Bioequivalent Solid State Dosimetry

Current Trends and Future Developments

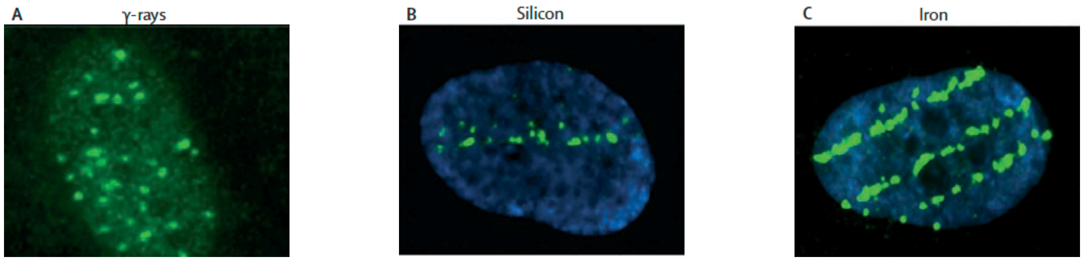
Michael Hajek

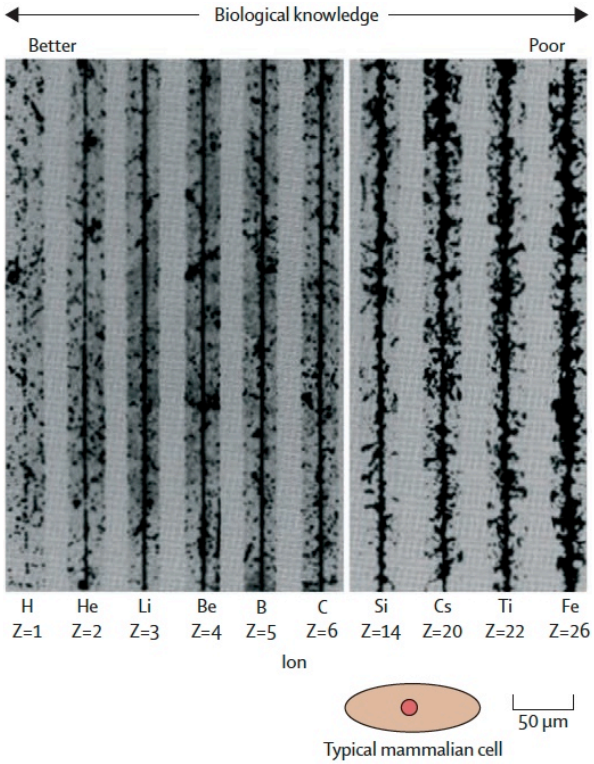
Institute of Atomic and Subatomic Physics, Vienna University of Technology

19 June 2012
2012 Spring Meeting of the Austrian Radiation Protection Association

Shortcomings of Macroscopic Dosimetry

- Macroscopic description of energy transfer in large volumes
  - Quasi-continuous energy deposition along particle track
  - Negligible statistical fluctuations
  - Absorbed dose, linear energy transfer
- Energy deposition by densely ionizing radiation is much more heterogeneous





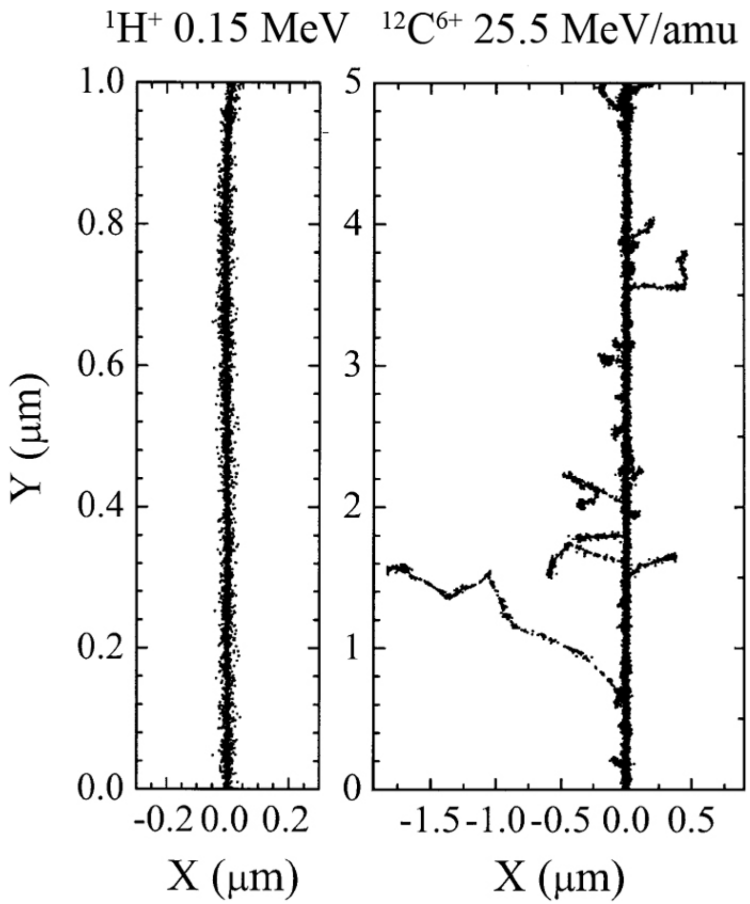
F. A. Cucinotta, M. Durante, *Lancet Oncol.* **7**, 431 (2006).

Development of Microdosimetry

- Macroscopic concepts are a poor basis for understanding radiation action

- Microdosimetry assesses energy transfer on microscopic scale of spatial distribution
  - Cellular and subcellular structures
  - Stochastic nature of energy deposition
  - Specific energy, lineal energy

H. H. Rossi, *Radiat. Res.* **10**, 522 (1959).



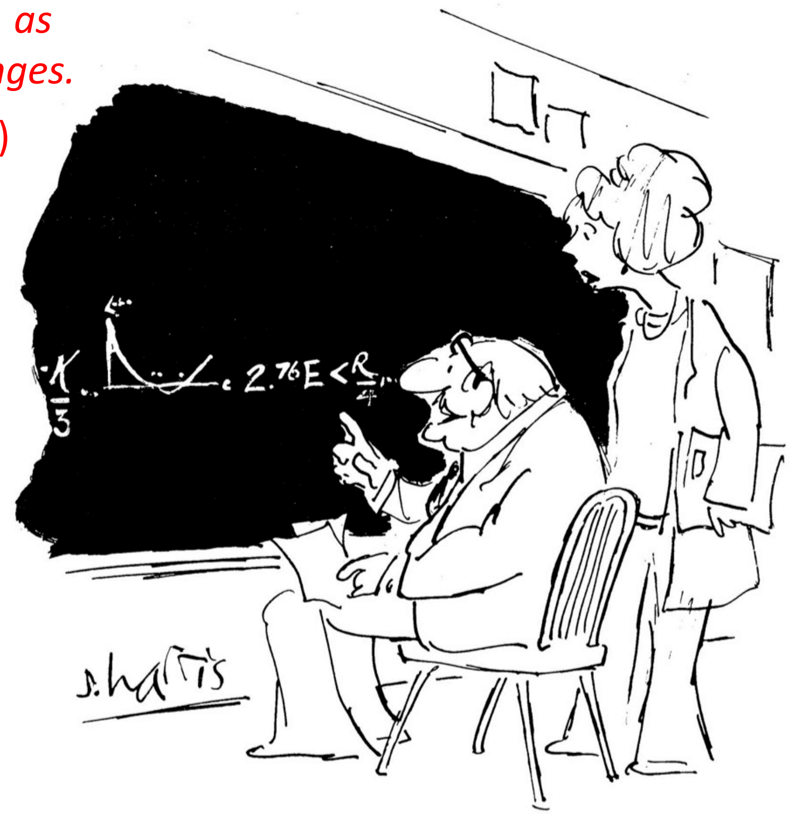
Y. Muroya *et al.*, *Radiat. Res.* **165**, 485 (2006).

