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Biological Radiation Effects

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本书着重介绍了辐射类型，辐射对DNA的损伤与修复，细胞与亚细胞结构的作用，辐射与物质间的相互作用，辐射化学，辐射防护，临床放射治疗等方面的内容。该书内容新颖取材广泛，理论联系实际适合放射生物学，放射医学，临床放射学及其相关专业的科研工作者参考。

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Preface

The biological action of radiation undoubtedly constitutes an issue of actual concern, particularly after incidences like those in Harrisburg or Chernobyl. These considerations, however, were not the reason for writing this book although it is hoped that it will also be helpful in this respect. The interaction of radiation with biological systems is such an interesting research objective that to my mind no special justification is needed to pursue these problems. The combination of physics, chemistry and biology presents on one hand a fascinating challenge to the student, on the other, it may lead to insights which are not possible if the different subjects remain clearly separated. Special problems of radiation biology have quite often led to new approaches in physics (or *vice versa*), a recent example is "microdosimetry" (chapter 4).

Biological radiation action comprises all levels of biological organization. It starts with the absorption in essential atoms and molecules and ends with the development of cancer and genetic hazards to future generations. The structure of the book reflects this. Beginning with physical and chemical fundamentals, it then turns to a description of chemical and subcellular systems. Cellular effects form a large part since they are the basis for understanding all further responses. Reactions of the whole organism, concentrating on mammals and especially humans, are subsequently treated. The book concludes with a short discussion of problems in radiation protection and the application of radiation in medical therapy. These last points are necessarily short and somewhat superficial. They are only planned to illustrate the practical aspects of the topic.

The questions and problems of biological radiation action are pursued by very many groups all over the world. The field is so vast that it seems rather presumptuous of a single author to cover it in a one-volume book. I am fully aware of these difficulties but the reason for attempting it nevertheless was prompted by the wish of many people – particularly university students – to have a short introduction to the subject. The book has been built on lectures which I have given over the years. This is reflected in the general approach: comprehensiveness is neither intended nor is it possible within the framework given. The manuscript does not pretend to be a "textbook" where everything may be found, important aspects are dealt with in a rather exemplary manner. The selection must be subjective and certainly guided by my one field of interest. It is hoped that nevertheless the number of serious omissions is not too high. It should also be said that the author is a physicist by training – although with a burning affection to biology. This very fact may, at places, have led to more mathematics than felt digestible by some readers. I tried, however, always to demonstrate how a certain result is obtained rather than just giving only the final expression. This caused an enlargement of the number of pages and too many formulae. The non-physicist should not be deterred by this because, even if it does not appear so at first sight, the mathematics is in fact not very complicated. Radiation biology is a special branch of quantitative biology, and this cannot exist without mathematics.

The interaction of radiation and biological systems is as old as life itself, it most certainly played an important role in the evolution of self-organizing structures. This aspect could not be covered here. The role of radiation for further evolution is also not negligible, the close similarity between the absorption spectra of ozone and DNA does not seem merely fortuitous.

I have tried to describe the present state of knowledge in an exemplary manner, sometimes superficially of necessity not just to limit the size of the volume. Historical aspects are more or less completely ignored. Although unavoidable within the given scope, this omission is regrettable since biology as a whole has received from radiation biology a number of important findings which reach far beyond this subdiscipline. Examples are the action spectrum for mutation induction which demonstrated the importance of nucleic acids as carriers of genetic information long before it was proven biochemically. The discovery and elucidation of repair processes and their relevance to human health has also to be mentioned in this context. The history of radiation biology has still to be written – it would make fascinating reading.

The bibliography had to be short, it is restricted mostly to review papers which may serve as starting points for further reading. The original sources are found in the figure legends which thus have an additional purpose. I hope that in this way the readability is retained, the volume limited without neglecting to give credit to the original authors.

