The nuclear track detector CR39: results from different experiments

M. Giorgini
Bologna University and INFN
The Nuclear Track Detectors (NTDs) technique

A very ionizing particle breaks the polymeric bonds around its trajectory. The produced damage is called the latent track. The latent track becomes visible and measurable after a chemical etching in a basic solution. Two (etch-pits) cones with the same dimensions develop around the particle trajectory. 200 A GeV S^{16+}
The nuclear track detector CR39

The most sensitive NTD employed in several scientific and technological applications is **CR39® (PPG Ind. Inc.)**

More than 1000 m² of CR39 detectors were used in the **MACRO** [Eur. Phys. Jou. C 25 (2002) 511] and **SLIM** experiments to search for massive rare particles in the cosmic radiation (magnetic monopoles, nuclearites, strangelets, Q-balls...)

![Chemical structure of CR39](image)

\[
C_{12}H_{18}O_7
\]

\[\rho = 1.32 \text{ g/cm}^3\]

**Accurate detector calibrations are required**
CR39 calibrations

Beams: 158 AGeV Pb$^{82+}$
158 AGeV In$^{49+}$

@ CERN-SPS

After exposure, the CR39 sheets were etched in 6N NaOH + 1% ethyl alcohol solution at 70 °C for 40 h
Automatic and manual measurements

Automatic image analyzer ELBEK

The base area, eccentricity and brightness are measured for each track.

**Tracking**: the trajectory of each ion is followed through the stack.

\[
L = (v_T - v_B) t
\]

\[
D = 2 v_B t \sqrt{\frac{(v_T - v_B)}{(v_T + v_B)}}
\]

\[
v_B = \frac{D^2}{4 t L} \left[1 + \sqrt{1 + \frac{4 L^2}{D^2}}\right]
\]

\[
L = \text{measured cone height}
\]

\[
D = \text{refractive index of the detector}
\]

\[
L = \text{measured cone height}
\]

\[
D = \text{refractive index of the detector}
\]

\[
D \quad \text{and} \quad L \quad \text{are measured with a Leica optical microscope coupled to a CCD camera and a video monitor}
\]

\[
L \quad \text{is obtained multiplying the measured cone height by the refractive index of the detector}
\]
Height and base area of conical tracks in CR39 exposed normally to In$^{49+}$ and Pb$^{82+}$ ions

Track area (μm²) vs. Number of events

Track area (pixel²) vs. Number of events

Cone height (arbitrary units) vs. Number of events
Best charge resolution

Charge distribution for tracks present in at least 10 out of 12 measured CR39 sheets located after the target

\[ \sigma_z = 0.05e \]
**Calibration graph for CR39**

Reduced etch rate $p = \frac{v_T}{v_B}$

For each detected charge $\rightarrow$ **Restricted Energy Loss** (REL)

$$
\text{REL} = \left( -\frac{dE}{dx} \right)_{E < T_{\text{max}}} = K \frac{Z^2}{\beta^2} \frac{Z}{A} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right]
$$

A unique calibration curve describes all the data
Fragmentation cross sections of Fe$^{26+}$, Si$^{14+}$ and C$^{6+}$ ions on CR39, CH$_2$ and Al targets


Beam: Fe$^{26+}$ (E = 0.3, 0.41, 1.0, 3.0, 5.0 AGeV)
Si$^{14+}$ (E = 1.0, 3.0, 5.0 AGeV)
C$^{6+}$ (E = 0.29 AGeV)

Exposures @ BNL-AGS and HIMAC (Japan)

CR39 sheets: area 11.5 × 11.5 cm$^2$
thickness 0.65 mm

Targets: CH$_2$, Al, CR39
thickness 1 mm

After exposure, the CR39 sheets were etched in 6N NaOH aqueous solution at 70 °C for 30 h
Total fragmentation cross sections

\[ \sigma_{\text{tot}} = \frac{A_T \ln(N_{\text{in}}/N_{\text{out}})}{\rho_T t_T N_{\text{AV}}} \]

- \( A_T \) = mass number of the target
- \( \rho_T \) = density of the target
- \( t_T \) = thickness of the target
- \( N_{\text{AV}} \) = Avogadro's number
- \( N_{\text{in}} \) = number of incident ions before the target
- \( N_{\text{out}} \) = number of incident ions after the target

