Nanodosimetric validation of MC methods

PhD Student Peter Lazarakis

S. Guatelli, A. B. Rosenfeld, M. Bug, H. Rabus, E. Gargioni
Outline

- Nanodosimetry
- Geant4-DNA
- MC code comparison
  - Geometry
  - Quantities of interest
  - Results
- What have we learnt?
- Effects of a Magnetic field on track structure
Nanodosimetry

Brief overview

- Dosimetry in nanometre volumes – same scale as a DSB
- Assume that ionisations are the most biologically relevant process
- Interactions are stochastic
Geant4 VeryLowEnergy package (Geant4-DNA)

- Allows you to track particles interaction-by-interaction
- Down to eV level
- In liquid water (soon to have other materials as well, including some DNA cross sections)
- Soon will be able to track the production and diffusion of some chemical species
## Physics models

<table>
<thead>
<tr>
<th></th>
<th>e-</th>
<th>p</th>
<th>H</th>
<th>α, He+, He⁰</th>
<th>C, N, O, Fe,…</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elastic scattering</strong></td>
<td>&gt; 9 eV – 1 MeV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Screened</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rutherford</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 4 eV – 1 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Champion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Excitation</strong></td>
<td>9 eV – 1 MeV</td>
<td>10 eV – 500 keV</td>
<td>10 eV – 500 keV</td>
<td>Effective charge scaling from same models as for proton</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Born</td>
<td>Miller Green</td>
<td>Miller Green</td>
<td>1 keV – 400 MeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 keV – 100 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Born</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Charge Change</strong></td>
<td>-</td>
<td>100 eV – 10 MeV</td>
<td>100 eV – 10 MeV</td>
<td>Effective charge scaling 0.5 MeV/ u - 10⁶ MeV/ u</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dingfelder</td>
<td>Dingfelder</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ionisation</strong></td>
<td>11 eV – 1 MeV</td>
<td>100 eV – 500 keV</td>
<td>100 eV – 100 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Born</td>
<td>Rudd</td>
<td>Rudd</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 keV – 100 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Born</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vibrational excitation</strong></td>
<td>2 – 100 eV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sanche</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Attachment</strong></td>
<td>4 – 13 eV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melton</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Validation

- **No experimental data** to directly compare to...
- Compare codes?
- **Not true validation**...
- Useful to compare calculated results
MC code comparison

Geometry, physics and results
Geant4.9.3
PTB MC code

- Track structure code developed specifically for nanodosimetry
- Electrons, protons, alpha particles and some heavier ions
- Can be used for water (liquid or gas), propane gas, nitrogen gas
Geometry

DNA segment

Nucleosome

3.4 nm

(0,0,0)

2.3 nm

6 nm

10 nm

z

y

x
Particle types and physical processes

- **Electrons**
  - 50 eV – 10 keV
  - Elastic scattering (G4Champion model, G4Screened Rutherford model), Ionisation, Excitation

- **Protons**
  - 300 keV – 10 MeV
  - Ionisation, Excitation, Charge Change

- **Alpha particles**
  - 1 MeV – 10 MeV
  - Ionisation, Excitation, Charge Change
Quantities of interest

- $M_1$ - mean number of ionisations in sensitive volume
- $F_2$ - cumulative probability of producing 2 or more ionisations in sensitive volume
- $P(\text{DSB})$ - probability of producing a DSB

All calculated using the ionisation cluster size distributions
Uncertainties...

- Statistical uncertainty normally determined by repeating a simulation several times with different seeds and averaging
  - Time consuming!
  - So....
Uncertainties...

- Novel methods...
  - Determine *ionisation cluster size distribution* (ICSD, for x primary particles)
  - Use AS183 algorithm to get a *uniform distribution of x random numbers between 0 and 1*
  - Bin distribution according to cumulative probabilities from ICSD (repeat 100 times)
  - Calculate quantities and use standard deviation as uncertainty
Results: electrons

- 200 eV electrons

- Typical of other energies
  - Only small differences seen for small clusters
  - Largest relative differences seen for larger clusters

- Only small differences seen between two elastic scatter models
Results: electrons

Largest differences seen for energies below \(~300\) eV

Differences are smaller for higher energies...

Relative difference is still significant

\[ F_2 = \text{prob. of 2 or more ionisations} \]

\[ M_1 = \text{mean number of ionisations} \]
Results: electrons

Again largest differences seen for energies below \( \sim 300 \text{ eV} \)

Generally...

Differences in cross sections have varying effects depending on:

1. Primary particle energy (to be expected!)

2. Size of sensitive volume...
Results: protons and alphas

Protons:
- 300 keV
- Typically largest relative differences seen for large clusters

Alphas:
- 1 MeV
- Significant differences seen for all cluster sizes
Results: protons and alphas

Variations in e-cross sections have only a small effect (to be expected...)

At low energies cross sections are more complex

Differences between theoretical and semi-empirical models is to be expected

\( F_2 = \) prob. of 2 or more ionisations

\( M_1 = \) mean number of ionisations
Results: protons and alphas

Again largest differences seen for lowest energies.

Differences in charge change and ionization cross sections have largest effect on results.
Relative differences...

**Electrons:** $F_2$ and $P(\text{DSB})$ relative differences are similar.

**Protons:** both follow same trend but $P(\text{DSB})$ relative differences are larger.

**Alphas:** $F_2$ relative differences are negligible, $P(\text{DSB})$ differences are significant.

$F_2 =$ prob. of 2 or more ionisations

$M_1 =$ mean number of ionisations
Nanodosimetry: what have we learnt?

- $F_2$ not always reliable...

- Generally mean or cumulative quantities can be tricky...
  - Not always relevant
  - Can have large variation

- When dealing with radiobiological quantities even if statistical uncertainties are small does not mean calculated values are accurate!
  - Relative differences may be more reliable than absolute values....
References and further info

- Geant4-DNA
  - http://geant4.org
  - The Geant4-DNA project

- PTB code
  - Grosswendt B 2002 Formation of ionization clusters in nanometric structures of propane-based tissue-equivalent gas or liquid water by electrons and alpha-particles Radiat. Environ. Biophys. 41 103-12

- Probability of DSB model