James E. Turner

Atoms, Radiation, and Radiation Protection

Third, Completely Revised and Enlarged Edition

WILEY-VCH Verlag GmbH & Co. KGaA

James E. Turner

Atoms, Radiation, and Radiation Protection

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To Renate

Contents

13 Chemical and Biological Effects of Radiation 399

14 Radiation-Protection Criteria and Exposure Limits 449

Appendices

Preface to the First Edition

Atoms, Radiation, and Radiation Protection was written from material developed by the author over a number of years of teaching courses in the Oak Ridge Resident Graduate Program of the University of Tennessee's Evening School. The courses dealt with introductory health physics, preparation for the American Board of Health Physics certification examinations, and related specialized subjects such as microdosimetry and the application of Monte Carlo techniques to radiation protection. As the title of the book is meant to imply, atomic and nuclear physics and the interaction of ionizing radiation with matter are central themes. These subjects are presented in their own right at the level of basic physics, and the discussions are developed further into the areas of applied radiation protection. Radiation dosimetry, instrumentation, and external and internal radiation protection are extensively treated. The chemical and biological effects of radiation are not dealt with at length, but are presented in a summary chapter preceding the discussion of radiation-protection criteria and standards. Non-ionizing radiation is not included. The book is written at the senior or beginning graduate level as a text for a one-year course in a curriculum of physics, nuclear engineering, environmental engineering, or an allied discipline. A large number of examples are worked in the text. The traditional units of radiation dosimetry are used in much of the book; SI units are employed in discussing newer subjects, such as ICRP Publications 26 and 30. SI abbreviations are used throughout. With the inclusion of formulas, tables, and specific physical data, *Atoms, Radiation, and Radiation Protection* is also intended as a reference for professionals in radiation protection.

I have tried to include some important material not readily available in textbooks on radiation protection. For example, the description of the electronic structure of isolated atoms, fundamental to understanding so much of radiation physics, is further developed to explain the basic physics of "collective" electron behavior in semiconductors and their special properties as radiation detectors. In another area, under active research today, the details of charged-particle tracks in water are described from the time of the initial physical, energy-depositing events through the subsequent chemical changes that take place within a track. Such concepts are basic for relating the biological effects of radiation to particle-track structure.

I am indebted to my students and a number of colleagues and organizations, who contributed substantially to this book. Many individual contributions are acknowledged in figure captions. In addition, I would like to thank J. H. Corbin and W. N. Drewery of Martin Marietta Energy Systems, Inc.; Joseph D. Eddleman of Pulcir, Inc.; Michael D. Shepherd of Eberline; and Morgan Cox of Victoreen for their interest and help. I am especially indebted to my former teacher, Myron F. Fair, from whom I learned many of the things found in this book in countless discussions since we first met at Vanderbilt University in 1952.

It has been a pleasure to work with the professional staff of Pergamon Press, to whom I express my gratitude for their untiring patience and efforts throughout the production of this volume.

The last, but greatest, thanks are reserved for my wife, Renate, to whom this book is dedicated. She typed the entire manuscript and the correspondence that went with it. Her constant encouragement, support, and work made the book a reality.

Oak Ridge, Tennessee *James E. Turner*
November 20, 1985

Preface to the Second Edition

The second edition of *Atoms, Radiation, and Radiation Protection* has several important new features. SI units are employed throughout, the older units being defined but used sparingly. There are two new chapters. One is on statistics for health physics. It starts with the description of radioactive decay as a Bernoulli process and treats sample counting, propagation of error, limits of detection, type-I and type-II errors, instrument response, and Monte Carlo radiation-transport computations. The other new chapter resulted from the addition of material on environmental radioactivity, particularly concerning radon and radon daughters (not much in vogue when the first edition was prepared in the early 1980s). New material has also been added to several earlier chapters: a derivation of the stopping-power formula for heavy charged particles in the impulse approximation, a more detailed discussion of beta-particle track structure and penetration in matter, and a fuller description of the various interaction coefficients for photons. The chapter on chemical and biological effects of radiation from the first edition has been considerably expanded. New material is also included there, and the earlier topics are generally dealt with in greater depth than before (e.g., the discussion of data on human exposures). The radiation exposure limits from ICRP Publications 60 and 61 and NCRP Report No. 116 are presented and discussed. Annotated bibliographies have been added at the end of each chapter. A number of new worked examples are presented in the text, and additional problems are included at the ends of the chapters. These have been tested in the classroom since the 1986 first edition. Answers are now provided to about half of the problems. In summary, in its new edition, *Atoms, Radiation, and Radiation Protection* has been updated and expanded both in breadth and in depth of coverage. Most of the new material is written at a somewhat more advanced level than the original.

