one could etch the Tuffak until $G \approx 25 \mu\text{m}$ and reduce σ_b/b to 0.5% and σ_s/s to 6.3%, which is still a poorer value than can be achieved with y or α .

4) The correlations between measurements on the minimized images and with an eyepiece micrometer made on the same tracks indicate that the digital and manual methods agree to within about 1%.

5) The correlation between y and α , measured on the same tracks with the picture-analysis method, is somewhat worse, typically $\sim 2.5\%$. In order to determine which of the two parameters provides the better measure of Z/β of a particle, and possibly to improve the algorithms used to determine track parameters, we need a source of ions with a smaller spread of values of Z/β . As Salamon et al. [12] have shown, one can achieve this by inserting sheets of a material with high atomic number, such as copper, between plastic sheets prior to the irradiation. This greatly increases the fraction of fast uranium ions that are fully stripped, reduces the standard deviation in Z/β , and removes any correlation in ionic charge between plastic sheets on opposite sides of a copper sheet. We plan to evaluate the picture-analysis method using interleaved copper and plastic detectors in the future.

5. Scope of Applicability of the Picture-Analysis Method

Provided the zenith angle of the particle and the value of s are sufficiently large for the projected cone tip to extend beyond the edge of the ellipse, one can determine Z/β from measurements of either α or y . Figure 12 shows, for Tuffak and CR-39(DOP), the range of zenith angles and values of Z/β for which α and y can be measured digitally. For cases in which the projected cone tip lies within the ellipse, one can measure a and b , the major and minor axes of the ellipse, digitally by a simple extension of the minimization method, or one can use the picture-

analysis method developed by Heinrich et al. for etchpit mouths [7].

To locate tracks of rare, very heavy, relativistic nuclei despite a background of tracks of less interesting lighter nuclei, it is a common procedure [13] to etch every n th sheet of a large stack (where n is ~ 4 to 10) for a sufficiently long time that the pairs of cones along the trajectories of the most highly ionizing particles have touched, forming hollow tapered cylinders with their narrowest parts in the center as illustrated in Fig. 6. Events with touching cones can then be quickly located either by detecting the flow of ammonia gas or producing an electric spark through the holes. The remainder of the stack is then etched for a shorter time so that cone tips do not touch. Our picture-analysis method enables one to measure the tapered cylinders, which could not be measured accurately with a manual technique based on cone length measurement.

Although the etchpit cone angles in most track-recording glasses are quite large, those in phosphate glass detectors [1] are small enough to be amenable to measurement with our picture-analysis technique. These glasses, being much less sensitive than plastic detectors, are used to identify particles with values of Z/β exceeding ~ 100 .

With further development our picture-analysis method should give significantly better resolution and reproducibility than any technique involving measurements by eye. This is so partly because of human fatigue and drift in judgment as to the proper focus and setting of an eyepiece micrometer. There are also fundamental advantages. The picture-analysis method uses all of the information in the projected image -- in effect, the width of

the cone at all points along the etched portion of the trajectory. In a visual technique s is determined from only one number -- the distance along the trajectory from the surface to the cone tip. For small cone angles the exact position of the tip is difficult or even impossible to determine, either because of residual liquid in the tip that makes the last few μm virtually invisible or because the width of the cone near the tip is below the limit of resolution of an optical microscope. The observer must attempt to compensate for the nearly invisible portion near the end of the cone by extrapolating the sides of the cone to an imaginary tip. Our method is immune to such problems because it uses only those pixels that are darkest, and the extrapolation of the sides of the cone to the tip is done automatically.

An important future application of our picture-analysis method will be the analysis of the atomic numbers and energies of the rarest elements in the cosmic rays -- those consisting of nuclei of the elements at the end of the Periodic Table such as uranium and possibly transuranic elements. It is expected that in late 1986 a gigantic spacecraft carrying 40 m^2 of two types of plastic detectors will orbit the earth for a period of about 2.5 years to collect tracks of such ultraheavy cosmic rays that can be analyzed when the plastic stacks are recovered and returned to earth.

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References

1. R. L. Fleischer, P. B. Price and R. M. Walker, Nuclear Tracks in Solids (University of California Press, Berkeley, 1975).
2. S. P. Ahlen, P. B. Price and G. Tarlé, Physics Today, Sept., 1981, p. 2.
3. P. B. Price, M. L. Tincknell, G. Tarlé, S. P. Ahlen, K. A. Frankel and S. Perlmutter, Phys. Rev. Lett. 50, 566 (1983).
4. E. K. Shirk and P. B. Price, Proc. 16th Inter. Cosmic Ray Conf., Kyoto, Japan, 11, 86 (1979).
5. J. H. Adams, Nucl. Tracks 4, 67 (1980).
6. J. Beer, J. Pipper and W. Heinrich, J. Phys. E 15, 439 (1982).
7. W. Trakowski, B. Schofer, J. Dreute, S. Sonntag, C. Brechtmann, J. Beer, H. Drechsel and W. Heinrich, Univ. of Siegen preprint SI-84-2 (1984).
8. W. Heinrich, H. Drechsel, W. Trakowski, J. Beer, C. Brechtmann, J. Dreute and S. Sonntag, Phys. Rev. Lett. 52, 1401 (1984).
9. P. B. Price, Shi-lun Guo, M. L. Tincknell, M. H. Salamon and G. Tarlé, submitted to Nucl. Instrum. Meth. (1984).
10. Shi-lun Guo, P. B. Price, M. H. Salamon, J. Drach, G. Tarlé, S. P. Ahlen and M. L. Tincknell, submitted to Nucl. Tracks (1984).
11. P. B. Price and G. Tarlé, preprint CERN-EP/84-72.
12. M. L. Salamon, J. Drach, Shi-lun Guo, P. B. Price, G. Tarlé and S. P. Ahlen, submitted to Nucl. Instrum. Meth. (1984).
13. E. K. Shirk and P. B. Price, Astrophys. J. 220, 719 (1978).

