Queen's University Belfast

UFRJ

2007 Crete
XX ISIAC

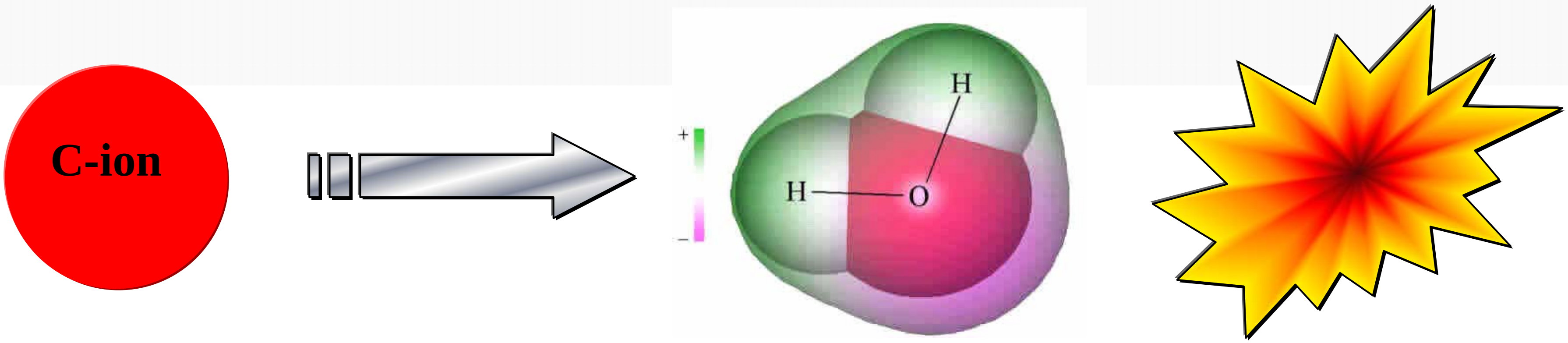
FRAGMENTATION OF WATER NEAR THE BRAGG PEAK

Collaborative programme involving:

Queen's University Belfast
Federal University, Rio de Janeiro

ALSO
Dublin City University
Centro Federal de Educacao Tecnologia, Brazil
Universite Catholique de Louvain

Interaction of Carbon ions with Water



Fragmentation and non-fragmentation channels for C^0 and C^+ projectiles have been measured over the 15 to 100 keV energy range

C+ and C0 projectiles on Water

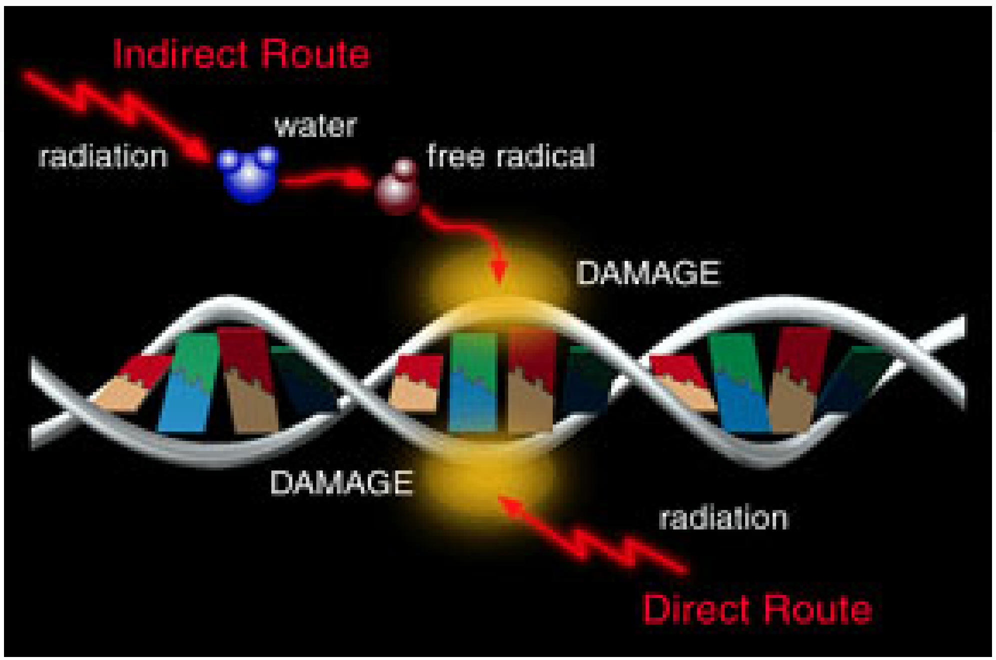
C^+ beam:

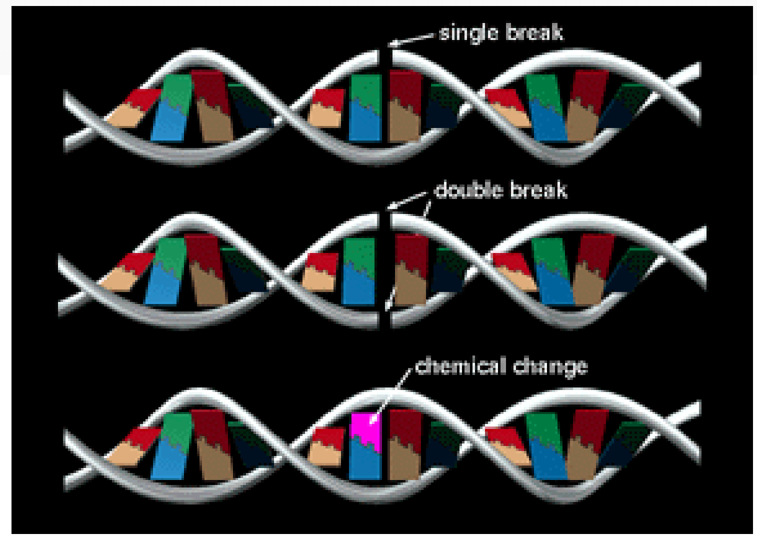
Pure Ionisation, pure capture and transfer ionisation channels measured

C^0 beam are:

Pure Ionisation, pure capture and projectile electron loss channels measured

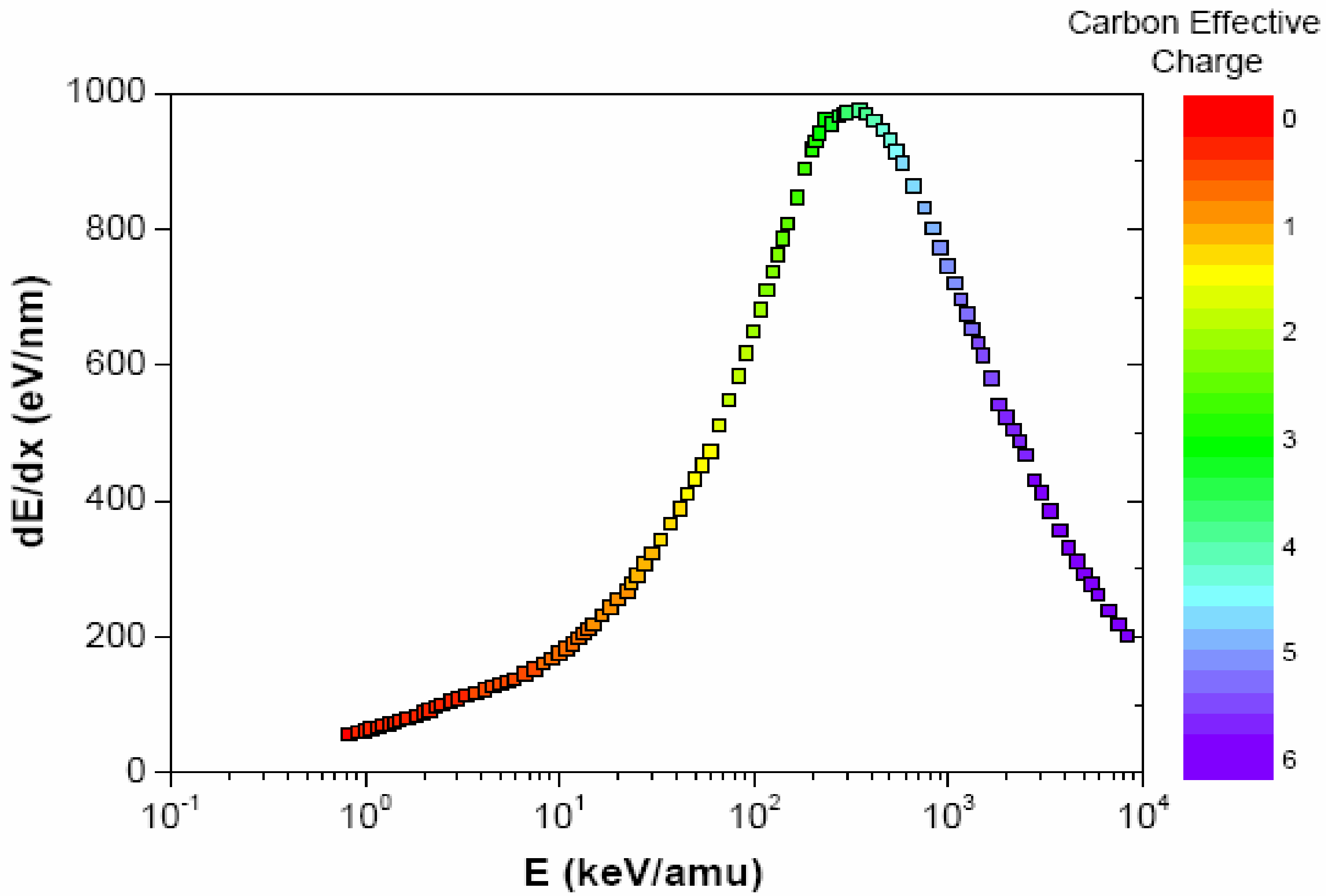
- Measurements are of great importance in the C-ion based radiotherapy



