GRADUATE TEXTS IN PHYS

Claus Grupen

# Introduction to Radiation Protection

## Practical Knowledge for Handling Radioactive Sources

## 辐射保护导论

Springer

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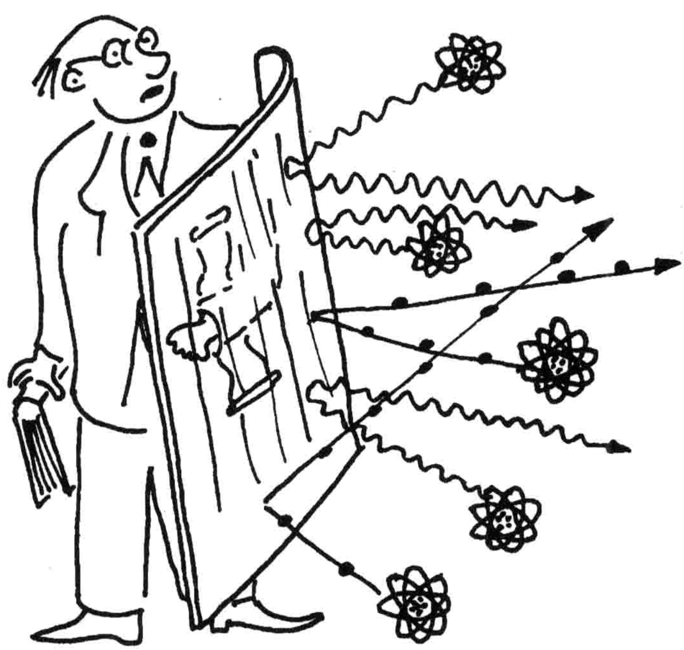
## Disclaimer

This book provides an overview of radiation physics and radiation-protection regulations. It is essentially meant for students and professionals concerned with problems of radiation aspects. We have tried to keep the information correct and up-to-date. However, any reliance on such information is strictly at your own risk. This refers to the availability of the shown commercial products and also to those places where web sites are given. Web addresses can change quite rapidly, but we have made sure that the sites given in the text are available at the time of printing of this book. The referred web sites are not under our control. We have also tried to get written permissions for all products on radiation detection and radiation instruments and other material which is shown in this book. Not in all cases did the companies providing such instruments or information respond to our request for permission to show their products. If material is being described which is not properly or incompletely referred to, we would be grateful to be informed so that we can consider this for future editions of the book.

Claus Grupen



"Radiation Protection"

# Preface

Radiation is everywhere. In this book, we are concerned with ionizing radiation, i.e. radiation that can ionize ordinary atoms. Translated into energies this corresponds to $\alpha$, $\beta$, or $\gamma$ rays with energies larger than, say, 30 eV. Almost everything is radioactive. Radiation emerges from the soil, it is in the air, and our planet is constantly bombarded with energetic cosmic radiation. Even the human body is radioactive: about 9000 decays of unstable nuclei occur per second in the human body. In the early days of the Earth, when our planet was formed from the debris of the proto-solar system, the radiation level was even higher. One can assume that the origin and development of life might have been positively influenced by ionizing radiation.

Since the beginning of the twentieth century, mankind has been able to artificially create radioactive nuclei, in particular, since the discovery of nuclear fission in the late 1930s. As early as 1905, Pierre Curie remarked that radium in the hands of criminals could be a disaster. Also, Louis de Broglie noted in his Nobel lecture in 1927 that he did not know whether science in the hands of humans is a good or a bad thing. The bombing of Hiroshima and Nagasaki in 1945 with nuclear weapons clearly demonstrated the disastrous effect of ionizing radiation. The Nobel laureate for medicine, Sir Maurice Hugh Frederick Wilkins, said contemplatively: "We have now reached the point where it is an open question as to whether doing more science is a good thing". The nuclear accidents near Harrisburg at the Three-Mile-Island reactor (1979), in Chernobyl (1986), and Tokaimura (1999) clearly demonstrated that nuclear fission requires high-quality safety systems.