Impact of Microdosimetry

Their employment has led to important insights but not, as yet, to a quantitative treatment of primary cellular changes.

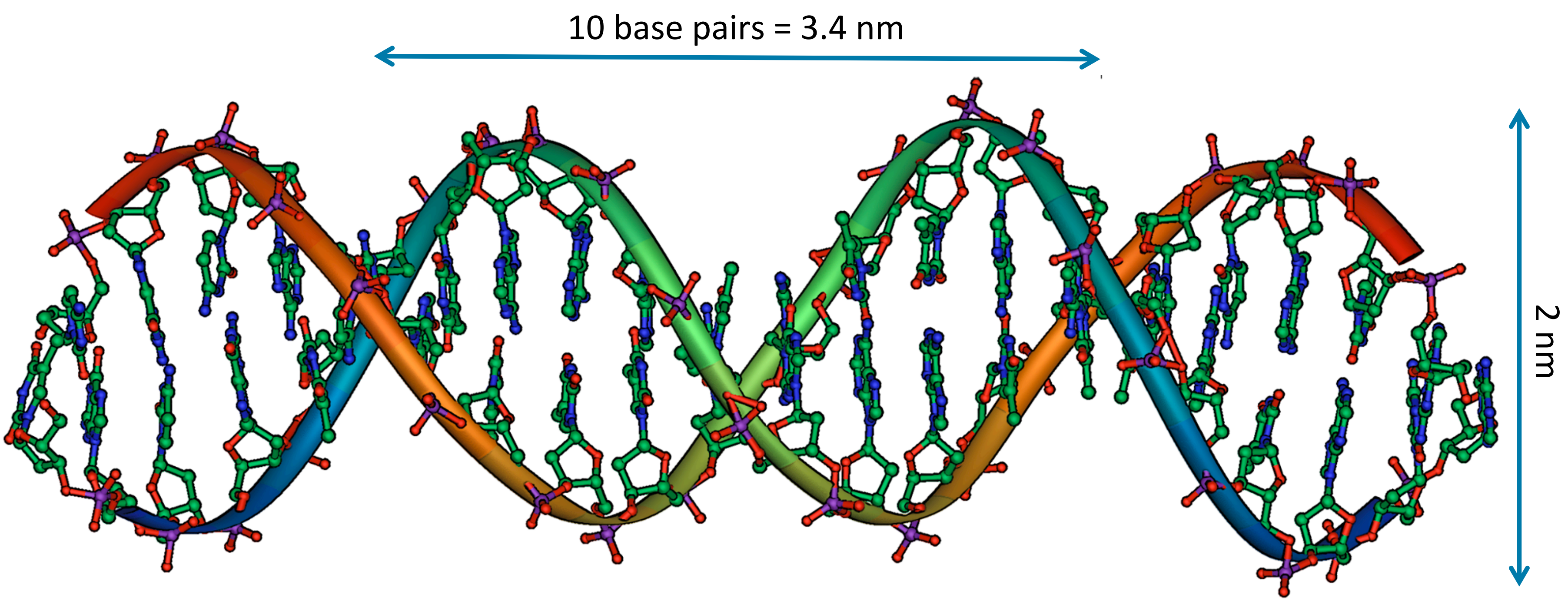
—Albrecht M. Kellerer, *Radiat. Prot. Dosim.* **31**, 9 (1990)

- Has microdosimetry led to any fundamental understanding of radiobiology?



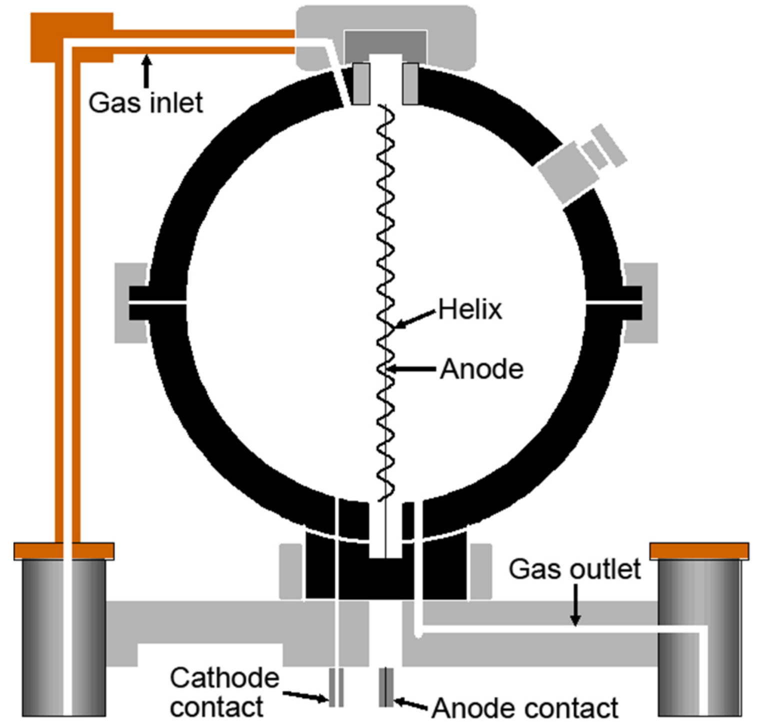
"THE BEAUTY OF THIS IS THAT IT IS ONLY OF THEORETICAL IMPORTANCE, AND THERE IS NO WAY IT CAN BE OF ANY PRACTICAL USE WHATSOEVER."

