Studies of the response of plastic nuclear track detectors to protons and alpha particles in nuclear reactions induced by cosmic muons

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Objectives

- Measuring the natural radiation background and some rare nuclear processes.

- Developing an experimental method for measuring the cosmic muons using capture induced effects and plastic nuclear track detectors.
Charged particle interactions

- Inelastic scattering on atomic electrons
- Elastic scattering on nuclei
- Cherenkov radiation
- Bremsstrahlung

Bethe – Bloch equation:

\[
\frac{-dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{Z^2}{\beta^2} \left[ \ln \left( \frac{2 m_e \gamma^2 v^2 W_{\text{max}}}{I^2} \right) - 2 \beta^2 - \delta - 2 \frac{C}{Z} \right]
\]

"Techniques for nuclear and particle physics" - W. R. Leo
Muon interactions

- **Electric charge:** $e = 1.602 \times 10^{-19} \text{C}$
- **Mass:** $\sim 200 m_e$
- **Negative muon:** $\mu^-$
- **Positive muon:** $\mu^+$
- **Mean lifetime:** $\sim 2.2 \mu s$

- **Spontaneous decays:**
  - $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

- **Interactions:**
  - a) Direct ionisation
  - b) Electromagnetic scattering
  - c) Capture

“Effects of low energy muons on electronics: physical insights and Geant4 Simulation” - S. Serre, S. Semikh, J. L. Autran, D. Munteanu, G. Gasiot, P. Roche
Muon induced nuclear reactions

- **Nuclear capture:** \( \mu^- + (A, Z) \rightarrow (A, Z-1) + \nu_\mu \)

- **Neutron emission:** \((A, Z)(\mu^-, xn)(A - x, Z - 1)\)

- **Proton emission:** \((A, Z)(\mu^-, p\ xn)(A - x - 1, Z - 2)\)

- **Alpha particle emission:** \((A, Z)(\mu, \alpha)(A - 4, Z - 3)\)

Experiment

- Study and detection of the cosmic muon capture using plastic detectors.
- Experimental setup: 1) Lead  
  2) Silicon (300 μm)  
  3) Detector

\[
\mu^- + Si^{28} \rightarrow Al^{28} + \nu + 100.5 \text{ MeV} \\
Al^{28} \rightarrow Al^{27} + n \ (12.4 \text{ MeV}) \\
\rightarrow Mg^{27} + n \ (14.2 \text{ MeV}) \\
\rightarrow Na^{24} + \alpha \ (15.5 \text{ MeV}) \\
\rightarrow Mg^{26} + d \ (18.4 \text{ MeV})
\]

- Cosmic radiation exposure: 120 days

Experiment

- Calibration made using a $^{241}$Am (3.7 kBq) source and nuclear reaction induced by fast neutrons.

- Dominant monoenergetic transitions:
  - 5.433 MeV (13.6%)
  - 5.476 MeV (84.4%)

- Fast neutron induced nuclear reactions:
  - $^{27}$Al$(n,p)^{27}$Mg
  - $^{27}$Al$(n,\alpha)^{24}$Na

$$\frac{\sigma_{n,p}}{\sigma_{n,\alpha}} \approx \frac{3}{5}$$
Detectors and etching technique

- Produced by TASL (Track Analysis Systems Ltd, Bristol, UK)
- Type: TASTRAK
- Polyallyl diglycol carbonate (C$_{12}$H$_{18}$O$_{7}$)
- Thickness: 1 mm
- 6.25 N NaOH, at 70°C
- Bulk etch rate:
  \[ V_b(C, T) = 1.276 \times 10^{(0.828 C + 0.049 T - 0.002 CT - 17.624)} \]
  \[ V_b = (1.580 +/- 0.022) \mu m/h \]
- Track etch rate: \[ V_t = (2.900 +/- 0.529) \mu m/h \]

http://www.tasl.co.uk/plastics.php
• Cone length: 

\[ L = \frac{L'}{2} + \frac{B}{\cos \theta} \] 

\[ \theta = \sin^{-1} \left( \frac{\sqrt{16D^2B^2 + (4B^2 - d^2)^2}}{4B^2 + d^2} \right) \] 

