Pitfalls in calculating charge response parameter from etch pit

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Outline of talk

- Motivation.
- Formation of etch pit inside Nuclear Track Detector.
- Estimation of the region of applicability of two widely used methods of calculating charge response parameter.
- Experimental confirmation.
- Conclusion.
Motivation

Nuclear Track Detectors (NTDs) are used to detect particles (size ~ nucleus) by observing their tracks inside detector material.

Currently two major experiments use NTDs as their detecting tool

**Magnetic Monopole search (MoEDAL experiment)** at LHCb, CERN

**Strangelet search at mountain altitude** at Bose Institute

In these two experiments, people use two different methods to calculate charge response parameter. Our aim is to study the region of applicability of these two methods.


Formation of etch pit inside Nuclear Track Detector (NTD)

NTDs belong to a class of passive detectors.

Solid State Nuclear Track Detectors are dielectric solids.

Organic polymer : Polyethylene Terephthalate (PET)

CR-39
Makrofol

Electronic energy loss of charged particles follows Bethe-Bloch formula

\[
- \frac{dE}{dx} = \frac{4\pi n Z^2}{m_e v^2} \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \ln \left( \frac{2m_e v^2}{I} \right)
\]

Ionizing particle produces ‘permanent’ damage trail along its direction of motion.
Latent Track (diameter 3-10 nm)

Electrostatic interaction

K.E of incoming nuclei

K.E of e⁻ of atom of detector medium

Ionization/Excitation
Damaged region contains more chemically active zones than surrounding undamaged portion.

Applying some chemical reagent (here we use 6.25 N aqueous solution of NaOH) makes the damaged portion etched out at a faster rate $V_T$ (Track etch rate) than the undamaged portion $V_B$ (Bulk etch rate) and after that size of the damaged portion increased to $\sim \mu m$.

Charge response parameter :: $(V_T/V_B)$ :: Necessary condition for the formation of etch-pit : $V_T/V_B > 1$

Now if the Detector (transparent) is kept under the microscope we can observe the etch pits.

Images of etch pit

Leica DM 4000 optical microscope

Screenshot during observation using QWin software under x100 dry objective
Why the shape of the etch pit is conical
Geometry of etch pit

![Graph showing the relationship between energy and -dE/dx for etch pit geometry.](image)

Original surface

Etched surface
Simulation of etch pit

**Schematic diagram of etch pit inside the detector**

<table>
<thead>
<tr>
<th>Measurable quantities</th>
<th>Precision of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major axis diameter [2a]</td>
<td>0.4 µm</td>
</tr>
<tr>
<td>Minor axis diameter [2b]</td>
<td>0.4 µm</td>
</tr>
<tr>
<td>Height of the cone [d]</td>
<td>1.0 µm</td>
</tr>
</tbody>
</table>
Formulae for calculating $V_T/V_B$

From depth measurement

$$p = \frac{V_t}{V_b} = \frac{OO't/t}{V_b} = \frac{\mu d + V_b \times t}{V_b \times t \times \cos \theta}$$

From diameter measurement

$$p = \frac{V_t}{V_b} = \sqrt{1 + \frac{4D^2}{(1-E^2)^2}}$$

Where,

$$E = \frac{b}{V_b \times t} \quad D = \frac{a}{V_b \times t}$$
Condition for conical etch pit

\[ V_B t = V_T \Delta t \]

\[ \sin \alpha = \frac{V_B}{V_T} \]
\[ \cos \alpha = \sqrt{1 - \left(\frac{V_B}{V_T}\right)^2} \]

\[ b = \frac{V_B(t - \Delta t)}{\cos \alpha} \]

