NUCLEAR TRACK DETECTORS FOR ENVIRONMENTAL STUDIES AND RADIATION MONITORING

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⇒ Introduction (NTDs)
⇒ Improvements in Chemical Processing
⇒ Calibration {CR39 & Makrofol}
  Thickness Method
  New D-$L_e$ Method
⇒ Cross sections
⇒ Search for Massive Rare Particles
⇒ Applications of NTDs
The detection principle of the NTDs is based on the fact that a throughgoing ionizing particle produces a cylindrical radiation-damaged region along the ion trajectory, forming the so-called "latent track".

The damaged region of the material becomes chemically reactive and can be etched by an appropriate chemical treatment. As a result, an etched cone is formed on both sides of the detector sheet.
Track Shape Parameters

**Track diameter:**
\[ D = 2v_B \left[ \frac{(v_T - v_B)}{(v_T + v_B)} \right]^{-1/2} \]

**Track length:**
\[ L_e = (v_T - v_B) \cdot t \]

**Reduced etch rate:**
\[ p = \frac{v_T}{v_B} \]

158 AGeV Pb^{82+}

0.414 AGeV Fe^{26+}
Control of pore geometry

\[ v_{track}: v_{bulk} = \sin \theta \rightarrow \text{pore geometry} \]

- Original surface
- Etched surface
- Ion track

1000 : 1
cylinder

10 : 1
cone

Single nanopores
Nanowires
CR39 and MAKROFOL

CR39® (PPG Industries Inc.) \( (C_{12}H_{18}O_7; \ 1.32 \text{ g/cm}^3) \)

Standard INTERCAST CR39: mainly used for sun glasses

Improved in order to achieve:
- low detection threshold; \( (Z/\beta \sim 5) \)
- high sensitivity in a large range of energy losses,
- high quality of the post-etched surface
- stability of the sensitivity over long periods of time (several years) [Aging effect]
- uniformity of sensitivity for mass-produced sheets

In order to achieve these goals, a specific scientific line of production was designed and implemented.

MAKROFOL® (BAYER) \( (C_{16}H_{14}O_3; \ 1.29 \text{ g/cm}^3) \)

Polycarbonate films
- high quality transmission,
- excellent surface uniformity
- high detection threshold; \( (Z/\beta \sim 50) \)
Improvements on Chemical Processing

Tracks of 158 A GeV Pb ions in CR39

6N NaOH, $70^\circ$C, 30 hr
$Z/\beta$ (min.) $\sim 5$

6N NaOH + 1% alcohol $70^\circ$C, 40 hr
$Z/\beta$ (min.) $\sim 7$
Improved Etching Conditions for the SLIM experiment

8N NaOH 90 °C, (24 +24) hr.

8N KOH + 1.5% alcohol, 75 °C (24 + 14) hr

"Soft"

6N KOH + 3% alcohol, 60 °C
Z/β (min.) ~ 21
6N NaOH + 1% alcohol, 70 °C
Z/β (min.) ~ 7 (at present)

7N KOH + 1.25% alcohol, 77 °C
Z/β (min.) ~ 14
8N KOH + 1.5% alcohol, 75 °C
Z/β (min.) ~ 17 (at present)

"Strong"

26+Fe (5 A GeV) Tracks of Iron and the fragments (48 hr)

SLIM detector (after 48 hr)

8N KOH + 1.5% alcohol, 75 °C (24 + 14) hr

26+Fe (5 A GeV) Tracks of Iron and the fragments (38 hr)

SLIM detector (after 38 hr)
"Soft & Strong" Etching review of CR39 NTDs

S. Kodaira et al., 23rd ICNTs, Beijing, China.
Tracks of 158 A GeV Pb ions + fragments in Makrofol

6N NaOH, 95 h, 50 °C

6N KOH + 30% ethyl alcohol, 10 h, 45 °C

Makrofol, 50 °C, 6N KOH + 20% ethyl alcohol 8 h (a) normal incidence and (b) for 45 incidence,

\[ Z/\beta \text{ (min.)} \sim 50 \]
Exposure setup

Alternating Gradient Synchrotron AGS

NIRS beam setup At HIMAC

NASA Space Radiation Laboratory NSRL

Beams: ► BNL (Brookhaven National Lab, NY, USA)
► CERN (Geneva, Switzerland)
► HIMAC (Chiba, Japan)
CALIBRATION OF CR39 WITH 158 A GeV In$^{49+}$ {CERN-SPS}

"Soft" calibration; area distribution (measurement on two faces) of 158 A GeV $^{49}$In ions and their fragments in CR39 after 40 h etching in 6N NaOH+1% Ethyl Alcohol (by volume) at 70 °C.

