

ADVANCES IN RADIATION RESEARCH

J.F. DUPLAN and A. CHAPIRO, Editors

BIOLOGY AND MEDICINE

Volume I

Volume II

Volume III

PHYSICS AND CHEMISTRY

Volume I

Volume II

# Advances in Radiation Research

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PHYSICS AND CHEMISTRY

Editors

J.F. DUPLAN and A. CHAPIRO

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# CONTENTS

## VOLUME I

### CHAPTER 1

#### Preface

A. CHAPIRO . . . . . xi

#### The International Commission on Radiation Units & Measurements (ICRU) and its relation to radiation research

H.H. ROSSI . . . . . 1

#### Energy transfer from charged particles

J.W. BOAG . . . . . 9

#### Role of radiation-produced intermediates in utilization of energy

J.L. MAGEE and A. MOZUMDER . . . . . 15

#### Energy deposition by fast electrons in small regions of matter

D. HARDER . . . . . 25

#### Track structure in photographic emulsion

P.H. FOWLER . . . . . 39

#### Critical levels of energy degradation

A. KELLERER . . . . . 53

#### Comparison of photoabsorption and resonance energy transfer processes

C.E. KLOTS . . . . . 61

#### Energy transfer effects in aromatic liquids

R.B. CUNDALL and G.B. EVANS . . . . . 69

#### Excitation energy transfer in Dye-polyanion complexes

R.B. CUNDALL, C. LEWIS, P.J. LLEWELLYN and G.O. PHILLIPS . . . 79

#### Radiolytic energy transfer induced by rare gases

L. KEVAN . . . . . 89

#### Energy transport and protection in carbohydrate systems following $\gamma$ -irradiation

G.O. PHILLIPS, J.S. MOORE and D. RHYS . . . . . 123

## CHAPTER 2

Interaction of low-energy electrons with molecules A. KUPPERMANN . . . . .	133
Long-lived parent negative ions formed by capture of low-energy electrons (0 to 3 eV) in the field of the ground and excited electronic states of organic molecules L.G. CHRISTOPHOROU, J.C. CARTER, E.L. CHANEY and P.M. COLLINS . . . . .	145
Irradiation d'hydrocarbures gazeux par des electrons de faibles energie J. DANON, R. DERAÏ and J. MILHAUD . . . . .	159
Free radicals formed in gaseous phase by low energy electrons: Neopentane, Isobutane, Isobutene R. MARX, G. MAUCLAIRE and M. WALLART . . . . .	173
Slow electrons and negative ions in organic liquids A. HUMMEL . . . . .	183
Electron transport in irradiated model chemical and biological systems G.E. ADAMS and R.L. WILLSON . . . . .	199
Intervention d l'oxygene moleculaire singuler dans les processus photobiologiques et radiobiologiques P. DOUZOU . . . . .	217
Some contributions of pulse radiolysis to general chemistry J.H. BAXENDALE . . . . .	229
Pulse radiolysis M.S. MATHESON . . . . .	247
Mathematical analysis of flash photolysis and pulse radiolysis data L.I. GROSSWEINER and . . . . .	261
A Stroboscopic pulse radiolysis system capable of 20 picosecond time resolution J.W. HUNT, M.J. BRONSKILL and R.K. WOLFF . . . . .	271

EPR detection of short-lived free radicals produced by pulsed radiolysis B. SMALLER, J.R. REMKO and E.C. AVERY . . . . .	279
Electrical conductivity in the pulse radiolysis of aqueous solutions K. SCHMIDT . . . . .	285
Special UV techniques in pulse radiolysis. The absorption spectra of D and OD S.O. NIELSEN, P. PAGESBERG, H. CHRISTENSEN and G. NILSSON . . . . .	297
Laser photolysis J.K. THOMAS . . . . .	303
Ion-molecule reactions J.H. FUTRELL . . . . .	311
Fast reaction methods in chemistry and biology J-M. LHOSTE and J-Ph. RIVET . . . . .	327
Use of photosynthesis flowing methods A.-L. ETIENNE . . . . .	339