Theoretical predictions:

\[ \sigma_{\text{tot}} = \sigma_{\text{nucl}} + \sigma_{\text{EMD}} = 10\pi r_o^2 (A_T^{1/3} + A_P^{1/3} - b_o)^2 + \alpha Z_T^\delta \]

- \( Z_T \) = atomic number of the target
- \( A_P \) = mass number of the beam

Numerical values:
- \( r_o = 1.31 \text{ fm} \)
- \( b_o = 1.0 \)
- \( \alpha = 1.57 \)
- \( \delta = 1.9 \)
Data-prediction comparison

The quoted uncertainties are statistical standard deviations.
Partial charge changing cross sections

Average base areas for tracks present in at least 2 out of 3 measured CR39 sheets located after the target

Charge resolution $\sigma_Z \sim 0.2e$

<table>
<thead>
<tr>
<th>$\Delta Z$</th>
<th>$\sigma_{\Delta Z}$ (mb)</th>
<th>$\sigma_{\Delta Z}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>-</td>
<td>293 ± 18</td>
</tr>
<tr>
<td>-2</td>
<td>338 ± 11</td>
<td>177 ± 12</td>
</tr>
<tr>
<td>-3</td>
<td>285 ± 11</td>
<td>123 ± 11</td>
</tr>
<tr>
<td>-4</td>
<td>252 ± 10</td>
<td>122 ± 11</td>
</tr>
<tr>
<td>-5</td>
<td>249 ± 10</td>
<td>62 ± 8</td>
</tr>
<tr>
<td>-6</td>
<td>197 ± 9</td>
<td>117 ± 11</td>
</tr>
<tr>
<td>-7</td>
<td>168 ± 8</td>
<td>83 ± 9</td>
</tr>
<tr>
<td>-8</td>
<td>132 ± 7</td>
<td>90 ± 10</td>
</tr>
<tr>
<td>-9</td>
<td>175 ± 8</td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>107 ± 7</td>
<td></td>
</tr>
<tr>
<td>-11</td>
<td>152 ± 6</td>
<td></td>
</tr>
<tr>
<td>-12</td>
<td>105 ± 8</td>
<td></td>
</tr>
<tr>
<td>-13</td>
<td>103 ± 6</td>
<td></td>
</tr>
<tr>
<td>-14</td>
<td>81 ± 6</td>
<td></td>
</tr>
<tr>
<td>-15</td>
<td>80 ± 6</td>
<td></td>
</tr>
<tr>
<td>-16</td>
<td>50 ± 4</td>
<td></td>
</tr>
<tr>
<td>-17</td>
<td>76 ± 5</td>
<td></td>
</tr>
<tr>
<td>-18</td>
<td>86 ± 6</td>
<td></td>
</tr>
</tbody>
</table>
The SLIM experiment

• Intermediate mass ($10^5 \leq M_M \leq 10^{12}$ GeV) Magnetic Monopoles
• Strange Quark Matter (nuclearites, strangelets)
• Charged Q-balls

Chacaltaya laboratory
(Bolivia, 5230 m a.s.l.)
Intermediate Mass Monopoles (IMMs)

SO(10) \[ \mathcal{10} \] \[ 10^{15} \text{ GeV} \] \[ 10^{-35} \text{ s} \] \rightarrow SU(4) \times SU(2)_L \times SU(2)_R \[ \mathcal{10} \] \[ 10^9 \text{ GeV} \] \[ 10^{-23} \text{ s} \] \rightarrow SU(3)_C \times [SU(2)_L \times U(1)_Y]_{EW} \[ \mathcal{10} \] \[ 10^2 \text{ GeV} \] \[ 10^{-10} \text{ s} \]

IMMs
\[ 10^5 - 10^{12} \text{ GeV} \]

A. De Rujula, CERN-TH 7273/94
E. Huguet and P. Peter, hep-ph/901370

Energy losses of IMMs

(a) \( \beta < 10^{-4} \) Elastic collisions

(b) \( 10^{-4} < \beta < 10^{-2} \) Excitation (Medium as Fermi gas)

(c) \( \beta > 10^{-2} \) Ionization (Bethe-Bloch)

\( (Ze_{eq})^2 = (g\beta)^2 \)
Strange Quark Matter (SQM)

- Aggregates of u, d, s quarks + electrons, \( n_e = 2/3 n_u - 1/3 n_d - 1/3 n_s \)
- Candidates for cold Dark Matter! Searched for in cosmic rays reaching the Earth

\[ R (\text{fm}) \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]
\[ M (\text{GeV}) \quad 10^6 \quad 10^9 \quad 10^{12} \quad 10^{15} \]

