High energy proton detection by PADC track etch detectors. (Results from Loma-Linda, NSRL-BNL proton IICHIBAN exposures and experiments at TSL accelerator, Uppsala, Sweden.)

J. K. Pálfalvi, J. Szabó and B. Dudás
HAS KFKI Atomic Energy Research Institute (AERI), P. O. B 49, H-1525 Budapest, Hungary.

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Proton induced $^{12}$C fragmentation

<table>
<thead>
<tr>
<th>Possible Coupled particles</th>
<th>$^6$Li+</th>
<th>$^7$Li+</th>
<th>$^7$Be+</th>
<th>$^9$Be+</th>
<th>$^{10}$Be+</th>
<th>$^{10}$B+</th>
<th>$^{11}$B+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Be</td>
<td></td>
<td></td>
<td></td>
<td>$^3$He+p</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha+2p$</td>
<td></td>
<td></td>
<td>$\alpha+D$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross section, mb</td>
<td>9.8</td>
<td>7.8</td>
<td>12.2</td>
<td>2.5</td>
<td>1.8</td>
<td>19</td>
<td>63</td>
</tr>
<tr>
<td>Rel. probability, %</td>
<td>8.46</td>
<td>6.73</td>
<td>10.5</td>
<td>2.17</td>
<td>1.57</td>
<td>16.3</td>
<td>54.3</td>
</tr>
<tr>
<td>$E_{my}$, MeV</td>
<td>$\sim$5</td>
<td>$\sim$6</td>
<td>$\sim$7</td>
<td>$\sim$9</td>
<td>$\sim$6</td>
<td>$\sim$6</td>
<td>$\sim$6</td>
</tr>
<tr>
<td>Max. range, $\mu$m</td>
<td>$\sim$13</td>
<td>$\sim$16</td>
<td>$\sim$13</td>
<td>$\sim$17</td>
<td>$\sim$11</td>
<td>$\sim$9</td>
<td>$\sim$8</td>
</tr>
</tbody>
</table>

The weighted averaged range $R_e = \sim 10 \, \mu m$
3DTrack formation dynamics, after Nikezic, 2003.
The purpose of the investigations was to estimate the real number and LET of secondary particles (fragments) produced by high energy trapped and GCR protons in a close tissue equivalent solid state nuclear track detector material (PADC) material composed of $\text{C}_{12}\text{H}_{18}\text{O}_{7}$, which indicates that $p \rightarrow ^{12}\text{C}$ is the most important fragmentation interaction.
170 MeV protons
TSL, Uppsala

No significant difference between LET spectra on top & bottom surfaces

TASTRAK, 1 mm
6 h etching, 8 mm removal
If $n$ is the fragmentation event producing two fragments in a unit volume then the number of tracks detected on unit detector surface (called track density, $T$) can be expressed as

$$T = T_1 + T_2 = \frac{1}{2} n \times (R_1 \sin^2 \Phi_c + R_2 \sin^2 \Theta_c)$$

where $T_1$ and $T_2$ are the track densities of the two different types of fragments ($^3\text{He}$ and $^{10}\text{B}$, for instance) having ranges $R_1$ and $R_2$, with critical detection angles $\Phi_c$ and $\Theta_c$, respectively.

The number of the tracks of detected twins is: $2T_2 = n \times R_2 \sin^2 \Theta_c$

and number of the lost heavier particles is then:

$$N_L = T - 2T_2 = \frac{1}{2} n \times (R_1 \sin^2 \Phi_c - R_2 \sin^2 \Theta_c)$$
Let us define the efficiency $\varepsilon$ as the ratio of the measured track density over the generated particle number ($2n$):

$$\varepsilon = \frac{T}{2n} = \frac{1}{4} \left( R_1 \sin^2 \Phi_c + R_2 \sin^2 \Theta_c \right)$$

If $R_2 = 10 \, \mu m$ is the averaged ranged of heavy products as estimated above and $R_1 = 300 \, \mu m$ is the averaged range of lighter particles, as well as, averaged $\Phi_c$ and $\Theta_c$ are $70^\circ$ and $45^\circ$, respectively, then

$$\varepsilon = \frac{1}{4} \left( 0.03 \sin^2 70 + 0.001 \sin^2 45 \right)$$

briefly $\varepsilon = 6.8 \times 10^{-3}$

~ 75 fragmentation events within a unit volume produce a single, visible track on the surface (assuming forward moving fragments).
EXAMPLE

The detector stack was exposed perpendicularly to 170 MeV protons with a fluence of $5.5 \times 10^8$ cm$^{-2}$, the measured track density on the bottom side of the first detector sheet was found to be $T = 3.8 \times 10^4$ cm$^{-2}$. Then, the number of fragmentation events in unit volume (1 cm$^3$) is

$$n = \frac{T}{2\varepsilon}$$

numerically $n = 2.8 \times 10^6$, which is 0.5 % of the proton fluence,

Protons trespassing without interaction should be neglected!

The number of the lost (not detected) particles (heavy products), $N_L$, then can be calculated as:

$$N_L = \frac{1}{2} \times 2.8 \times 10^6 (0.03 \sin^2 70 - 0.001 \sin^2 45) = 3.6 \times 10^4$$
No significant difference between LET spectra of different proton energies
1 GeV & 170 MeV protons

6 etching, 8 µm removal, top surfaces

Exposures at NSRL-BNL (USA) and TSL (Sweden)
No significant difference between LET spectra of different proton energies
Difference of LET spectra $(7t - 2t)$ provide info on $^{12}$C spallation
170 MeV protons in PADC

6h etching, 8 µm removal

Short range target fragments Z>2 are registered with LET > ~230 keV/µm
230 MeV protons, under carbon, 6 & 15h

6h & 15h etching, 8 & 20 µm removal

15 h: High LET, over etched tracks are eliminated by software

Corrected Prt. No.

LET in water, keV/µm

Nikezic model
SUMMARY

If short range target fragment and GCR particle tracks can be separated (multi-layered stack, multiple etching, track recognition program) then:

1. External (to detector) GCR (or projectile fragment) particle fluence and dose can be “easily” calculated from track parameter measurements. Traditional way! Calibration! Correction! LET spectrum!

2. Proton induced target fragment event & particle No. can be determined. Detection efficiency! Correction for the LET spectrum above ~230 keV/µm (???) needed. HOW?

3. The total dose is the sum of GCR and target fragment doses.
The authors wish to express their appreciation and thanks to the ICCHIBAN working group, for making possible to participate in the intercomparison experiments, and especially to Eric Benton for taking care of the AERI detectors during the proton experiments at Loma Linda and NSRL-BNL.
Thanks for your attention