VOLUME II

CHAPTER 1

Comparison between the radiolysis of gases and that of the condensed phases G.R. FREEMAN . . . . .	351
New insights into primary mechanisms of gas phase radiolysis by yield measurements at high dose rates C. WILLIS and A.W. BOYD . . . . .	361
Pulse radiolysis: formation of the N <sub>3</sub> -radical in gaseous nitrogen mixtures D. PERNER, M.W. BOSNALI, J.W. DREYER and L. SÜTTERLIN . . . . .	369
A comparison of radiolytic and photolytic systems P. AUSLOOS . . . . .	377

Etude des ions metastables dans le spectre de masse des éthylènes deutérés I. BAUMEL, R. HAGEMMAN and R. BOTTER . . . . .	393
Unimolecular decomposition of excited ions Ch. OTTINGER . . . . .	405
Electron-ion neutralization in the radiolysis of gases L.P. THEARD . . . . .	419
CHAPTER 2	
Nonhomogeneous kinetics of ionic reactions in organic liquids G.R. FREEMAN . . . . .	431
Solvated electrons and ions in organic systems L.B. MAGNUSSON, J.T. RICHARDS and J.K. THOMAS . . . . .	441
Pulse optical and electrical methods in investigating certain radiation-induced ionic reactions N. BACH, A. REVINA and A. VANNIKOV . . . . .	449
Ionic reactions in $\gamma$ -irradiated cyclohexane J. KROH, S. KAROLCZAK and H. ZEGOTA . . . . .	459
Spectroscopic studies of anion-radicals in $\gamma$ -irradiated frozen solutions T. SHIDA . . . . .	469
Application de la méthode de thermoluminescence à l'étude d'espèces ioniques dans les solides organiques irradiés A. DEROLEDE, F. KIEFFER, C. MEYER and J. RIGAUT . . . . .	483
Charge neutralization and scavenging in irradiated condensed media A. MOZUMDER . . . . .	493
Kinetics of exciton interactions in molecular crystals M. POPE . . . . .	501
Free radicals in irradiated naphthalene single crystals N. ITOH, T. CHONG and T. OKUBO . . . . .	507

A discussion of charge carrier generation and scintillation yields in anthracene crystals under electron or particle bombardment	
M. SCHOTT . . . . .	515
Excitation of fluorescence of anthracene by low energy electrons	
E.L. FRANKEVICH and I. KULES . . . . .	525
Radiothermoluminescence kinetics for amorphous organic solids	
V.G. NIKOL'SKII and V.A. TOCHIN . . . . .	535
Scintillation efficiency assessment of radiation damage in plastic media	
R. HARDWICK and V. SCHWARTZENBACH . . . . .	547
Ionic processes in irradiated organic glasses	
H. YOSHIDA, M. IRIE and K. HAYASHI . . . . .	555
CHAPTER 3	
Introduction to industrial applications	
C. ROSSI . . . . .	567
Tri-dimensional network formation in elastomers under irradiation	
A.S. KUZMINSKII . . . . .	571
Ennoblement des textiles par le greffage radiochimique	
G.Y. GAUSSENS . . . . .	589
Perm-selective membranes obtained by radiation grafting: a promising tool for industrial application	
S. MUNARI . . . . .	599
Cost analysis and economics of electron radiation in industrial chemical processes	
P.J.C.A. SIMONIS . . . . .	623
Progress and prospects in Physics and Chemistry	
J.W. BOAG . . . . .	633

## CRITICAL LEVELS OF ENERGY DEGRADATION

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The term ionization is so readily employed in theoretical radiobiology that it has occasionally become a synonym for critical event in the primary stage of radiation action. In practical dosimetry and in its recent branch microdosimetry ionization is the basis of most measurements. Yet one must be aware that the notion of an ionization applied to a condensed medium is vague as there are no sharp criteria separating atomic, molecular, and unbound states of the electrons.