Towards Nanometre Dimensions



Tissue-Equivalent Proportional Counter

- Small gaseous proportional counter, scaled by density to cellular volumes [nm…µm]
- Walls (A150) and fill gas (propane) mimic elemental composition of biological tissue
- Measures distributions of specific or lineal energy



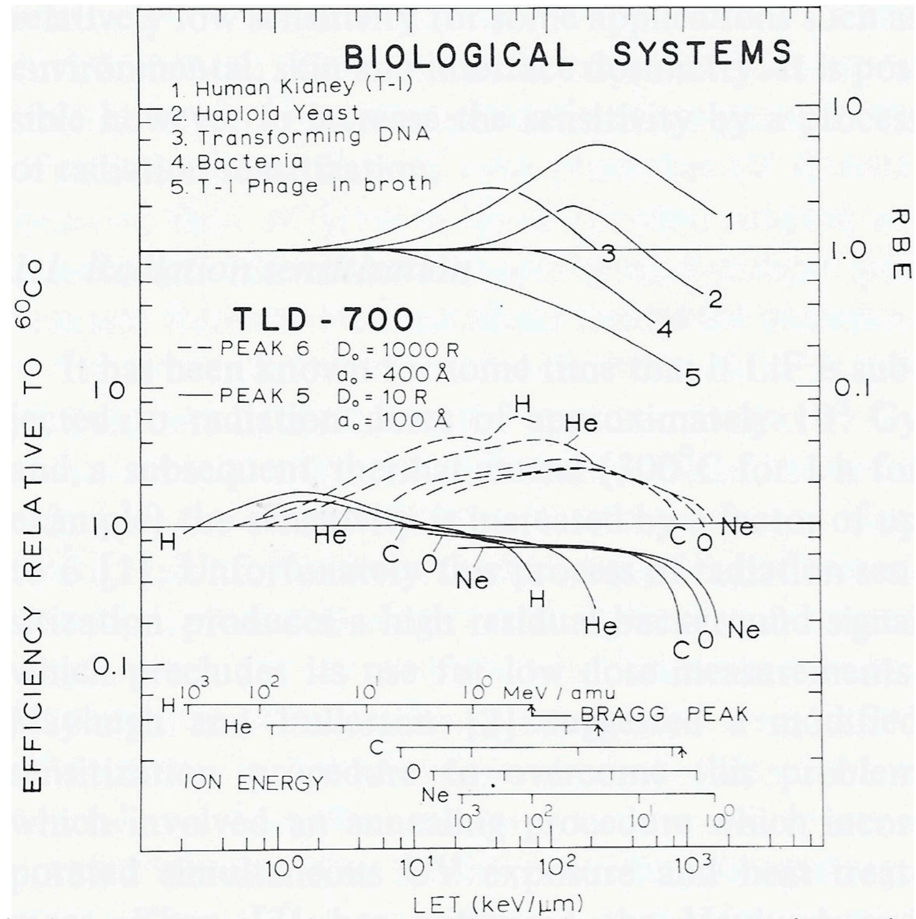
Courtesy ORAU

Mimicking Radiobiological Response

It appears that TLDs are good candidates for mimicking the response of biological systems to heavy-ion irradiations.

—M. P. R. Waligórski, R. Katz, *Nucl. Instrum. Methods* **175**, 48 (1980)

- Detector for which the structure of energy-deposition events resembles situation in a cell



M. P. R. Waligórski, R. Katz, *Nucl. Instrum. Methods* **175**, 48 (1980).

Chronology of Luminescence Observations

Robert Boyle after Johann Kerseboom (ca 1689)
National Portrait Gallery, London

OBSERVATIONS

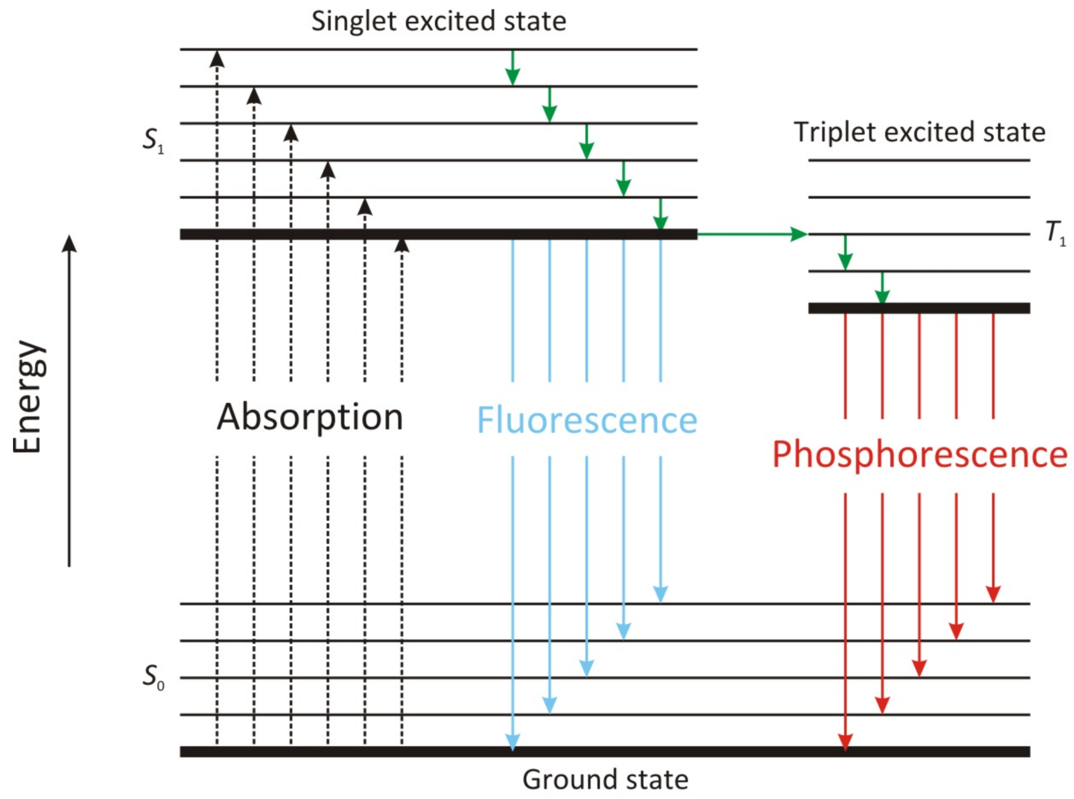
Made this 27th of October 1663 about Mr. Clayton's Diamond.

Eleventhly, I also brought it to some kind of Glimmering Light, by taking it into Bed with me, and holding it a good while upon a warm part of my Naked Body.

—Sir Robert Boyle,
Experiments and Considerations Touching Colours (1664)

- Thermoluminescence induced by electron beams in alkali halides
  E. Wiedemann, G. C. Schmidt, *Ann. Phys. Chem. N. F.* **54**, 604 (1895).
- Early studies of emission bands in alkali halides
  F. Urbach, *Wiener Ber.* **139**, 363 (1930).
- Application to radiation dosimetry and archaeological dating
  F. Daniels *et al.*, *Science* **117**, 343 (1953).