There is a long way from the inception of the idea to write a book until its final completion. Quite often the author feels the "loneliness of the long-distance runner" and the pressing desire to give up. I owe a lot of thanks to my family and many colleagues and coworkers for efficient coaching on this long path. This was already the case when the first edition which appeared 1981 in German was prepared but even more so with this English version. It grew out of the German book but it is not just a translation but has been amended and extended in many places. The reader is kindly asked to be merciful to the author whose native language is not English. I thank the publisher SPRINGER for all kinds of support – not just with improving the language. My coworker Michael Kost was very helpful in the final writing of the manuscript and patient in the deciphering of my sometimes obscure handwritten notes. Many students and colleagues gave valuable advice – thanks to them all!

I am sure that in spite of good will and critical proofreading there will still be a number of errors for which I have to take the responsibility. I should be grateful if they were pointed out to me for future corrections.

In closing, I sincerely hope that the book might help to arise interest in our fascinating field and win us new friends within and outside the scientific community.

Giessen, fall 1989 Jürgen Kiefer

Contents

Chapter 1
Types of Radiation: Characterization and Sources

This introductory chapter gives a description of the different types of radiation and briefly outlines the means of their production. Spectral distributions are explained and discussed. A final paragraph deals with the fundamentals of radioactivity.

1.1 Types of Radiation

Radiation is the transport of energy without the necessary intervention of a transporting medium. This may be accomplished either by electromagnetic waves or by particles, e.g. electrons, neutrons or ions.

According to PLANCK and EINSTEIN, the energy transfer by electromagnetic waves can also be described by discrete processes involving elementary units called "photons" or "quanta".

Their energy E is given by:

$$E = h \cdot \nu \tag{1.1}$$

where h is PLANCK's constant and ν the frequency.

Since velocity c, wavelength λ and frequency ν are related as:

$$c = \lambda \cdot \nu$$

this also means that:

$$E = \frac{hc}{\lambda}$$

A sometimes convenient unit for the number of quanta is the "EINSTEIN" (often used in photochemistry) which is the number of quanta in multiples of AVOGADRO's number.

Figure 1.1 gives a survey of relations for parts of the total spectrum of electromagnetic waves. Apart from γ and X rays, ultraviolet radiation will be of particular importance in this book. Its lower wavelength limit is not clearly defined; for most practical purposes it may be set at $\lambda = 200\,\text{nm}$.

Further subdivisions are customary:

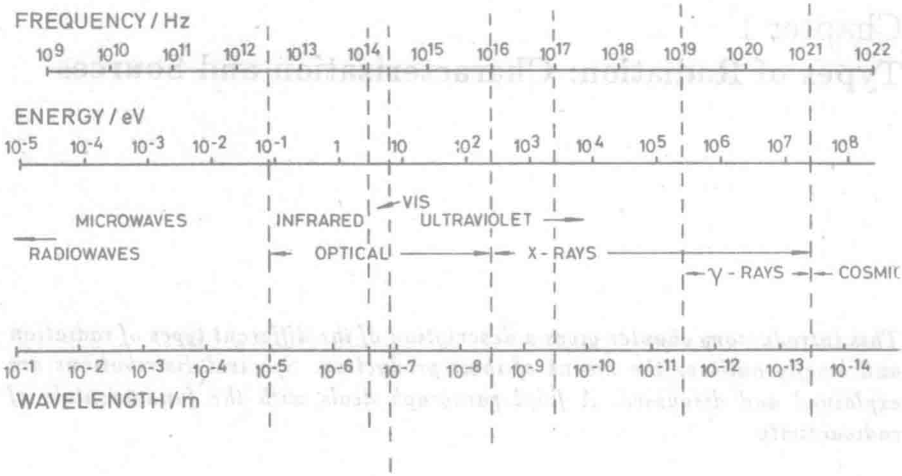

Figure 1.1. The spectrum of electromagnetic waves

far UV: 200–300 nm
near UV: 300–380 nm

or (often used in medicine and biology):

UV A: 315–380 nm
UV B: 280–315 nm
UV C: 200–280 nm

Ionizing corpusculate radiation may consist of charged or uncharged particles. Nuclear physics knows a great variety of such particles, but for radiation biology only a few are important. Table 1.1 lists some examples and their main properties.