$0.13 \leq \sigma_Z \leq 0.23$

\begin{align*}
Z/\beta &= 10 \\
Z/\beta &= 46 \\
Z/\beta &= 49
\end{align*}
Area distribution of 158 A GeV Pb ions and their fragments (measurement on two faces) in Makrofol after 8 h etching in 6N KOH + Ethyl Alcohol (80 : 20 % by volume) at 50 °C. (Measurements made with the Elbek automatic image analyzer)
DISTRIBUTION OF ETCHED CONE BASE AREAS

Average Area (pixel²)

Z/β = 16.1

Z/β = 29.2

Z/β = 37.8

Z/β = 16.0

Z/β = 29.5

1 A GeV Si^{14+}

1 A GeV Fe^{26+}

0.41 A GeV Fe^{26+}
Bulk Etch Rate ($v_B$) Measurements

By Thickness method

$$v_B = \Delta x / 2 \cdot t$$

By D-L$_e$ method

$$L_e = (v_T - v_B)t$$

$$D = 2v_Bt \left[ \frac{(v_T - v_B)}{(v_T + v_B)} \right]$$

$$v_B = \frac{D^2}{4tL_e} \left[ 1 + \sqrt{1 + \frac{4L_e^2}{D^2}} \right]$$

S. Balestra et al., to be submitted to NIMB
Sensitivity vs. REL for Different Energetic Heavy Ions

By thickness Method

- $158 \text{ AGeV Pb}^{82+} + \text{Pb (10 mm)}$; $v_B = 1.15 \ \mu\text{m/h}$
- $1 \text{ AGeV Fe}^{26+} + \text{CH}_2 (10 \ \text{mm})$; $v_B = 1.30 \ \mu\text{m/h}$
- $0.41 \text{ AGeV Fe}^{26+} + \text{CH}_2 (13 \ \text{mm})$; $v_B = 1.10 \ \mu\text{m/h}$
- $1 \text{ AGeV Si}^{14+} + \text{CH}_2 (10 \ \text{mm})$; $v_B = 0.96 \ \mu\text{m/h}$

$6\text{N NaOH 70 °C, 30 h}$
Sensitivity vs. REL for Different Energetic Heavy Ions

By D-L_e Method

158 AGeV Pb^{82+} + Pb (10 mm)
1 AGeV Fe^{26+} + CH_2 (10 mm)
0.414 AGeV Fe^{26+} + CH_2 (13 mm)
1 AGeV Si^{14+} + CH_2 (10 mm)

V_B = 1.10 \mu m/h

6N NaOH 70 °C, 30h
Cross Sections

We report on the measurements of total charge changing fragmentation cross sections in high-energy Fe$^{26+}$, Si$^{14+}$ and Pb$^{82+}$ ions interactions with different target materials.

Fragmentation cross-sections are essential input parameters needed to describe the propagation of energetic heavy ions through matter.

Experimental results on the fragmentation properties of high-energy nuclei are relevant for nuclear physics, cosmic ray physics, astrophysics and applied physics.
Important applications of the propagation of a heavy ion beam through matter are given in the field of:

**Space radiation protection**  
**Space craft shielding**

**Cancer therapy**  
with beams of fast heavy ions
Several stacks of CR39 nuclear track detectors with different target combinations were exposed at normal incidence to high energy accelerator beams to an integrated density of about 2000 ions/cm²

**Beams:**
BNL (Brookhaven National Lab, NY, USA)
- Fe ions: 1 AGeV
- Si ions: 1 AGeV
CERN (Geneva, Switzerland)
- Pb ions: 158 AGeV
HIMAC (Chiba, Japan)
- Fe ions: 0.414 AGeV
We require the presence of a reconstructed track both before and after the target. A reconstructed track must have at least 3 measured CR39 faces immediately before the target and at least 3 measured faces immediately after the target.