Classification of Luminescence Phenomena



FLUORESCENCE
Instantaneous emission upon relaxation to the ground state, essentially independent of temperature

PHOSPHORESCENCE
Involves metastable states, strong temperature dependence

Radiative transitions

Non-radiative transitions

Absorption

ELECTRONIC TRANSITIONS IN INSULATORS
(Jablonski diagram)

Thermoluminescence

- Emission of light from an insulator when it is heated, following the previous absorption of energy from ionizing radiation

- Essential ingredients for TL generation
  - Material must be an inorganic insulator (metals do not show luminescence)
  - Material must have at some time absorbed energy during exposure to radiation
  - Luminescence emission is triggered by heating the material
  - More than two-thirds of naturally occurring minerals exhibit luminescent properties
  - Once heated to excite light emission, material cannot be made to emit TL again by simply cooling and reheating
  - Not to be confused with incandescence

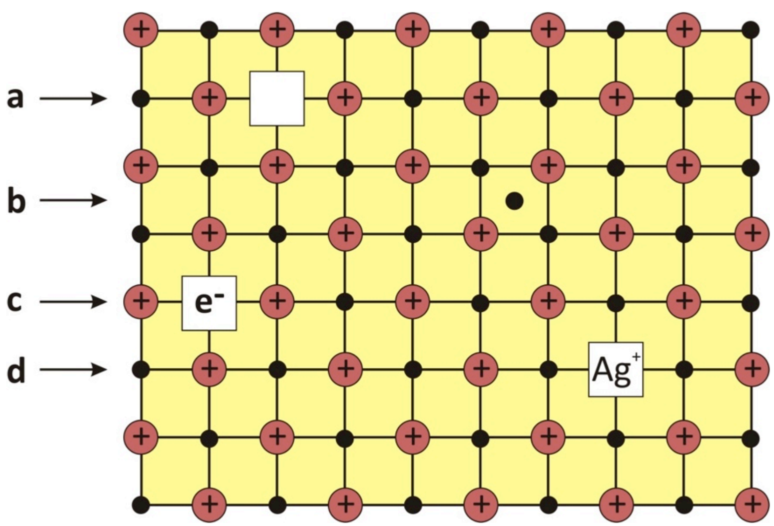
Storage of Energy in Crystal Lattice

Crystals are like people:
it is the defects that makes them interesting.

—Peter D. Townsend, University of Sussex

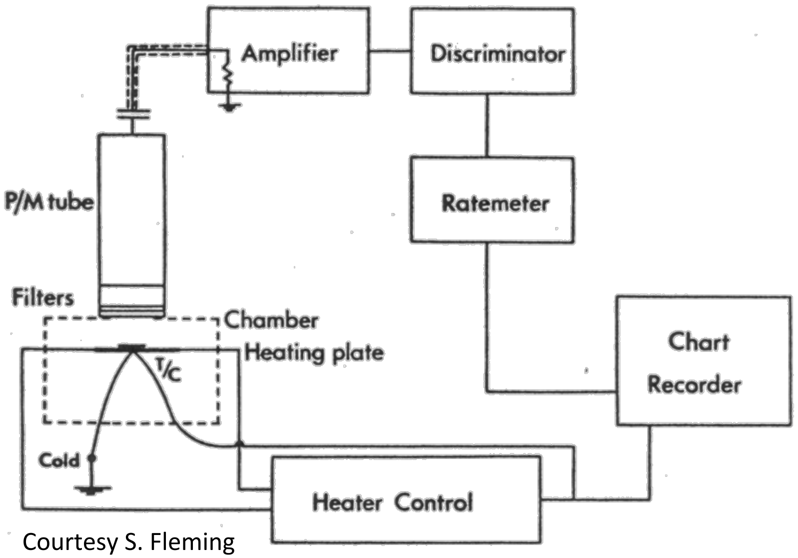
- Crystallographic point defects
  - Interstitials
  - Vacancies
  - Frenkel defects (vacancy-interstitial pair)
  - Impurities (substitutional defects)
  - Radiation-induced defects

☞ Cause colouration (colour centres)

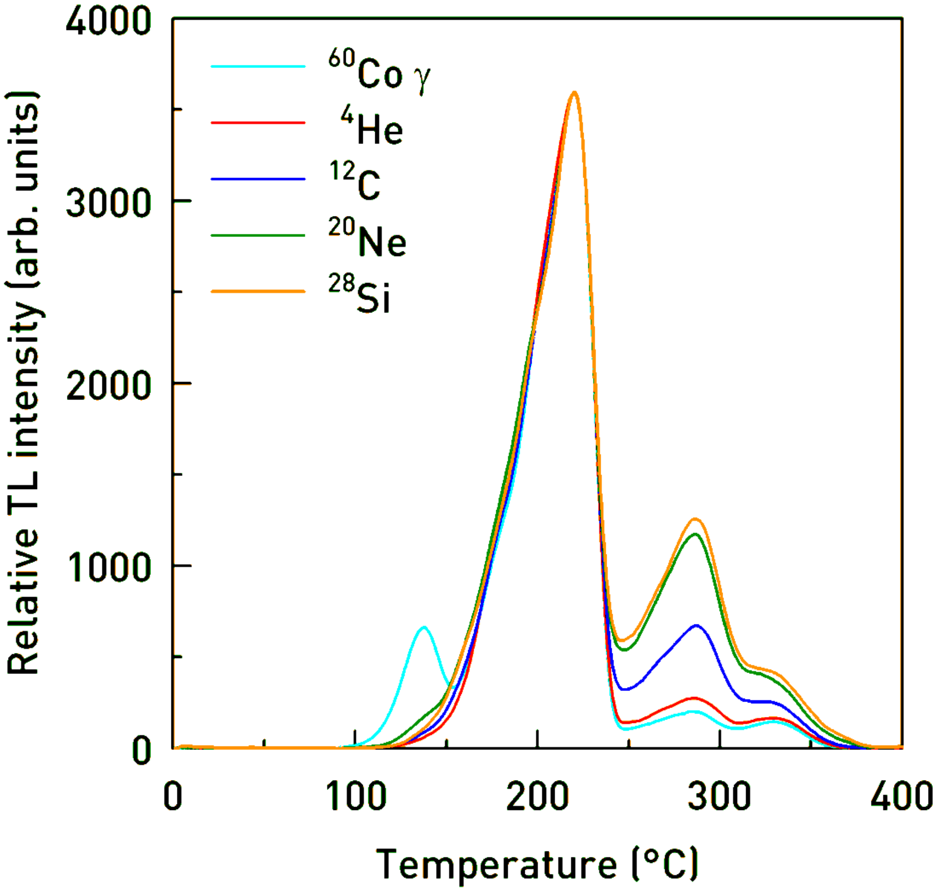


a **Anion vacancy**
b **Anion interstitial**
c **F centre** (electron-anion vacancy pair)
d **Substitutional impurity centre**