It is paradoxical that one of the most widely used terms in radiobiology should also be one of the most ill-defined, and it seems therefore appropriate to ask how far the nature of the critical primary events influences the proper definitions of radiation quantities, and how far it determines the direction which microdosimetric research has to take in the future.

It will be pointed out here that the existing looseness in the fundamental definitions, specifically in that of absorbed dose, represents no practical disadvantage. On the other hand it will be noted that the critical levels of energy degradation have to be well defined if one deals with spatial distributions of energy deposition in volumes smaller than 100 Å. Present techniques based on ionization measurements are severely limited by this fact. There is, however, reason to assume that the microdosimetry data most relevant to radiobiological studies are those for regions



of the order of magnitude of  $1 \mu$ . These data are valid regardless of the nature of the critical events.

### 1. THE AMBIGUITY IN THE DEFINITION OF ABSORBED DOSE

Interaction of radiation and matter is a succession of steps of energy transformation and degradation. In a rough simplification one may distinguish three pools of energy:

- 1 Rest mass
- 2 Kinetic energy of ionizing particles (charged and uncharged)
- 3 Energy of chemical bonds and thermal energy

ICRU [1] defines absorbed dose as the flow from 1 and 2 to 3 per unit mass. The definition is somewhat loose in so far as the term 'ionizing' is not specified. Electrons with kinetic energy between 1 eV and 100 eV contribute appreciably to the fluence,  $\Phi$ , and even to the energy fluence,  $\Psi$ , of any degradation spectrum of ionizing radiation. Yet it is not stated, down to exactly what energy this fluence has to be included in 2. One must therefore ask how this uncertainty affects the definition of absorbed dose.

For such a consideration it is useful to formulate the definition of absorbed dose in the rigorous manner proposed by Rossi and Roesch [5]:

$$D = \frac{-\nabla \cdot \vec{\Psi} + Q}{\rho} \quad (1)$$

where the vectorial energy fluence,  $\vec{\Psi}$ , is the vectorial integral over the angular distribution,  $\Psi_{\Omega}$ , of energy fluence:

$$\vec{\Psi} = \int \Psi_{\Omega} \vec{\Omega} d\Omega, \quad (2)$$

and  $Q$  is the net energy transformed per unit volume from rest mass into other forms of energy.

equation (1) defines a quantity which in many practical cases is equal to Kerma.

Though the sum remains equal and the mean value of  $D$  over a certain volume remains unchanged, exclusion of a certain part of the fluence spectrum can lead to distortions of the dose profile in a strongly inhomogeneous field. The effect is significant only if the fluence varies appreciably over distances comparable to the range of the particles which are excluded. If this is the case choice of a higher cut-off always leads to somewhat steeper dose profiles. This corresponds to the fact that Kerma inhomogeneities exceed those of absorbed dose.

## 2. SPATIAL DISTRIBUTION OF DEGRADATION EVENTS

If one is concerned with regions large enough that each traversing particle produces numerous collisions in this region then it matters little which events of energy degradation are considered as critical. In a first approximation the yields,  $k$ , of various radiation products per rad in the region of interest can be assumed to be independent of the energy of the primary particle. If one knows the microdosimetric probability distribution,  $f(z)$ , of specific energy,  $z$ , in a certain region one can therefore compute the probability distribution,  $p(v)$ , of the number of critical events according to the  $k$  value in question:

$$p(v) = \int_0^{\infty} e^{-kz} \frac{(kz)^v}{v!} f(z) dz \quad (3)$$

The relative variance of  $z$  usually exceeds that of the Poissonian terms by far whenever  $\bar{v} > 1$ . Direct equality of the two distributions is then a good approximation:

$$p(v) = f(z)/k, \quad v = kz \quad (4)$$

Eqs. (3) and (4) are important because it is often erroneously assumed that the applicability of microdosimetric distributions depends on the condition that ionizations are the relevant 'activation events'.