Using the survival fraction of the beam for each stack, we determined the total charge-changing cross sections on different targets.
Total Charge Changing Cross-Section

\[ \sigma_{\text{tot}(\text{exp})} = X \cdot \ln \left( \frac{N_i}{N_s} \right) \]

Where

\[ X = \frac{A_T}{\rho_T t_T N_{\text{av}}} \]

- \( N_i \) = No of incident ions before target
- \( N_s \) = No of survived ions after target
- \( A_T \) = Target mass
- \( \rho_T \) = Target density (g/cm\(^3\))
- \( t_T \) = Target thickness (cm)
- \( N_{\text{av}} \) = Avogadro’s number

\[ \sigma_{\text{tot(th)}} = \pi r_o^2 \left( A_P^{1/3} + A_T^{1/3} - b \right)^2 \]

Where

- \( A_P \) = Projectile mass
- \( r_o = 1.35 \) fm
- \( b = 0.83 \)
### Experimental and Theoretical Total Charge Changing Cross sections in Different Targets

<table>
<thead>
<tr>
<th>Target</th>
<th>$A_T$</th>
<th>$Z_T$</th>
<th>$\rho_T$ (g/cm$^3$)</th>
<th>$t$ (cm)</th>
<th>$\sigma_{\text{tot}}^{\text{exp.}}$ (mb)</th>
<th>$\sigma_{\text{tot}}^{\text{th.}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1.0</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>1944 $\pm$ 275</td>
<td>2120</td>
</tr>
<tr>
<td>CH$_2$</td>
<td>4.7</td>
<td>2.7</td>
<td>0.952 $\pm$ 0.002</td>
<td>1.02 $\pm$ 0.01</td>
<td>2266 $\pm$ 156</td>
<td>2616</td>
</tr>
<tr>
<td>CH$_2$+CR39</td>
<td>6.4</td>
<td>3.5</td>
<td>1.19 $\pm$ 0.01</td>
<td>3.09 $\pm$ 0.01</td>
<td>2515 $\pm$ 81</td>
<td>2758</td>
</tr>
<tr>
<td>CR39</td>
<td>7.4</td>
<td>4.0</td>
<td>1.310 $\pm$ 0.003</td>
<td>3.07 $\pm$ 0.01</td>
<td>2642 $\pm$ 81</td>
<td>2832</td>
</tr>
<tr>
<td>C+CR39</td>
<td>8.7</td>
<td>4.6</td>
<td>1.44 $\pm$ 0.01</td>
<td>3.18 $\pm$ 0.01</td>
<td>2726 $\pm$ 84</td>
<td>2920</td>
</tr>
<tr>
<td>Al+CR39</td>
<td>11.5</td>
<td>6.0</td>
<td>1.75 $\pm$ 0.01</td>
<td>3.26 $\pm$ 0.01</td>
<td>2882 $\pm$ 66</td>
<td>3086</td>
</tr>
<tr>
<td>C</td>
<td>12.0</td>
<td>6.0</td>
<td>1.733 $\pm$ 0.004</td>
<td>1.01 $\pm$ 0.01</td>
<td>2910 $\pm$ 210</td>
<td>3113</td>
</tr>
<tr>
<td>Cu+CR39</td>
<td>22.0</td>
<td>11.3</td>
<td>3.65 $\pm$ 0.01</td>
<td>3.22 $\pm$ 0.01</td>
<td>3282 $\pm$ 93</td>
<td>3561</td>
</tr>
<tr>
<td>Al</td>
<td>27.0</td>
<td>13.0</td>
<td>2.692 $\pm$ 0.002</td>
<td>1.04 $\pm$ 0.01</td>
<td>3804 $\pm$ 164</td>
<td>3742</td>
</tr>
<tr>
<td>Pb+CR39</td>
<td>31.0</td>
<td>15.9</td>
<td>4.34 $\pm$ 0.01</td>
<td>3.23 $\pm$ 0.01</td>
<td>3842 $\pm$ 116</td>
<td>3874</td>
</tr>
<tr>
<td>Cu</td>
<td>63.5</td>
<td>29.0</td>
<td>8.901 $\pm$ 0.002</td>
<td>0.99 $\pm$ 0.01</td>
<td>5089 $\pm$ 274</td>
<td>4714</td>
</tr>
</tbody>
</table>