TL Glow Curve of LiF:Mg,Ti

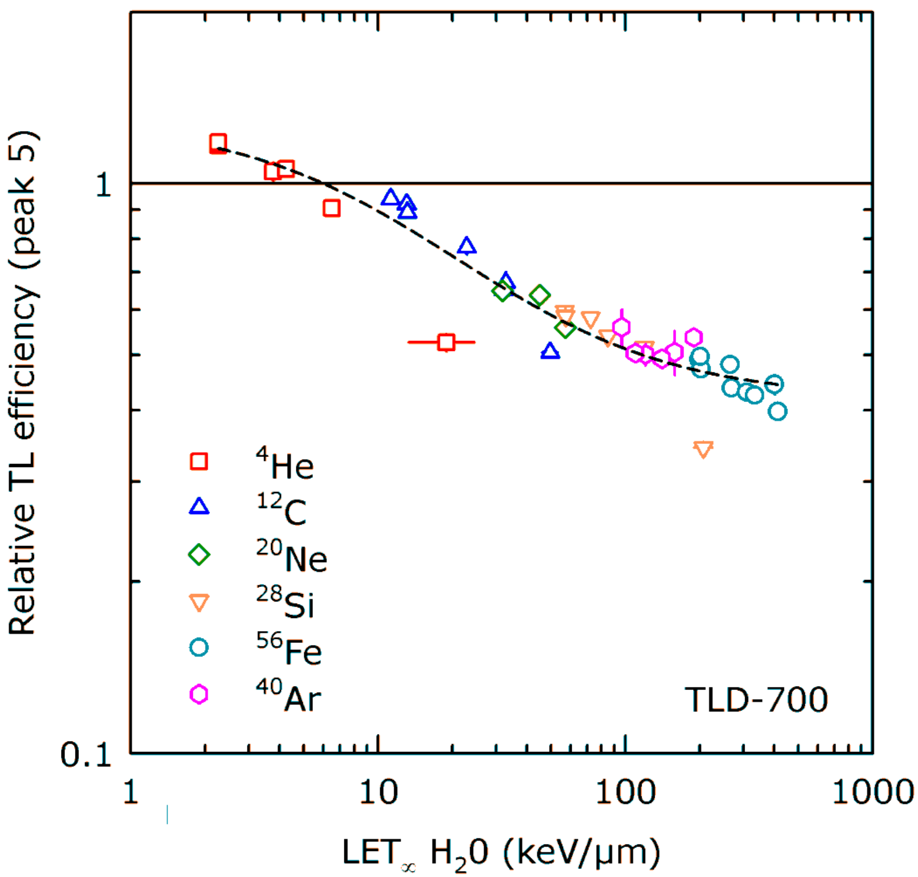


Courtesy S. Fleming

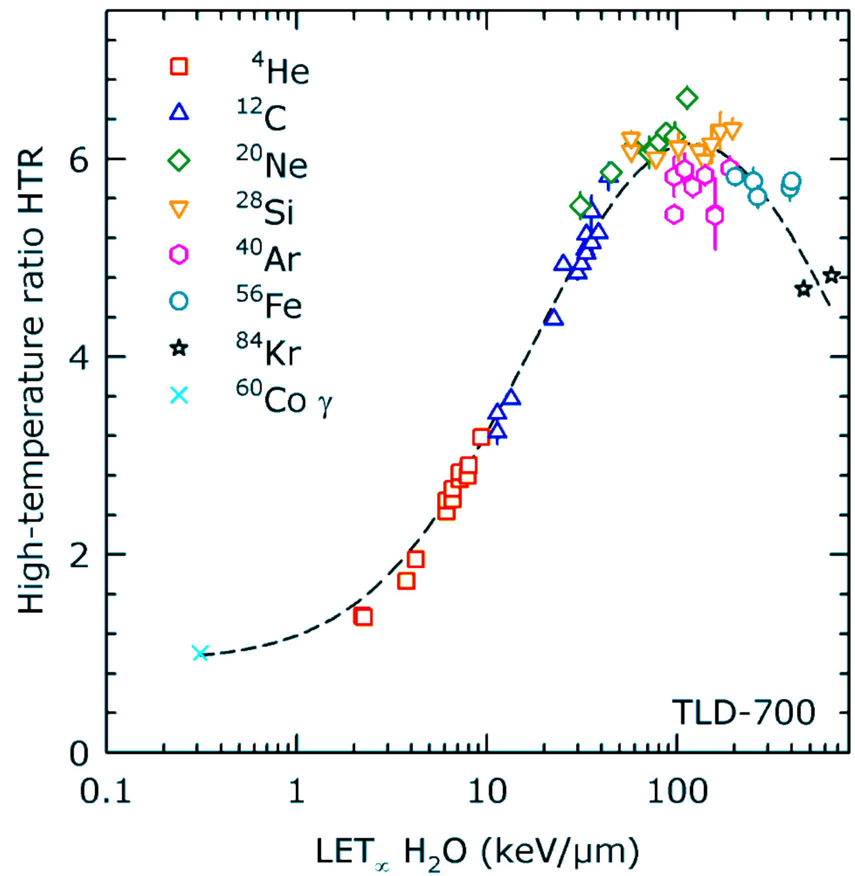


T. Berger, M. Hajek, *Radiat. Meas.* **43**, 146 (2008).

Relative TL Efficiency of LiF:Mg,Ti

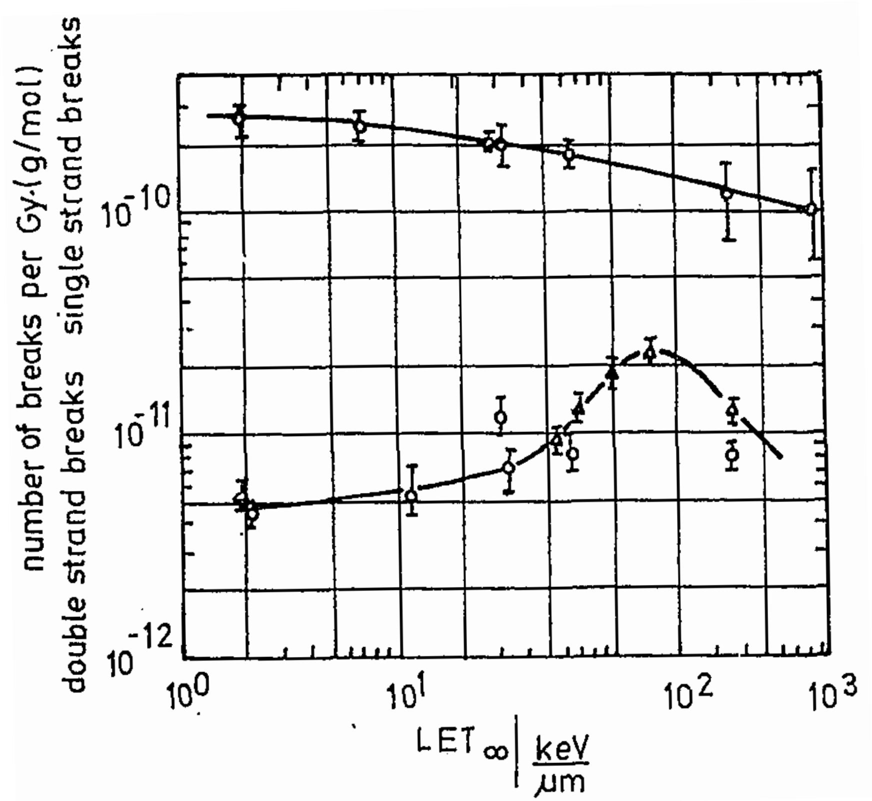


M. Hajek *et al.*, *Radiat. Prot. Dosim.* **120**, 446 (2006).



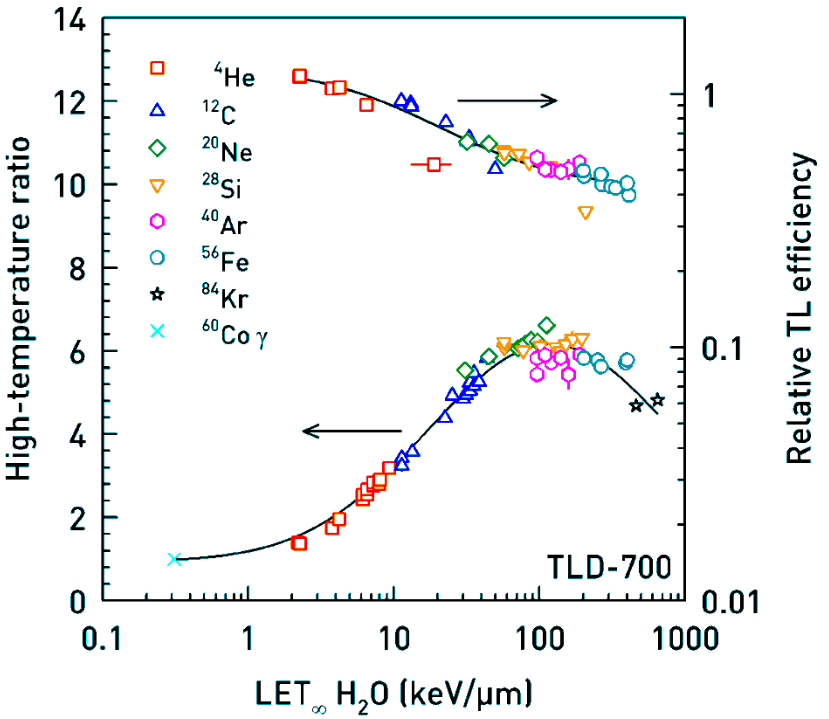
M. Hajek *et al.*, *Adv. Space Res.* **37**, 1664 (2006).

Correlation of Physical and Radiobiological Response



Ionization density dependence of SSB and DSB induction in DNA of V79 Chinese hamster cells

G. Kampf, *Radiobiol. Radiother.* **29**, 631 (1988).

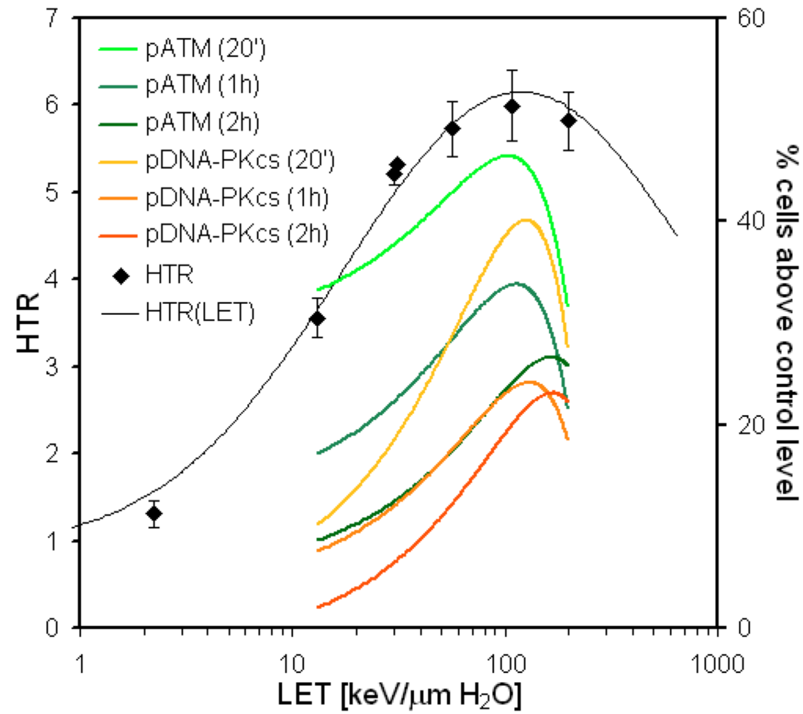


Ionization density dependence of HTR and TL efficiency relative to ^{60}Co γ-rays

M. Hajek, arXiv:0906.4898 (2009).

Supporting Experiments in Co-operation with MEDIZINISCHE UNIVERSITÄT WIEN

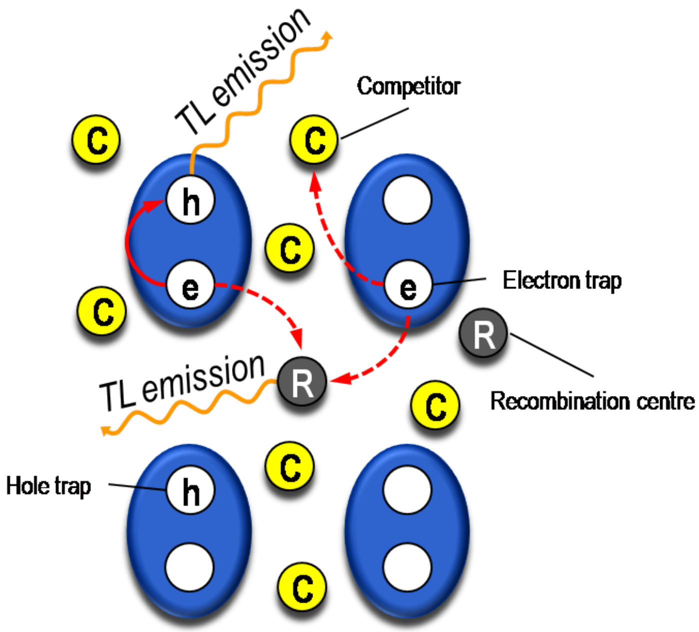
- Cultivated human skin fibroblasts and LiF:Mg,Ti TLDs exposed to $^{4}He^{2+}$, $^{12}C^{6+}$, $^{20}Ne^{10+}$, $^{28}Si^{14+}$, $^{56}Fe^{26+}$
- Special emphasis on low doses to investigate bystander response
- Investigated endpoints included several DNA-dependent protein kinases such as pATM, γH2AX, pDNA-PKcs



C. Fürweger *et al.*, *Radiat. Prot. Dosim.* **126**, 418 (2007).
C. Fürweger *et al.*, Proc. IBIBAM, FS-07-144-T, 179 (2007).
C. Fürweger, PhD Thesis, Vienna Univ. Technol. (2007).

Physical Modelling of TL Response

- Describe the formation of molecular structures acting as electron traps and recombination centres
- Investigate spatial correlation of recombination processes leading to specific TL glow peaks



F. Aumayr, G. Badurek, M. Benedikt, M. Hajek *et al.*, *Physics Opportunities at MedAustron: White Book* (Vienna University of Technology, 2009).