From this relation one can readily see that  $D$  is very insensitive to the choice of the limit of kinetic energy below which particles are not counted in  $\Psi$ . The low-energy part of the degradation spectrum is always the most isotropic one, because low energy delta-rays are emitted nearly isotropically and because particles near the end of their track become isotropic due to repeated angular scattering. If a field is isotropic  $\vec{\Psi}$  is zero even if  $\Psi$  is large. Thus the contribution of the low energy part of the spectrum to  $\nabla \cdot \vec{\Psi}$  is negligible even if the condition for equilibrium ( $\nabla \Psi_E = 0$ ) is not fulfilled. One can therefore state that in equation (1) one may choose any arbitrary cut-off energy in the order of magnitude of the binding energies of the outer-shell electrons.

This answers the question as far as absorbed dose is concerned. A somewhat more detailed consideration is, however, useful because it will show that in the definition of microdosimetric functions a classification of the ultimate steps of energy degradation can be crucial.

Consider a proton track as schematized in Fig. 1a. The proton is released through the impact of a neutron (broken line). The branches along the proton track are delta-rays. Each dot on the proton track and on the electron tracks is an energy degradation step in an electronic collision. Branching points represent 'ionizations', the other points excitations in which no secondary charged particle is liberated. The term  $\nabla \cdot \Psi / \rho$  is made up of the differences,  $\epsilon$ , of the kinetic energy of the particle entering and the particle(s) leaving each point.  $\epsilon$  represents that portion of the energy which flows from pool 2 into 3 in inelastic collisions.

If one excludes particles below a certain energy, the diagram is modified as indicated in Fig. 1b and c. The two cases represent exclusion of electrons below 100 eV and complete exclusion of electrons. The sum of all differences,  $\epsilon$ , is not changed because the values  $\epsilon$  are increased in those points which are marked by a circle. If one goes a step further and excludes all charged particles,

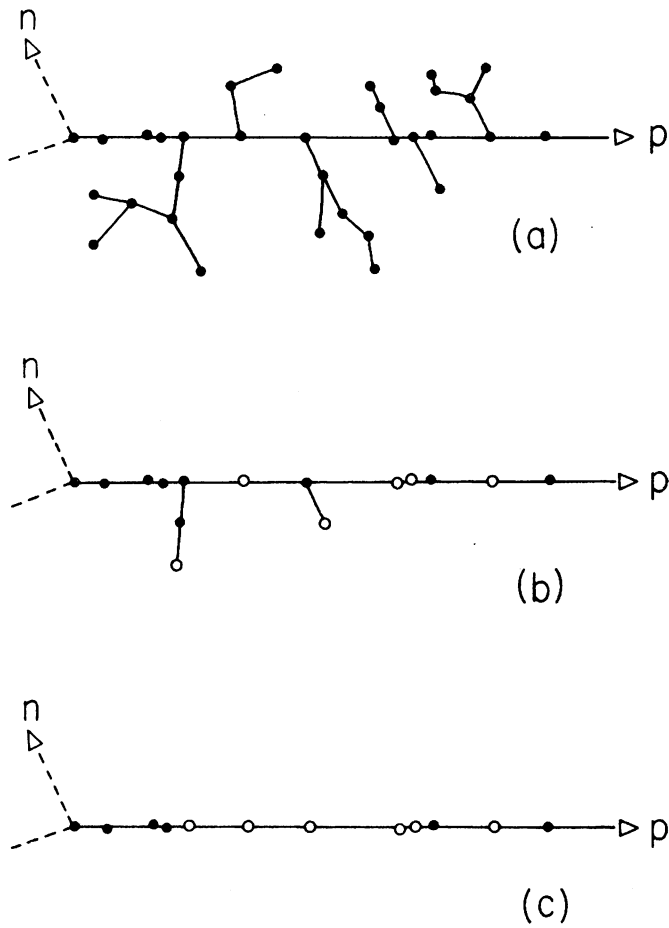


Fig. 1. Schematic representation of a segment of a proton track ( $\sim 2\text{MeV}$ ) and the contribution to the term  $\nabla \bar{\psi}/\rho$ .