\[ E = \frac{b}{V_B t} = \frac{V_B \left( t - \frac{V_B t}{V_T} \right)}{V_B t \cos \alpha} = \frac{1 - \frac{V_B}{V_T}}{\sqrt{1 + \frac{V_B}{V_T} \left(1 + \frac{V_B}{V_T}\right)}} = \sqrt{\frac{1 - \frac{V_B}{V_T}}{1 + \frac{V_B}{V_T}}} < 1 \]
<table>
<thead>
<tr>
<th>Ion</th>
<th>Incident energy (MeV)</th>
<th>Energy at the surface after etching (MeV)</th>
<th>dE/dx after etching [MeV/(mg/cm^2)]</th>
<th>E=2b/2V_Bt</th>
<th>V_T/V_B from depth measurement (eqn.1)</th>
<th>V_T/V_B from diameter measurement (eqn.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{238}U</td>
<td>1724.5</td>
<td>2590.0</td>
<td>146.3</td>
<td>1.88±0.04</td>
<td>15.29±0.71</td>
<td>1.79±0.79</td>
</tr>
<tr>
<td></td>
<td>2641.8</td>
<td>1680.0</td>
<td>136.6</td>
<td>1.31±0.03</td>
<td>14.32±0.67</td>
<td>3.89±0.29</td>
</tr>
<tr>
<td>^{129}Xe</td>
<td>363.8</td>
<td>350.0</td>
<td>88.2</td>
<td>1.35±0.03</td>
<td>14.96±0.54</td>
<td>4.97±3.35</td>
</tr>
<tr>
<td>^{78}Kr</td>
<td>220.0</td>
<td>194.5</td>
<td>53.6</td>
<td>1.25±0.05</td>
<td>12.21±0.42</td>
<td>6.7±7.2</td>
</tr>
<tr>
<td>^{56}Fe</td>
<td>113.0</td>
<td>94.0</td>
<td>39.7</td>
<td>1.22±0.07</td>
<td>8.61±0.29</td>
<td>113±145</td>
</tr>
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<td></td>
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<td>111.2</td>
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<td>8.53±0.27</td>
<td>28.7±67.4</td>
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<td>134.4</td>
<td>116.0</td>
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<td>1.36±0.04</td>
<td>8.12±0.29</td>
<td>25.5±46.1</td>
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<tr>
<td>^{49}Ti</td>
<td>138.2</td>
<td>130.0</td>
<td>30.2</td>
<td>1.14±0.03</td>
<td>6.26±0.24</td>
<td>12.5±24.7</td>
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<tr>
<td>^{32}S</td>
<td>67.4</td>
<td>62.0</td>
<td>21.1</td>
<td>0.79±0.02</td>
<td>4.54±0.14</td>
<td>3.78±0.49</td>
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<td></td>
<td>70.4</td>
<td>63.8</td>
<td>20.9</td>
<td>0.73±0.05</td>
<td>4.23±0.19</td>
<td>3.63±0.50</td>
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<tr>
<td></td>
<td>110.2</td>
<td>105.4</td>
<td>17.4</td>
<td>0.72±0.02</td>
<td>3.66±0.16</td>
<td>3.21±0.26</td>
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<td>115.6</td>
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<td>3.29±0.18</td>
<td>3.08±0.21</td>
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<tr>
<td>^{12}C</td>
<td>8.0</td>
<td>5.0</td>
<td>7.7</td>
<td>0.51±0.04</td>
<td>2.09±0.10</td>
<td>1.84±0.15</td>
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<td>11.0</td>
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<td>7.6</td>
<td>0.34±0.04</td>
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<td>1.40±0.08</td>
</tr>
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General Purpose Scattering Chamber (GPSC) at IUAC

PET films (5 cm × 5 cm) inside aluminium holders
Beam details

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV)</th>
<th>Charge state</th>
<th>Beam current (pnA)</th>
</tr>
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<tr>
<td>$^{35}\text{Cl}$</td>
<td>132</td>
<td>$10^+$</td>
<td>1.5</td>
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# Updated table of PET

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<td>56.9±58.5</td>
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<tr>
<td></td>
<td>76.9</td>
<td>67.50</td>
<td>22.4</td>
<td>0.87±0.07</td>
<td>4.58±0.19</td>
<td>7.97±1.68</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>67.4</td>
<td>62.0</td>
<td>21.1</td>
<td>0.79±.02</td>
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E vs. dE/dx plot for PET
Calibration curve of PET

Using depth measurement method

Using diameter measurement method

\[ Y = 0.54282 + 0.20711 X - 9.43026 \times 10^{-4} X^2 \]

\[ Y = 0.31 + 0.18 X - 7.7 \times 10^{-4} X^2 \]
Results from CR-39 and Makrofol detectors

Base area distribution of etched cones in CR39 from 158 A GeV In$^{49+}$ ions and their fragments

Base area distribution of etched cones in Makrofol from 158 A GeV Pb$^{82+}$ ions and their fragment

p versus REL for CR39

p versus REL for Makrofol

Conclusion

- Although by diameter measurement, one can easily get the value of 'p' at the surface we found that this formula can't be used blindly.

- For $dE/dx > 23 \text{[MeV/(mg/cm^2)]}$ we observe that $b > \sqrt[4]{V_B} \times t$ (so $E > 1$); So in this region conical approximation of etch pits doesn't hold good. Moreover near $E \sim 1$ this formula started giving absurd results and value of ‘p’ diverges.

- Above $p \sim 4$ from diameter measurement method or above $p \sim 5$ from depth measurement method, depth measurement method provides more reliable results.
Acknowledgement

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