A "qualitative picture" (hep-ex/0004019)

```
black points are electrons
```

```
A (u.m.a.) \geq 300 \quad \geq 10^6 \quad \sim 10^{57}
```

Nuclearites: large neutral SQM bags. Core of u, d and s quarks with an electron cloud

```
Typical galactic velocities: \( \beta \approx 10^{-3} \)
Dominant interaction: elastic collisions with atoms in the medium
```

Strangelets: small charged SQM nuggets
Behave like ordinary nuclei
\( \rightarrow \) same acceleration processes and energy loss

Very low charge to mass \( Z/A \) ratio

\[ 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \]

```
\[ M_N = 10^5 \text{ GeV} \quad M_N = 10^7 \text{ GeV} \quad M_N = 1.9 \times 10^8 \text{ GeV} \]
```

CR39 Threshold

REL vs \( \beta \) of nuclearites in CR39

REL vs \( \beta \) of strangelets in CR39

```
\( \varepsilon \) of
\( u \)
\( 1 \)
\( co \]
\( \rightarrow \) s
\( rat \)
• Super-symmetric coherent states of squarks, sleptons and Higgs fields
• Candidates for Dark Matter!

- **Neutral Q-balls (SENS)**: the main interaction process is the catalysis of proton decay. Not relevant for NTDs.

- **Charged Q-balls (SECS)** are similar to ordinary nuclei → same interaction process

![Diagram of Q-balls with labels](image)

[black points are electrons, empty dots are s-electrons]
The detector

Total area $\sim 440 \text{ m}^2$

One module ($24.5 \times 24.5 \text{ cm}^2$)
The search technique

**Strong etching*** (large tracks, easy to detect)

General scan of the top surface

**Soft etching****

Scan in the predicted position measurement of REL and direction of incident particle.

* 8N KOH + 1.5% Ethyl alcohol at 70 °C for 30 h

** 6N NaOH + 1% Ethyl alcohol at 70 °C for 40 h

No candidate passed the search criteria
Upper limits for downgoing IMMs and dyons

Analyzed area: \(427 \text{ m}^2\)  
Average exposure time: \(4.22 \text{ years}\)

90\% C.L. upper limits for a downgoing flux of
IMMs with \(g = g_D, 2g_D, 3g_D\) and for dyons \((M+p)\):

\[
1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad \text{for} \quad \beta \geq 4 \cdot 10^{-2}
\]
90% C.L. upper limits for a downgoing flux of NUCLEARITES and charged Q-balls:
\[1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\] for \(\beta > 10^{-4}\)
CONCLUSIONS

The nuclear track detector CR39 was calibrated with different ions of different energies. A unique curve of \( p \text{ vs REL} \) describes all the data. The best charge resolution obtained is \( \sigma_Z \sim 0.05e \).

The **total** and **partial fragmentation cross sections** for \( \text{Fe}^{26+} \), \( \text{Si}^{14+} \) and \( \text{C}^{6+} \) ions on polyethylene, CR39 and aluminum targets were measured using CR39. The total cross sections for all the targets and energies used in the present work **do not show any observable energy dependence**. There is a **dependence on target mass**, mainly due to the contribution of electromagnetic dissociation.

The **SLIM** experiment (427 m\(^2\) of CR39, with an average exposure time of 4.22 y) set 90% C.L. upper limits for a downgoing flux of:

- **IMMs** with \( g = g_D \), \( 2g_D \), \( 3g_D \) and **dyons**:
  \[
  1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad \text{for} \quad \beta \geq 4 \cdot 10^{-2}
  \]
- **Nuclearites and strangelets**:
  \[
  1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad \text{for} \quad \beta \geq 10^{-4}
  \]
- **Charged Q-balls**:
  \[
  1.3 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad \text{for} \quad \beta \geq 10^{-4}
  \]
**SLIM scan**

**L1 scan** 3 X Mag, stereo microscope; scanned twice ~ 99%
20 – 40 X Mag

Coincidence area ~ 0.5 cm²

**L5 scan**: 500 – 1000 X Mag

Measured with $6.3_{ob} \times 25_{oc}$ Mag
Event $\equiv \rho$ and $\theta$ are equal within 20%