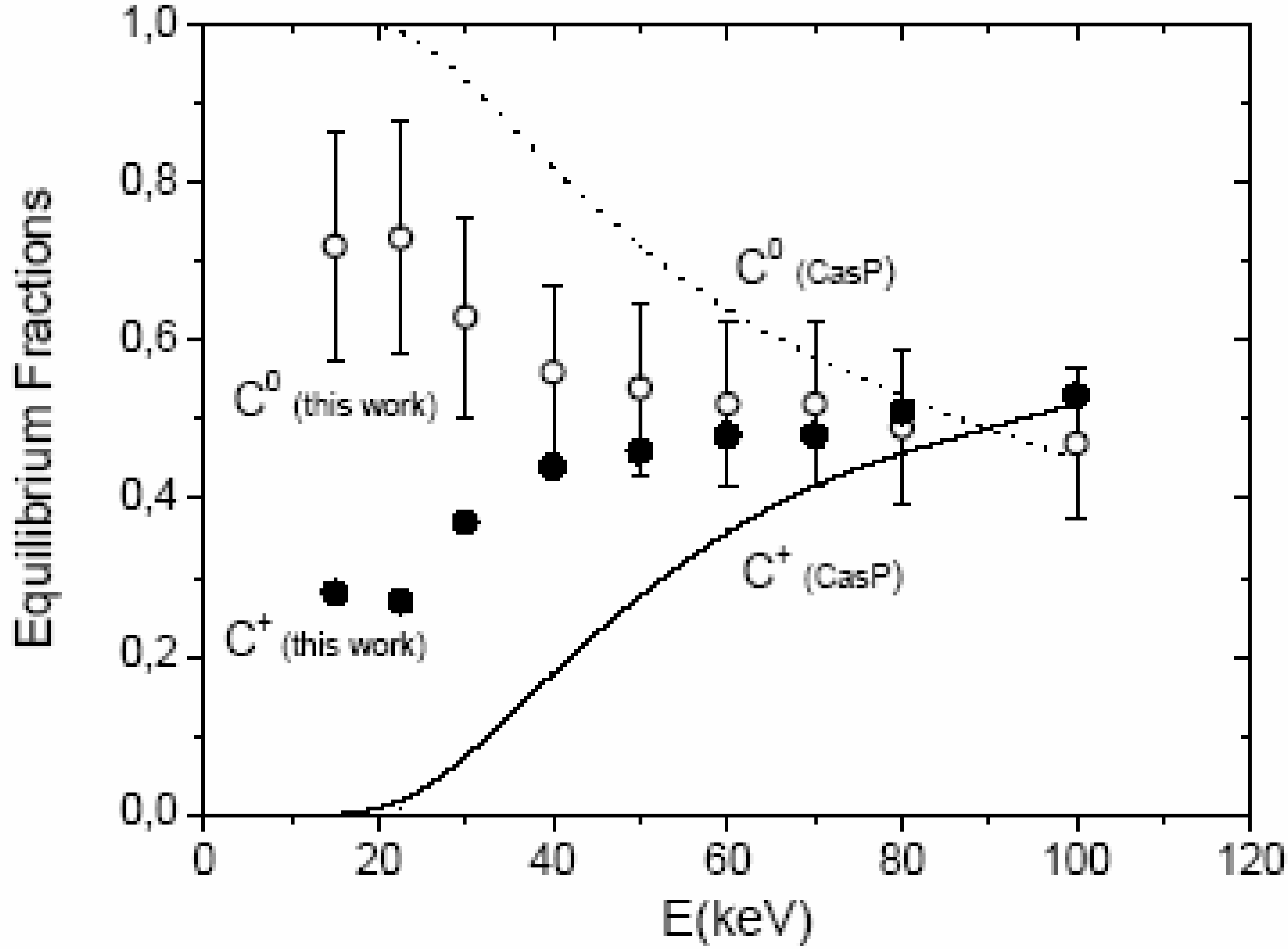


70% of tumour damage is known to occur through chemistry with water radicals

- Present energy range covers the distal part of the Bragg peak
- Knowledge of water radical formation around the Bragg peak is thus of fundamental importance
- Present measurements are first to supply such data of relevance to C-ion therapy



Bragg peak for C-ion therapy. Charge state fractions present in the C-beam are colour coded according to the inset on the right.