#### 158 A GeV Pb$^{22+}$

#### 1 A GeV Fe$^{26+}$

| CH$_2$  | 4.7   | 2.7   | 0.952 $\pm$ 0.002    | 1.02 $\pm$ 0.01 | 1512 $\pm$ 284                     | 1249                              |

#### 0.41 A GeV Fe$^{26+}$

| CH$_2$  | 4.7   | 2.7   | 0.952 $\pm$ 0.002    | 1.02 $\pm$ 0.01 | 1124 $\pm$ 270                     | 1249                              |

#### 1 A GeV Si$^{14+}$

| CH$_2$  | 4.7   | 2.7   | 0.952 $\pm$ 0.002    | 1.32 $\pm$ 0.01 | 1207 $\pm$ 252                     | 863                               |
SLIM-IMM searches at high altitudes

Chacaltaya, Bolivia  5290 m asl
440 m² of nuclear track detectors

Koksil, Himalaya, 4275 m asl
100 m² of nuclear track detectors

Collaborators
Bologna, Torino, Alberta (Canada), PINSTECH (Pakistan)

Total Area  ~ 440 m²

SLIM Module (24×24 cm²)
Energy Loss of MMs in NTDs

Makrofol threshold

Z=50

CR39 threshold (strong)

Z=17

CR39 threshold (soft)

Z=7
The search technique

- **Strong etching** (large tracks, easy to detect)
- **General scan of the surface**
- **If a signal is found in the first sheet...**
  - **Soft etching**
  - Scan in the predicted position
  - Measurement of REL and direction of incident particle.
- **Up to now, no double coincidences found**
Analysis of 308 m² of SLIM NTDs exposed for 3.87 y: no candidate was found → 90% CL Upper flux limit for down going intermediate mass magnetic monopole with $g = g_D$, $2g_D$, $3g_D$ and $M+p < 1.951 \times 10^{-15} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$; for $\beta \geq 0.1$
Applications of NTDs

⇒ Neutron Dosimetry

⇒ Gamma Dosimetry
Determination of Boron content in plants and metals

 Autoradiography (making use of Alpha's & Proton's)
 Radiography of Spent fuel elements
 Radiography of micro objects
 Fission Track Dating
 Applications in radiobiological studies
 Detection of Rare Decay Particles
 Nano Technology (Production of nano wires)
Radon Measurements

Radon level at Chacaltaya near SLIM NTDs was from 40 – 50 Bq/m³ (By active method)

Radon level near Koksil was from 10 – 20 Bq/m³ (By passive method, CR39)

By active method:

- PRD, PINSTECH Radon Dosimeter
- ENEA Radon Dosimeter

By Radon signal:

- Radon level in construction materials
- Earthquake predictions
- Uranium exploration
Applications of NTDs in heavy ions interaction, neutron and Pion induced fission studies

Exposure Geometry

Target Thickness
$\approx 1 \text{ mg/cm}^2$

Fluence $= 9 \times 10^5 \text{ (#/cm}^2\text{)}$
SIDE VIEW AND VIEW IN THE PLANE OF THE DETECTOR OF SOME TRACKS

INCIDENT IONS

Detector Surface

Target Layer

Side View

View in the plane of the detector

Parameter $\phi$

- $\phi = 180^\circ$
- $\phi < 180^\circ$
- $\phi > 180^\circ$

2-Pronged Events

3-Pronged Events

4-Pronged Events

5-Pronged Events

$\theta_{1/4}$

$\sigma_3$

$\sigma_4$

$\sigma_5$

D = Direct

I = Indirect
Alpha Radioactivity Measurements of Lead Sheets

CR39 NTD without refreshing
Surface contamination (α’s + surface activity 6N NaOH, 70 °C 6hr)

CR39 NTD with refreshing (8N KOH + 3% alcohol, 75 °C, 3 hr.)
No surface contamination and the detector has zero noise (only α-particles)
6N NaOH, 70 °C 6hr