It is in the nature of humans to try to further the understanding of the world around us. No law will stop people undertaking research which might carry them into new domains and which carries the risk of misusing the new technology. Therefore, it is important to understand the results of research and to explain the benefits and possible risks to everybody who is interested. The benefits of nuclear energy and ionizing radiation are already clearly visible in medical diagnosis and therapy. Successful tumor treatment with particle beams is an example of a remarkable achievement. Also nuclear fusion – the energy source of the stars – will very likely solve the energy problem of mankind in less than a century.

Since one cannot 'see' or 'smell' ionizing radiation, one needs measurement devices which can detect it, and also a scale on which to judge on its possible dangerous effects. This leads to the definition of units for the activity of radioactive nuclei and quantifications for the effect on humans in terms of absorbed energy and biological effectiveness of different types of radiation.

This book originated from a series of lectures that I gave over a period of more than thirty years. The main body of the text was first published in German by Vieweg and in updated later editions by Springer. It included mainly chapters on the units of radiation protection, the necessary ingredients from nuclear and quantum physics, and the interaction of ionizing radiation with matter and radiation detectors. Also environmental radioactivity, X rays, and the biological effects of radiation and radiation accidents were described. The German versions contained chapters on the legal aspects and regulations for safe handling of radioactive material. Since these sections concerning national laws of one country are not of common interest, I have replaced these regulations by describing the European and American perspectives on the legal aspects of the handling of radioactive sources, and on radiation protection at accelerators and in nuclear medicine. Also the main outlines of radiation-protection regulations from some other countries are included. I have added two chapters on nuclear power plants and radiation sources, not present in the original German version. Since all of us are living in electromagnetic radiation fields from all kinds of sources, I have also added a short chapter on the effects of non-ionizing radiation.

Radiation protection concerns, among others, physicists, engineers, lawyers, and health-care professionals. The phenomena of radioactivity and their effects on matter are most elegantly described by the language of mathematics. I have added, therefore, a small mathematical appendix for those who want to refresh their knowledge of basic calculus, logarithms, and exponentials.

This work was only possible with the help of colleagues who contributed to the completion of the book. Ms. Ute Smolik typed the first version of this translation from my tape recordings. My 'Germanic' English benefitted significantly from the linguistic improvement and polishing by the native speakers Mark Rodgers, M. Sci., and Dr. Matthew Beckingham who worked in our group in Siegen. Dr. Ulrich Werthenbach made valuable contributions to the description of the detection of radioactivity and practical measurement devices, and Dr. Tilo Stroh proofread everything and took over the very important job of typesetting the text in LaTeX and optimizing the figure layout. He also checked all the problems and the appendices, and he created the table of isotopes. In particular we would like to thank the Project Manager Asher Ebenezer of the Integra Software Services in Puducherry, India for their excellent work and cooperation during the production of the book. Thank you all!

Claus Grupen, Siegen, January 2010

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With cartoons by N. Downes, C. Grupen (partly inspired by my son Cornelius), L. Murchetz, V. Renčín, J. Wolter; copyright by the cartoonists.

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Introduction to Radiation Protection
by Claus Grupen

# Contents

# 1 Introduction

*"All problems are finally scientific problems."*
*G. B. Shaw 1856–1950*

Life on Earth has developed under permanent exposure to radiation. In addition to ionizing radiation from natural sources a multitude of exposures from artificial sources produced by mankind came into play in the twentieth century. These radioactive sources have been introduced and used in the course of the rapid development of medical diagnostics and therapy and natural science and technology.

Humans have no senses for ionizing radiation. Therefore, possible risks related to ionizing radiation were often underestimated. Even today it happens quite frequently that strong radioactive sources, which had been used in medicine or technology and disposed off illegally as scrap metal are 'found', for example, by children. Since no particular danger appears to originate from such sources, they are sometimes handled by the children and even stored in their homes. Considering the strength of radioactive sources used in medicine and technology, the irradiation from these sources over a period of several days can easily lead to radiation sickness and even death.