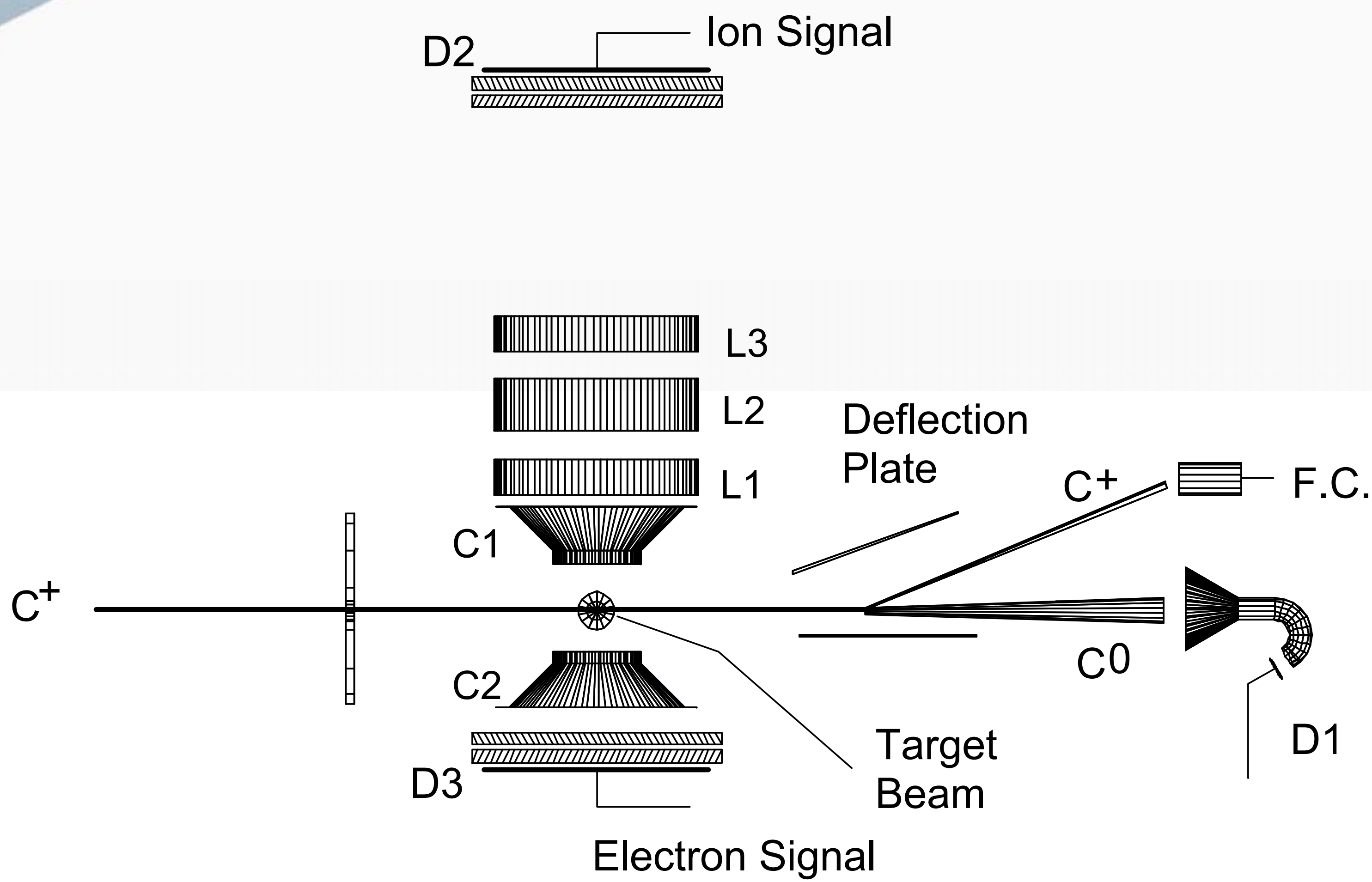


C^0 and C^+ equilibrium fractions over 15 to 100 keV energies. Data points: this work using $f_0/f_1 = \sigma_{loss}/ \sigma_{cap}$. Lines: Casp calculations.

- Currently Bragg peak is assessed using energy loss data at high energies for a range of projectiles in solids and liquids.
- No experimental data on water molecules have been available

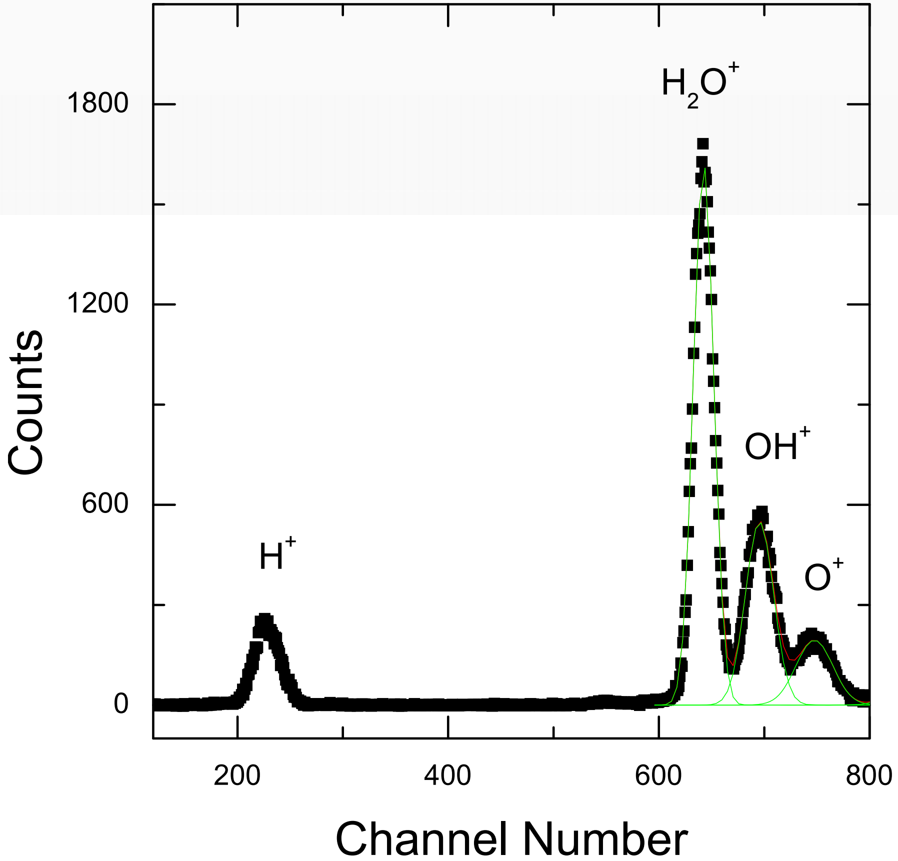
- So how accurately is the Bragg peak determined in water?
- Further should the peak be sharp?
- This affects how close treatment scans can be taken near vital organs such as the OPTICAL NERVES