Track Structure Theory

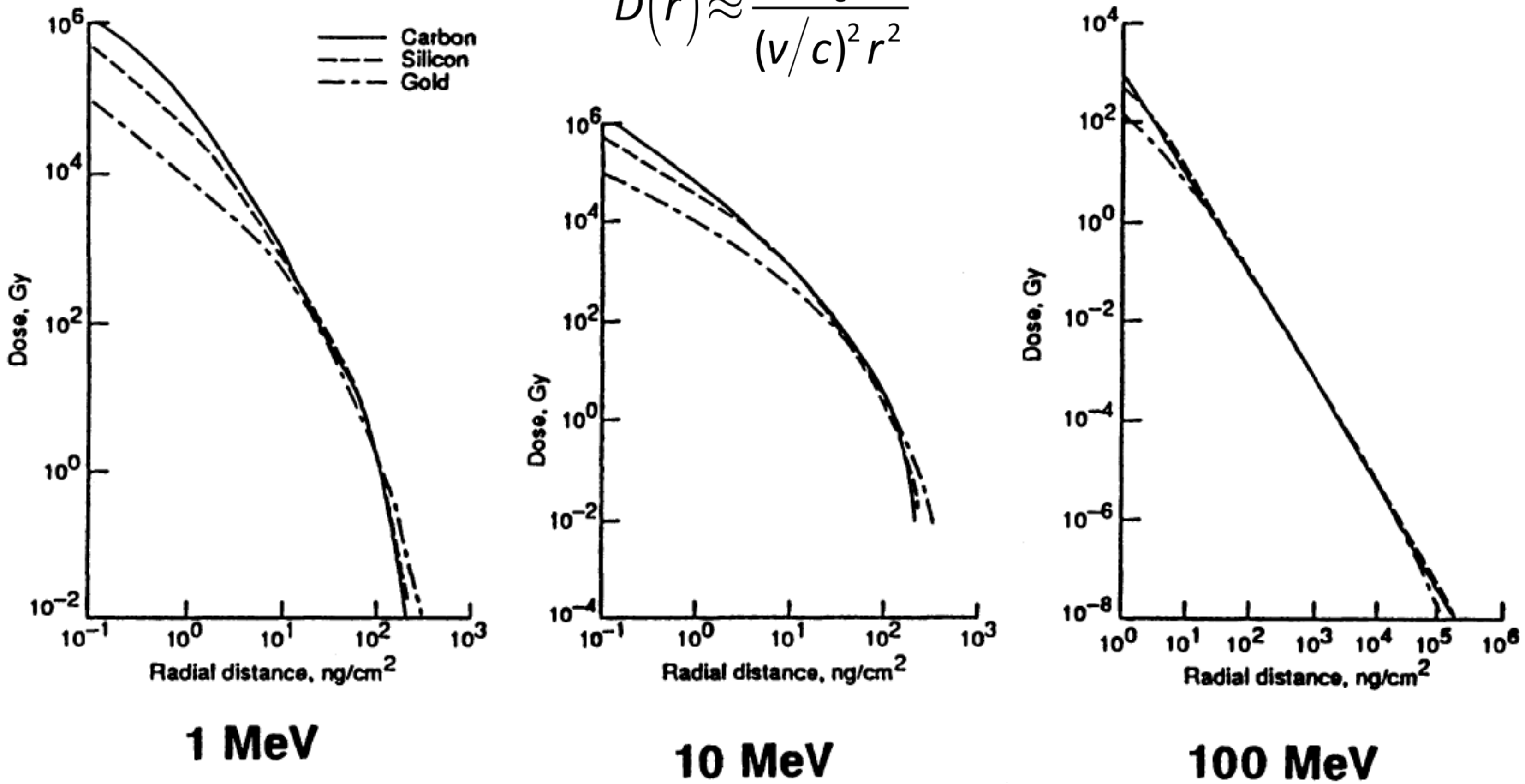
- Observed effects are attributed to the interaction of secondary electrons with the medium (physical, chemical or biological systems)
  - Spatial distribution of energy deposited by secondary electrons around ion path ("track structure")
  - Gamma-ray dose-response curves as basis for understanding of particle tracks

- Variables describing the incident particle and the medium are not separable
  - Problem in assigning a quality factor to radiation

- Cells are represented by measured parameters, from which their response to a particular radiation environment may be calculated

Track Structure Theory

$$D(r) \approx \frac{Z_e^2}{(v/c)^2 r^2}$$



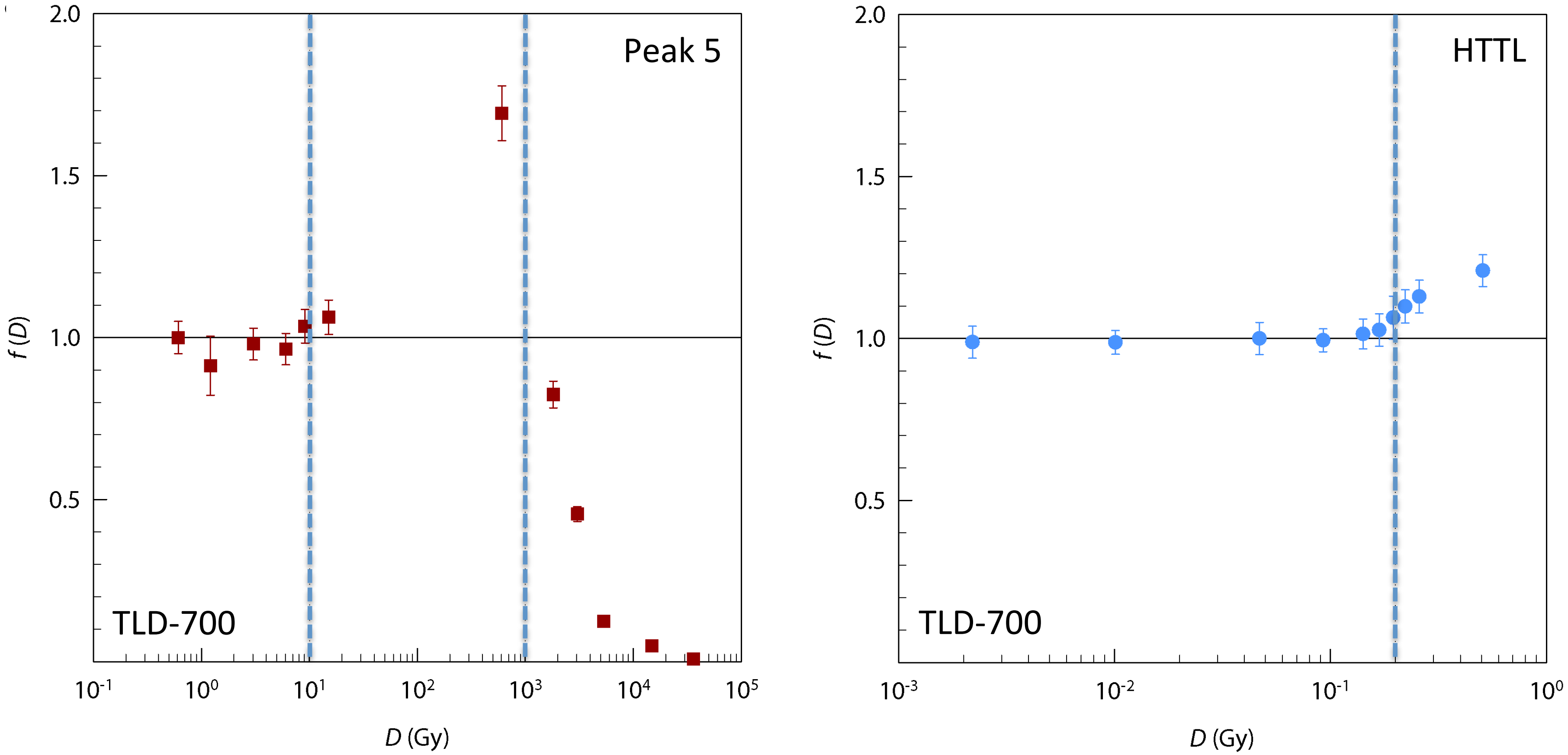
R. Katz *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **107**, 287 (1996).