Table 1. Measurements on 1 A GeV Uranium Ion Tracks in Tuffak

1. Means and standard deviations for tracks at 3 zenith angles

Method	$\bar{\theta}$	53X oil obj.		45X dry obj.		45X dry obj.	
		$\bar{s}$	$\sigma_s / \bar{s}$	$\bar{s}$	σ_s / s	$\bar{b} (\mu m)$	σ_b / b
eyepiece	all	13.12	3.7%	-	-	-	-
min. image	15.0°	13.03	3.2%	13.23	3.4%	6.05	1.8%
"	30.8°	13.35	3.8%	13.47	3.3%	6.07	2.1%
"	47.6°	13.02	3.8%	13.12	4.9%	6.15	2.0%
"	all	$\bar{s} = 13.25; \sigma_s / \bar{s} = 3.9%; \bar{b} = 6.09; \sigma_b / \bar{b} = 2\%$					

Difference between $\bar{s}$ (min. image) and $\bar{s}$ (eyepiece) = 1%

2. Measurements of the same tracks by image analysis and by eyepiece

$\bar{\theta}$	$\bar{\alpha}$	$\delta s / \bar{s}$	$\bar{y}$	$\delta y / \bar{y}$
15.0°	13.26°	2.7%	27.7 μm	1.3%
30.8°	6.58°	1.5%	47.7 μm	1.0%
47.6°	4.61°	1.3%	65.4 μm	0.9%

Note: δs and δy are rms deviations from best-fit correlation line between measurements of α and y made by image-analysis method and y made by eyepiece method.

3. Percentage deviation from correlation line between $s(\alpha)$ and $s(y)$ measured by image analysis

$\bar{\theta}$	$\delta s / \bar{s}$ (45X obj.)	$\delta s / \bar{s}$ (53X obj.)
15.0°	2.9%	2.3%
30.8°	2.1%	1.5%
47.6°	1.9%	--- *

* Image of cone mouth not contrasty enough with oil objective to measure y .

Table 2. Measurements of 1 A GeV Uranium Ion Tracks in CR-73

Method	$\bar{\theta}$	22X oil obj.		10X dry obj.	
		$\bar{s}$	$\sigma_s/\bar{s}$	$\bar{s}$	$\sigma_s/\bar{s}$
eyepiece	34.0°	9.32	3.9%	---	---
min. image	34.0°	9.40	3.8%	9.72	4.8%

1. Geometry of etched tracks of particles passing through a track-recording solid. In (a) the cone sharpness s ($\equiv v_T/v_G$), which is a measure of ionization rate, is small and unchanging; in (b) s is large and unchanging; in (c) s is small and increasing, indicating that the particle is slowing rapidly.
2. (a) Experimentally determined dependence of s^{-1} on Z/β for the CR-39(DOP) plastic detector; (b) comparison of fractional error in s as a function of Z/β determined from measurements of cone mouth diameters for normally incident particles and determined from measurements of cone lengths with errors $\sigma_L = 1, 2$ and $3 \mu\text{m}$.
3. Steps in the automatic determination of projected length, y , projected width, $2b$, and projected cone angle, α , from digitized images of etched track of a 1 A GeV uranium ion that passed through a $250 \mu\text{m}$ thick Tuffak polycarbonate sheet at a 16° zenith angle. (a) Digitized image at a single focus partway down the top cone; (b) composite made by minimizing images at all depths; (c) image of gradients above a preset threshold; (d) result of track-following algorithm in which y , $2b$, and α are found (shown only for top cone). A 53X oil objective was used.
4. Intensity profile along line AB through an out-of-focus portion of a single image, showing a gradual intensity drop, and through the minimized image, showing a steep drop to zero intensity. The track was left by a 1 A GeV uranium ion at a 31° angle in Tuffak. A 53X oil objective was used.
5. Schematic diagram of image acquisition and minimization procedure.
6. Single image, minimized image, and indicators of y , $2b$, and sides (labeled 1 and 2) of cone angle for tapered cylindrical

etched track of a slow cosmic ray nucleus with $Z = 26$ in CR-39(DOP), taken with a 10X objective (labels printed only for top cone; negative images printed to improve visibility of edges).

7. Minimized images of top cones of 1 A GeV uranium ion tracks at zenith angles of 48° , 31° , and 15° in Tuffak, made using a 45X objective.

8. Image analysis for a 1 A GeV uranium ion track at a 34° angle in CR-73 detector, using a 7X objective (labels printed only for top cone).

9. Minimized images of tracks of cosmic ray nuclei in CR-39(DOP), using a 7X objective. Track on left was made by a slow nucleus with $Z = 20$; track on right was made by a fast nucleus with $Z = 26$.

10. Distributions of values of s calculated for tracks of 1 A GeV uranium ions in CR-73 and Tuffak. The zenith angles were 34° for CR-73 and equal populations at $\sim 16^\circ$, $\sim 32^\circ$, and $\sim 48^\circ$ for Tuffak.

11. Comparison of projected cone lengths for 1 A GeV uranium ions at three angles in Tuffak, measured by the minimization method and with an eyepiece micrometer.

12. Angular interval within which tracks in CR-39(DOP) and Tuffak can be measured with the minimization method, as function of Z/β .

Fig.1

Fig.2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig.10

Fig.11

Fig.12