- After this talk I will let you to be the judge.

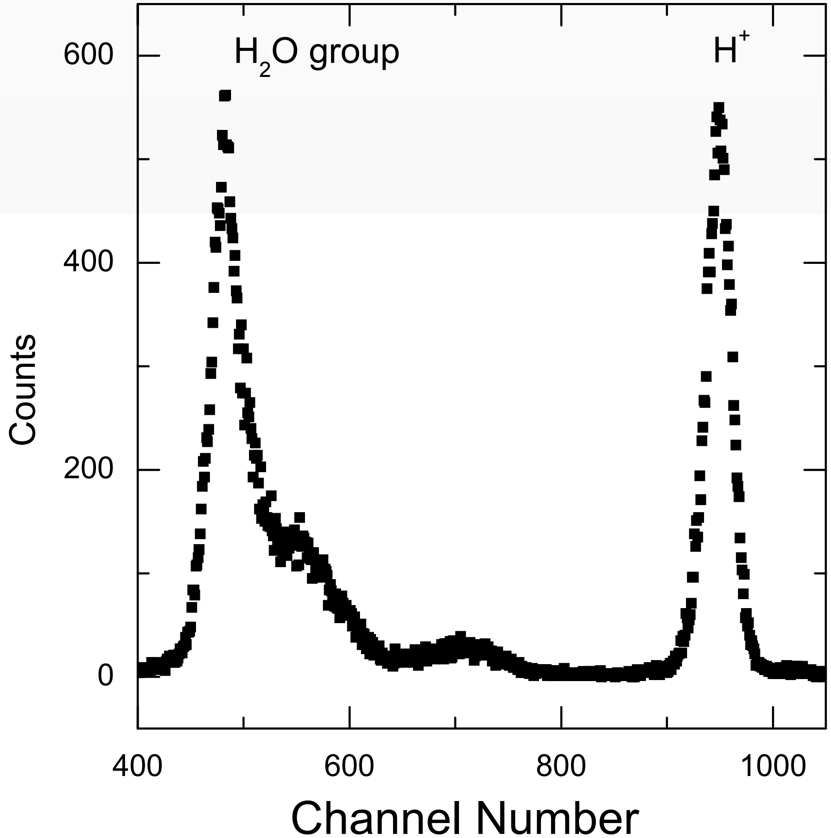


Schematic diagram of the apparatus

TOF spectra with 240mm drift length



TOF spectra with 35mm drift length



- **Notice changes in the H^+ peak**

Coincidences between target ion products and projectile products give pure electron capture channels:

$$C^{+} + H_2O \rightarrow C^{0} + H_2O^{+}$$

$$\rightarrow C^{0} + OH^{+} + H$$

$$\rightarrow C^{0} + H^{+} + OH$$

$$\rightarrow C^{0} + O^{+} + [2H]$$

And the transfer ionisation channel

$$\rightarrow C^{0} + [OH^{+} + H^{+}] + e$$

Coincidences between target ion products and target electrons give pure ionisation channels:

$$C^+ + H_2O \rightarrow C^+ + H_2O^+ + e$$
$$\rightarrow C^+ + OH^+ + H + e$$
$$\rightarrow C^+ + H^+ + OH + e$$
$$\rightarrow C^+ + O^+ + [2H] + e$$

As well as the transfer ionisation channel

$$\rightarrow C^0 + [OH^+ + H^+] + e$$

- Transfer ionisation produces an electron as well as a fast neutral projectile and is thus recorded in both the spectra.

For C^0, an additional electron-loss channel is present:

$$C^0 + H_2O \rightarrow C^+ + H_2O + e$$

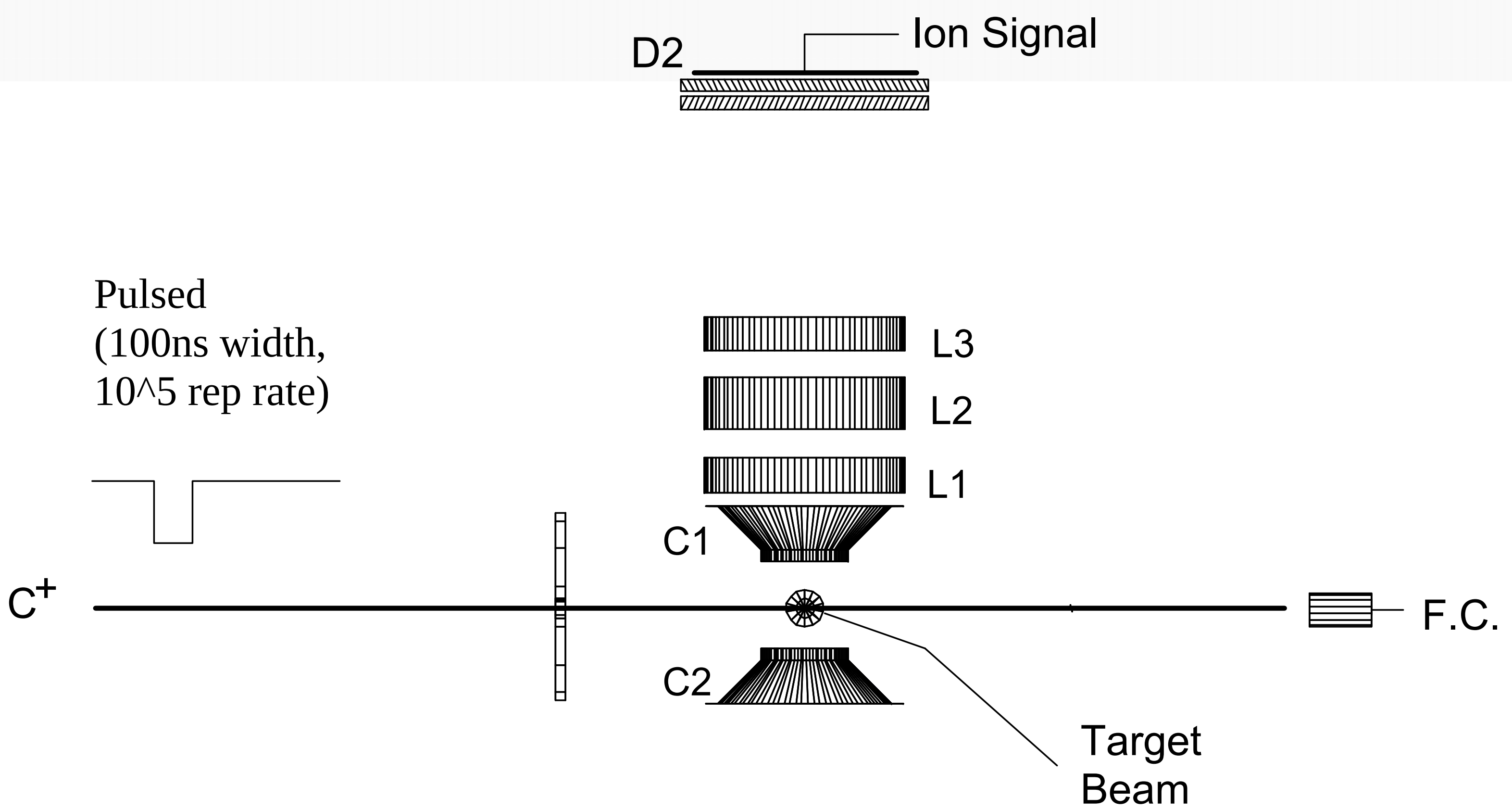
where the target acts as a simple screened scattering centre.

Also present are the electron-loss/ionisation channels

$$C0 + H_2O \rightarrow C+ + H_2O^+ + 2e$$
$$\rightarrow C^+ + OH^+ + H + 2e$$
$$\rightarrow C^+ + H^+ + OH + 2e$$
$$\rightarrow C^+ + O^+ + [2H] + 2e$$

where the target becomes ionised

Transfer ionisation for C^+ is assessed using the “Pulsed Beam” technique



- Pulsed mode:

  Pure capture + pure ionisation + transfer ionisation (1)

- Target ion/projectile product coincidence mode:

  Pure capture + transfer ionisation (2)

- Target ion/target electron coincidence mode:

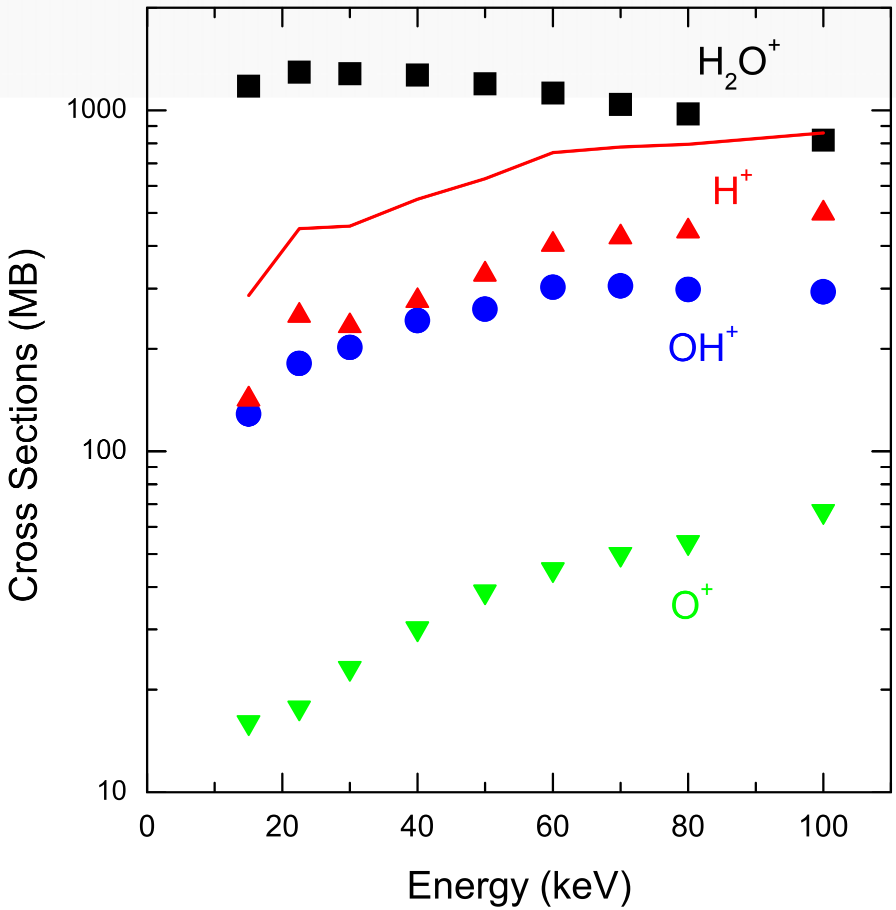
  Pure ionisation + transfer ionisation (3)

Thus

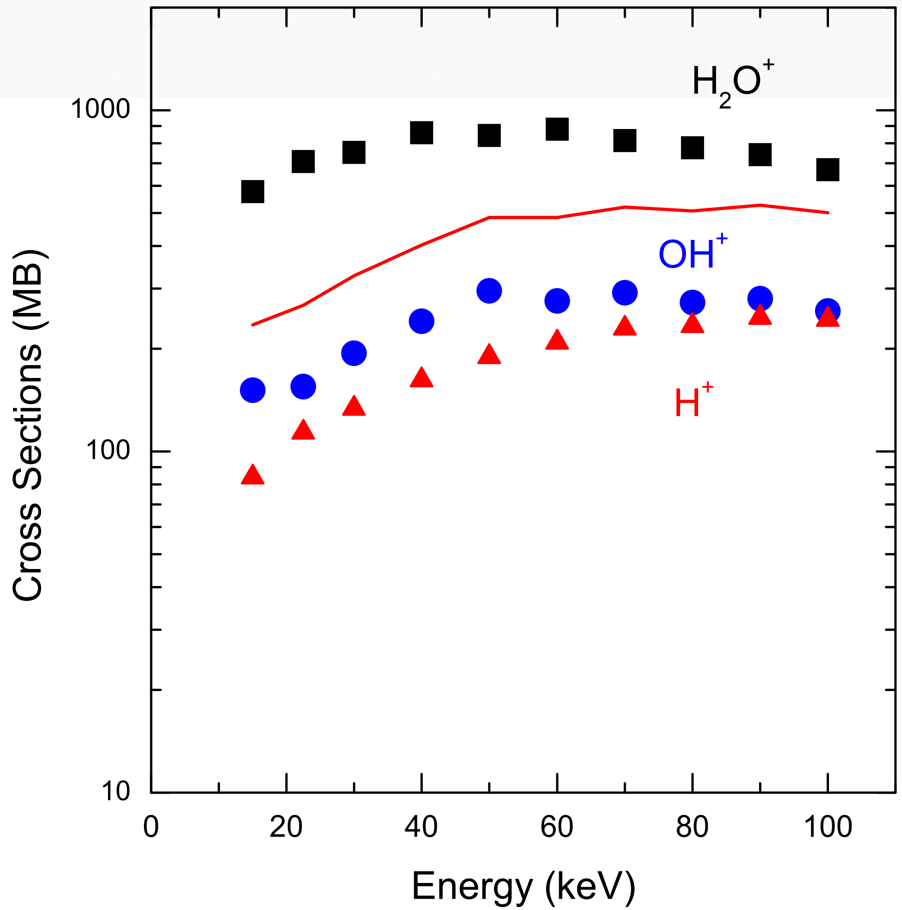
(2)+ (3) - (1) directly gives transfer ionisation

Cross sections for fragmented and non-fragmented channels

C+ projectile



C0 projectile



Energy loss Calculations

- First need to know energy loss ΔE per collision

$$\Delta E = \overbrace{I_p + \epsilon_i}^{\Delta E_{loss}} + \overbrace{I_T + E_p - 1/2u^2}^{\Delta E_{cap}} + \Delta_{exc}$$