Table 1.1. Properties of particles. (After WACHSMANN and DREXLER, 1976)

name	symbol	rest mass m_0 10^{-27} kg	rest mass m_0/m_{e0} [a)]	charge	rest energy MeV	half life /s
photon	γ		0	0	0	∞
neutrino, antineutrino	ν,ν		0	0	0	∞
electron	e^-, β^-	$9.1\cdot10^{-4}$	1	−1	0.511	∞
positron	e^+, β^+	$9.1\cdot10^{-4}$	1	+1	0.511	∞
π-meson	π^-, π^+	0.2489	273.2	−1,+1	139.6	$18\cdot10^{-9}$
proton	p^+	1.6725	1836.1	+1	938.26	∞
neutron	n	1.6748	1838.6	0	939.55	700
deuteron	d	3.3443	3675.1	+1	1875.5	∞
α-particle	α	6.6440	7301.1	+2	3727.2	∞

a) m_{e0}: electron rest mass

The total energy of a particle is the sum of its rest energy E_0 (see below) and its kinetic energy T. The latter is related to the mass m and the velocity v by the well known expression:

$$T = \frac{m}{2}v^2 \tag{1.2}$$

which holds as long as v is very much smaller than c, the velocity of light in vacuo. Therefore, v is often measured in units relative to c, the dimensionless quantity is normally called β:

$$\beta = \frac{v}{c} = \frac{1}{c}\sqrt{\frac{2T}{m}} \quad (v \ll c) \tag{1.3}$$

The following relation is also practical if T is measured in MeV and m in atomic mass units u:

$$\beta = 4.63 \cdot 10^{-2}\sqrt{\frac{T/\mathrm{MeV}}{m/u}} \tag{1.3a}$$

Since the velocity is often the important parameter, which is proportional to the ratio of kinetic energy/mass, sometimes – particularly with accelerated ions – the "specific particle energy", i.e. T/m, is given, usually in MeV/u.

Another quantity is the momentum p:

$$p = m \cdot v \tag{1.4}$$

which is related to the kinetic energy by:

$$T = \frac{mv^2}{2} = \frac{p^2}{2m} \quad . \tag{1.5}$$

All expressions given so far are only applicable in "non-relativistic" cases, i.e. where $v \ll c$. If this condition is no longer fulfilled, one has to take into account that the mass is no longer constant but increases with velocity:

$$m = \frac{m_0}{\sqrt{1-\beta^2}} \tag{1.6}$$

where m_0 is the "rest mass". For a free particle, the total energy E is now given by the sum of "rest energy" E_0 and kinetic energy T. According to EINSTEIN's famous equation:

$$E_0 = m_0c^2 \tag{1.7}$$

$$E = T + E_0 \tag{1.8}$$

and

$$E = mc^2 = \frac{m_0c^2}{\sqrt{1-\beta^2}} \tag{1.9}$$

so that

$$T = \frac{m_0c^2}{\sqrt{1-\beta^2}} - m_0c^2 \quad . \tag{1.10}$$

The momentum is then:

$$p = mv = \frac{m_0 v}{\sqrt{1-\beta^2}} \quad . \tag{1.11}$$

Total energy and momentum are related in the following way:

$$E^2 = p^2c^2 + m_0c^4 \tag{1.12}$$

This very useful expression can be verified simply by insertion.

For the relative velocity β, in the general case:

$$\beta = \sqrt{1 - \frac{m_0^2 c^4}{E^2}} \tag{1.13}$$

or related to the kinetic energy:

$$\beta = \frac{1 + 2E_0/T}{1 + E_0/T} \quad . \tag{1.14}$$

For practical calculations, when T is measured in MeV and m in atomic mass units (u), the following expression is helpful:

$$\beta = \frac{\sqrt{1 + 1862 \frac{m_0/u}{T/MeV}}}{1 + 931 \frac{m_0/u}{T/MeV}} \tag{1.14a}$$

and for the special case of electrons:

$$\beta = \frac{\sqrt{1 + \frac{1.022}{T/MeV}}}{1 + \frac{0.511}{T/MeV}} \quad . \tag{1.14b}$$

As an example, one may compare electrons and protons with the same kinetic energy of 1 MeV. While the electron travels with 94% of the speed of light, the respective value for the proton is only about 5%.