The equivalence is, however, limited to regions large as compared to the distances spanned in the degradation process from energies of the order of magnitudes of outer-shell binding energies down to thermal energies. This implies a much more serious limitation of the use of proportional counters than the fact that such counters respond only to ionizations. From experiments with UV light it is apparent that excitations are much less efficient than ionizations, and ionization in gas is in so far a sound basis of microdosimetric measurements. The spatial shift in the degradation process is, however, a serious obstacle in dealing with very small regions. Fig. 2 illustrates the point; the example of a proton track is used again. Excitations are not considered. In scheme a) positive ions are marked as dots. One may assume that in many cases, specifically in dry systems, the positive ions are the focal points of the reaction chain which leads to the primary lesions. A proportional counter, or any other electron-collecting device, does, however, not respond to the pattern represented in Fig. 2a. Instead it collects the electrons after they are thermalized. The typical thermalization distances for electrons are of the order of magnitude of 100 Å. This means that the counter responds to the pattern of thermalized or nearly thermalized electrons schematically represented in Fig. 2b. The pattern is clearly distinct from that of the positive ions. The main effect is one of decreased local concentrations. If, for example, one determines 'associated volumes' (see Lea [2]) for radii below 100 Å, the values derived with electron collecting devices must significantly exceed those derived with a device which collects positive ions. It is important to note that this is not a discrepancy due to diffusion of the electrons in the collecting process. The critical step is the thermalization process. One must conclude that microdosimetric experiments on extremely small volumes have to be based on the counting of positive ions.

It should, however, be mentioned that a recent analysis of various RBE data on the basis of ideas

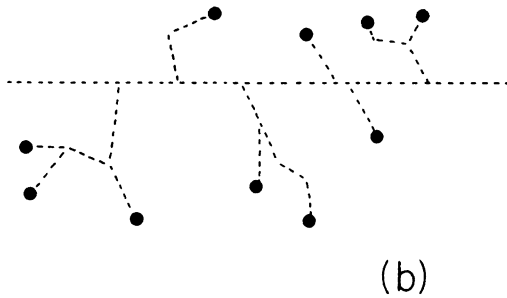
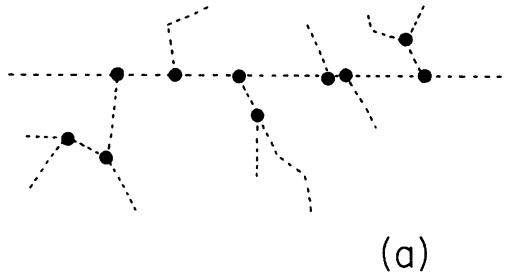


Fig. 2. Schematic representation of the spatial pattern of positive ions (a) and of thermalized electrons (b) around a proton track.

expressed by Rossi [4] reaffirms the usefulness of existing microdosimetric data for larger volumes. In agreement with conclusion reached earlier [3,6] it appears that the critical primary lesions in the cell are due to two events, each induced by a single electronic collision; these events interact over a distance of about one micrometer [7].

#### SUMMARY

Radiation quantities, as for example absorbed dose, and microdosimetric functions for regions of the order of magnitude of  $1 \mu$  are meaningful without specification of the critical steps of energy degradation. This is not true for microdosimetric quantities related to regions with linear dimensions near or below  $100 \text{ \AA}$ ; the usual techniques of ionization collection are not applicable in this case and measurements have to be based on the collection of positive ions.

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