• Incident angle: 

\[ R_0 = \frac{D + d}{2} + \frac{B}{\sin \theta} \] 

Etching technique

\[ r_i = A \times \left( \frac{dE}{dx} \right)^\alpha \]

\[ \frac{dE}{dx} \] - stopping power (in keV/μm)

\[ A = 0.519 \]
\[ \alpha = 0.39 \]

<table>
<thead>
<tr>
<th>Proton energy</th>
<th>0.9 MeV</th>
<th>0.5 MeV</th>
<th>0.38 MeV</th>
<th>0.3 MeV</th>
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<tbody>
<tr>
<td>Incident angle θ</td>
<td>76.1°</td>
<td>71.2°</td>
<td>68.3°</td>
<td>65.4°</td>
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<td>Depth H</td>
<td>32.5 μm</td>
<td>30 μm</td>
<td>26 μm</td>
<td>25 μm</td>
</tr>
<tr>
<td>Diameter D</td>
<td>8.4 μm</td>
<td>12.5 μm</td>
<td>14 μm</td>
<td>14.3 μm</td>
</tr>
</tbody>
</table>

Image of etched CR39

Experimental results

- Al(n,p); Al(n,α)
- Irradiation time: 3 h and 44 min
- Etching time: 6 h and 30 min

- Reference (without Al)
  - Irradiation time: 25 min
  - Etching time: 6 h and 30 min

- Surface

- 6 μm depth
Experimental results

- Source: $^{241}$Am
- Particle energy: 4.565 MeV
- Irradiation time: 1 min
- Etching time: 6 h and 30 min

- Source: $^{241}$Am
- Particle energy: 4.321 MeV
- 2 μm of mylar
- Irradiation time: 2 min
- Etching time: 6 h and 30 min
Experimental results

- Source: $^{241}$Am
- Particle energy: 4.067 MeV
- 4 μm of mylar
- Irradiation time: 2 min
- Etching time: 6 h and 30 min
Experimental results

- Source: $^{241}$Am
- Particle energy: 0.575 MeV
- 23 μm of mylar
- Irradiation time: 2 min
- Etching time: 6 h and 30 min

Surface

14 μm depth
Experimental results

Source: $^{241}\text{Am}$
Irradiation time: 30 sec
Etching time: 6 h

4.565 MeV (Direct irradiation)
4.321 MeV (2 μm mylar)
4.067 MeV (4 μm mylar)
0.575 MeV (23 μm mylar)
Experimental results

- Cosmic radiation
- Irradiation time: 120 days
- Etching time: 6 h and 30 min
Experimental results

Surface

10 μm depth
Experimental results

- AFM (Atomic Force Microscopy)
  - Source: $^{241}$Am
  - Particle energy: 4.321 MeV
  - 2 µm mylar
Applications

- Radon measurements
  - passive monitors;
  - the distribution of $\alpha$ active nuclei in the human lung – extremely low activities ($\sim 10^{-15}$ Ci/g).

- Quality assurance of mixed oxide pellets
  - for next generation nuclear power plants;
  - automatic Pu detection system based on dense $\alpha$-radiation tracks.

- High-temperature plasma diagnostics
  - the ability to detect low energy protons, deuterons, tritons, $^3$He or $^4$He against a simultaneous background of X-rays, electrons and heavy ions.

“Applications of CR-39 nuclear track detector in medicine and technology” – D. L. Henshaw
Conclusions

- The possibility of using plastic detectors for measuring low energy cosmic muons.

- Visual analysis (optical microscope) and AFM

- Unambiguous and energy independent discrimination between the tracks produced by protons and α particles.

- Applications in different fields: dosimetry, nuclear power plants, plasma diagnostics.