**Figure 1.1**
Portrait of
Henri Antoine Becquerel
(Drawing: C. Grupen)

To judge correctly the potential danger caused by radioactive sources, one has to develop a feeling for the biological effects of ionizing radiation. It is impossible to eliminate radiation exposure altogether. This relates to the fact that one cannot possibly avoid natural radioactivity from the environment. Therefore, additional exposures have to be compared and judged with respect to the natural radiation exposure. To estimate the potential risk from radiation from the environment and from other sources, a minimum knowledge about physics, chemistry, and biology is required which will replace in some sense the missing senses for radioactivity.

**Figure 1.2**
Portrait of
Wilhelm Conrad Röntgen
(Drawing: C. Grupen)

**1896**
**discovery of radioactivity by Henri Antoine Becquerel**

Radioactivity was discovered by Henri Antoine Becquerel in 1896, when he realized that radiation emerging from uranium ores could blacken photosensitive paper. Originally it was believed that this was due to some fluorescence radiation from uranium salts. However, the photosensitive paper was also blackened without previous exposure of the uranium ore to light. The radiation spontaneously emerging from uranium was not visible to the human

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eye. Therefore, it was clear that one was dealing with a new phenomenon.

**1895**
**discovery of X rays by Wilhelm Conrad Röntgen**

In the context of radiation protection also the discovery of X rays by Wilhelm Conrad Röntgen has to be mentioned. This radiation emerged from materials after bombardment with energetic electrons. Actually the discovery by Röntgen in December 1895 had been a factor of stimulating Becquerel to investigate fluorescence radiation from uranium salts.

**discovery of polonium and radium**

The new research field of radioactivity became particularly important when Marie and Pierre Curie in 1898 succeeded in isolating new radioactive elements (polonium and radium) from pitchblende. Marie Curie was awarded with two Nobel Prizes for her research (1903 Henri Becquerel, Pierre Curie, Marie Curie: Physics Nobel Prize for the discovery and research on radioactivity; 1911 Marie Curie: Nobel Prize for Chemistry for the discovery of the elements polonium and radium by chemical separation techniques from pitchblende).

**$\alpha, \beta, \gamma$ rays**

At the turn of the century (1899–1902) the investigation by Ernest Rutherford clearly demonstrated that there are different types of ionizing radiation. Since initially it was impossible to identify these different types, they were named after the first letters of the Greek alphabet $\alpha$, $\beta$, and $\gamma$ rays. It could be shown that $\alpha$ and $\beta$ rays could be deflected by magnetic fields, in contrast to $\gamma$ rays.

**artificial radioactivity**
**nuclear fission**

This radioactivity was a phenomenon of the natural environment. Nobody was able to turn inactive materials into radioactive sources by chemical techniques. Not until 1934 Frederic Joliot and Irène Curie managed to produce new radioactive materials artificially using nuclear physics methods. Only a few years later Otto Hahn and Fritz Straßmann (1938/39) succeeded in inducing fission of uranium nuclei. The intention of Hahn and Straßmann was to produce elements beyond this heaviest naturally occurring element by neutron bombardment. The particular importance of fission was recognized by Lise Meitner and Otto Frisch.