Multi-Target, Multi-Hit Models

- Originally proposed to explain inactivation of microorganisms, adapted to describe TL dose response and efficiency

- TL detector or biological system contains numerous independent structures ("targets")
  - Each target can respond upon an energy deposit ("hit") and tolerate $m-1$ hits without being affected; m or more hits lead to response (TL emission, cell inactivation, …)
  - Target size can be varied as free parameter

TL Gamma-Ray Dose Response of LiF:Mg,Ti



T. Berger, M. Hajek, *Radiat. Meas.* **43**, 1467 (2008).

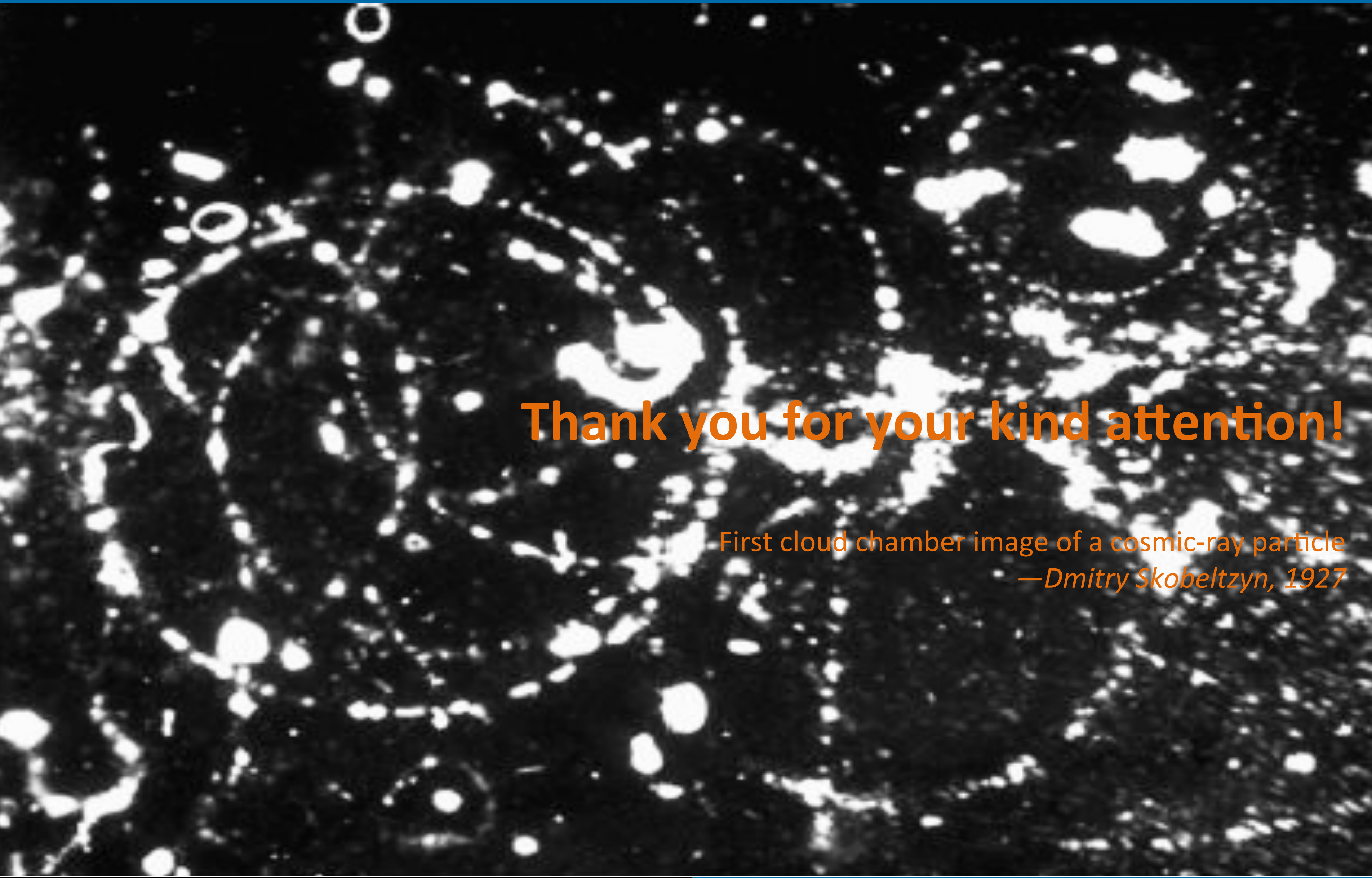
Interpretation of Experimental Evidence

- Linear gamma-ray dose response
  - "One-hit" response due to single energy deposit
  - Single-strand break in DNA; TL response at lower doses
  - Target size was estimated to be ≈ 10 nm
- Supralinear gamma-ray dose response
  - "Two-hit" response due to double energy deposit
  - Double-strand breaks in DNA; TL response at higher doses
  - Preferential occurrence of "two-hit" events as probability of multiple ionizations increases at high LET
  - Target size was estimated to be ≈ 40 nm
- General description through combination of "one-hit" and "two-hit" response

  $f(D) = a.D + b.D^2$

Outlook

- Availability of bioequivalent dosimeters would …
  - represent a major progress in radiation protection, radiation biophysics and medical radiation physics
  - allow evaluating the biological effectiveness of radiations of different quality, largely independent of dose and dose rate
  - directly support the development of new radiation protection concepts
  - concern a broad spectrum of applications ranging from environmental physics, medical diagnosis and therapy to human space exploration



Thank you for your kind attention!

First cloud chamber image of a cosmic-ray particle
—Dmitry Skobeltzyn, 1927