$$\Delta E_{ion} = \epsilon_i + I_T$$

I_p & I_T – IP of the projectile and the target electron

ϵ_i - K.E. of the ejected electron

E_p & $1/2u^2$ - Final energy and c.m. energy of captured electron

Δ_{exc} - excitation energy of the active electron

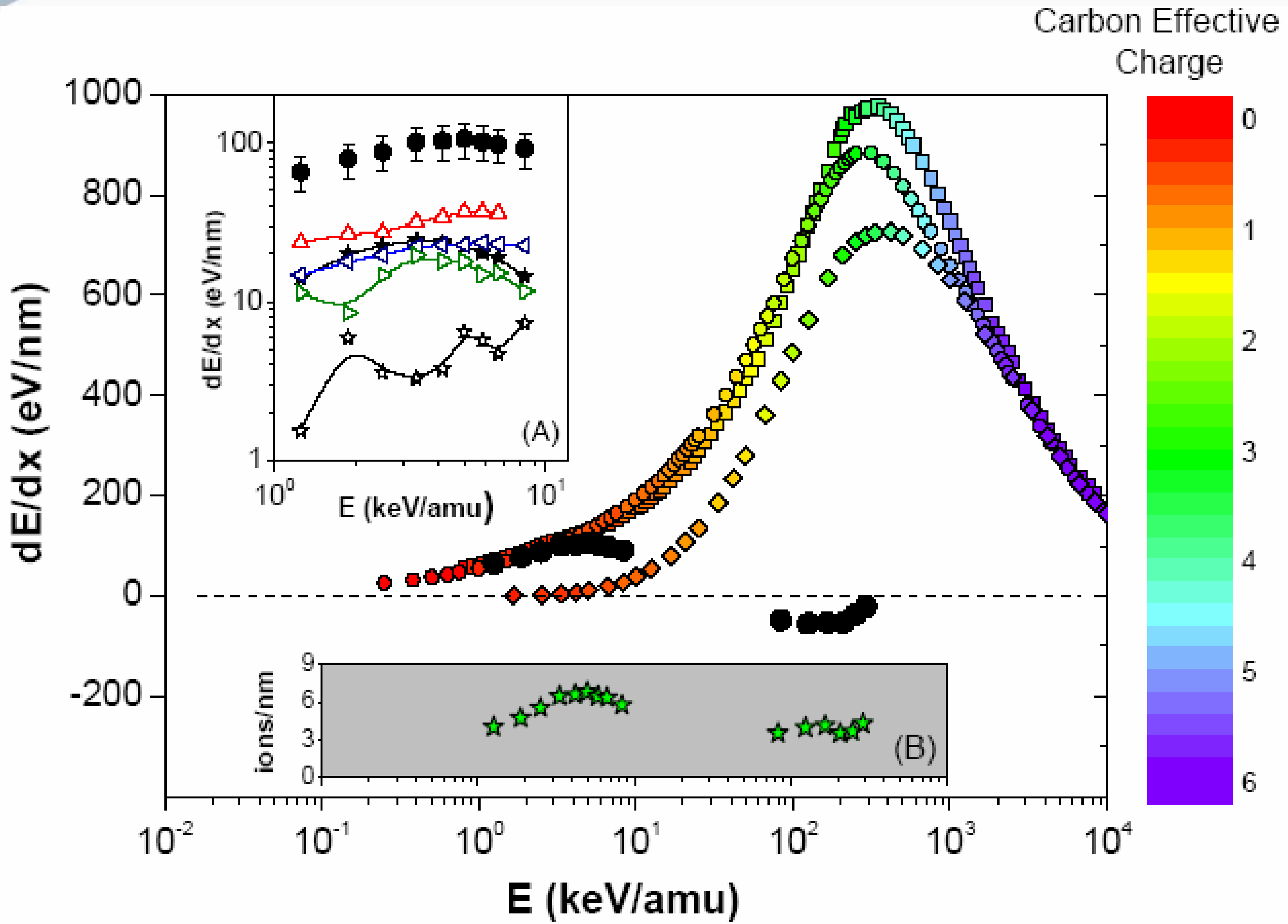
- Electrons are removed from the $2a_1$, $1b_2$, $3a_1$ or the $1b_1$ water orbitals
- H_2O^+ channel removes the outermost $3a_1$, and $1b_1$ electrons
- Fragmentation channels remove the deep lying $2a_1$ and $1b_2$ electrons
- ΔE can then be calculated using binding energies of these appropriate electrons

- Density of water, n, in the body and cross sections, σ, then give the energy loss rate

- $\Delta E/dx = (n*10^{-9}*\sigma)*\ \Delta E$

  where n is per M^3 and σ is in units of M^2. ΔE/dx is in eV/nm

These values are given in the next slide



Carbon Effective Charge
0
1
2
3
4
5
6
dE/dx (eV/nm)
1000
800
600
400
200
0
-200
E (keV/amu)
dE/dx (eV/nm)
E (keV/amu)
(A)
ions/nm
(B)

Conclusions

- Water related damage is mainly though radical chemistry
- Therefore it is the number of radical formation which is an important factor and not necessarily the amount of energy deposited
- Present stopping power based energy loss models seem to over estimate likely damage at the centre of the Bragg peak compared to the distal peripheral region.
- Radical formation is almost flat over an extended portion of the distal region
- The radicals should thus give a much more uniform damage profile

People involved

Eduardo Montenegro – Federal University, Rio de Janeiro, Brazil

Shane Scully – Queen's University, Belfast

Jean Wyer – Queen's University, Belfast

Hugo de Luna – Dublin City University

Ana Barros - Centro Federal de Educacao Tecnologia, Brazil

Julien Lecointre – Universite Catholique de Louvain, Belgium

Thank you

2007 Crete
XX ISIAC