**transuranic elements**

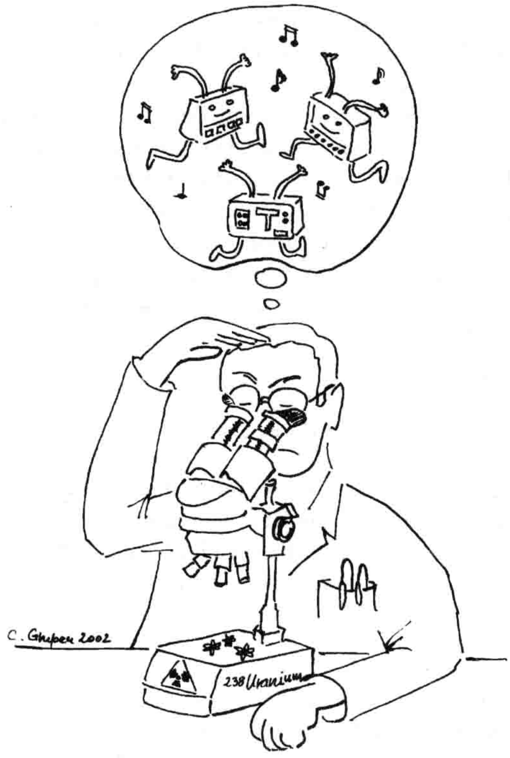
Since then physicists have been trying to produce artificially superheavy elements beyond uranium ('transuranic elements') which do not occur in nature. Most of these elements are highly radioactive. This group also includes the chemically toxic plutonium and americium. Up to now 26 elements which do not occur in the natural environment have been artificially synthesized.

**effects of ionizing radiation**

The importance of radioactivity and of radiation protection for mankind and the environment is quite substantial. The judgment on the effects of ionizing radiation on humans should not be left only to so-called experts. Everybody who is prepared to get involved in these problems should be in a position to come to his own judgment.

It is highly desirable that, for example, discussions on the benefits and risks of nuclear power are not dominated by emotional antipathy or blind support, but rather by solid facts about radiation and radiation-related effects.

The intention of this book is to introduce the reader into the physical, technical, medical, and legal aspects of radiation. At the same time this book will hopefully contribute to the readers' understanding of the necessary scientific issues, allowing, for example, discussions on nuclear energy with higher objectivity.




Dr. Linkenstein was baffled when he found 'radio-activity' had a literal meaning.

# 2 Units of Radiation Protection

*"All composed things tend to decay."*
*Buddha 563–483 B. C.*

A large number of units has been proposed and used in the course of historical development and research in the field of radioactivity. Only those which have survived to today shall be used and defined here. I will introduce the modern units which are recommended by the International Commission on Radiological Protection (ICRP). In addition, I will also mention those units which are still in use in countries like in the USA, and give the relations to the ICRP-recommended units used in Europe and elsewhere.

**1 becquerel (Bq) = 1 decay per second**

**1 curie (Ci) = 3.7 x $10^{10}$ Bq**

The unit of activity is becquerel (Bq). 1 Bq is one decay per second. The old unit curie (Ci) corresponds to the activity of 1 g of radium-226:[1]

$$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}\ ,$$
$$1\,\mathrm{Bq} = 27 \times 10^{-12}\,\mathrm{Ci} = 27\,\mathrm{pCi}\ . \tag{2.1}$$

In radioactive decays the number of decaying nuclei $\Delta N$ is proportional to the number of existing nuclei $N$ and the observation time $\Delta t$. The number of nuclei decreases by decay. This fact gives the negative sign for $\Delta N$. Therefore, one has

$$\Delta N \sim -N\,\Delta t\ . \tag{2.2}$$

Since the decay rate changes in time it makes sense to use very small, indeed infinitesimal times $\mathrm{d}t$ and numbers $\mathrm{d}N$ (see Appendix Q),

$$\mathrm{d}N \sim -N\,\mathrm{d}t\ . \tag{2.3}$$

**decay constant**

Starting from this relation one obtains the equation by introducing a constant of proportionality, namely, the decay constant $\lambda$,

[1] Because of the frequently occurring very large and very small numbers I will use throughout the notation using powers, e.g. $10^6 = 1\,000\,000$ and $10^{-6} = 0.000\,001$. A word of caution is in order here: A billion is in most parts of the world $10^9$ while in some parts, e.g. in Germany, a billion is $10^{12}$.

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