I am very fortunate in having students, colleagues, and teachers who care about the subjects in this book and who have shared their enthusiasm, knowledge, and talents. I would like to thank especially the following persons for help I have received in many ways: James S. Bogard, Wesley E. Bolch, Allen B. Brodsky, Darryl J. Downing, R. J. Michael Fry, Robert N. Hamm, Jerry B. Hunt, Patrick J. Papin, Herwig G. Paretzke, Tony A. Rhea, Robert W. Wood, Harvel A. Wright, and Jacquelyn Yanch. The continuing help and encouragement of my wife, Renate, are gratefully acknowledged. I would also like to thank the staff of John Wiley & Sons, with whom

I have enjoyed working, particularly Gregory T. Franklin, John P. Falcone, and Angioline Loredo.

Oak Ridge, Tennessee *James E. Turner*
January 15, 1995

Preface to the Third Edition

Since the preparation of the second edition (1995) of *Atoms, Radiation, and Radiation Protection*, many important developments have taken place that affect the profession of radiological health protection. The International Commission on Radiological Protection (ICRP) has issued new documents in a number of areas that are addressed in this third edition. These include updated and greatly expanded anatomical and physiological data that replace "reference man" and revised models of the human respiratory tract, alimentary tract, and skeleton. At this writing, the Main Commission has just adopted the Recommendations 2007, thus laying the foundation and framework for continuing work from an expanded contemporary agenda into future practice. *Dose constraints, dose limits*, and *optimization* are given roles as core concepts. Medical exposures, exclusion levels, and radiation protection of nonhuman species are encompassed. The National Council on Radiation Protection and Measurements (NCRP) in the United States has introduced new limiting criteria and provided extensive data for the design of structural shielding for medical X-ray imaging facilities. *Kerma* replaces the traditional *exposure* as the shielding design parameter. The Council also completed its shielding report for megavoltage X- and gamma-ray radiotherapy installations. In other areas, the National Research Council's Committee on the Biological Effects of Ionizing Radiation published the BEIR VI and BEIR VII Reports, respectively dealing with indoor radon and with health risks from low levels of radiation. The very successful completion of the DS02 dosimetry system and the continuing Life Span Study of the Japanese atomic-bomb survivors represent additional major accomplishments discussed here.

Rapid advances since the last edition of this text have been made in instrumentation for the detection, monitoring, and measurement of ionizing radiation. These have been driven by improvements in computers, computer interfacing, and, in no small part, by heightened concern for nuclear safeguards and home security. Chapter 10 on Methods of Radiation Detection required extensive revision and the addition of considerable new material.

As in the previous edition, the primary regulatory criteria used here for discussions and working problems follow those given in ICRP Publication 60 with limits on *effective dose* to an individual. These recommendations are the principal ones employed throughout the world today, except in the United States. The ICRP-60 limits for individual effective dose, with which current NCRP recommendations are consistent, are also generally encompassed within the new ICRP Recommendations 2007. The earlier version of the protection system, limiting *effective dose equivalent* to an individual, is generally employed in the U.S. Some discussion and comparison of the two systems, which both adhere to the ALARA principle ("as low as reasonable achievable"), has been added in the present text. As a practical matter, both maintain a comparable degree of protection in operating experience.

It will be some time until the new model revisions and other recent work of the ICRP become fully integrated into unified general protocols for internal dosimetry. While there has been partial updating at this time, much of the formalism of ICRP Publication 30 remains in current use at the operating levels of health physics in many places. After some thought, this formalism continues to be the primary focus in Chapter 16 on Internal Dosimetry and Radiation Protection. To a considerable extent, the newer ICRP Publications follow the established format. They are described here in the text where appropriate, and their relationships to Publication 30 are discussed.

As evident from acknowledgements made throughout the book, I am indebted to many sources for material used in this third edition. I would like to express my gratitude particularly to the following persons for help during its preparation: M. I. Al-Jarallah, James S. Bogard, Rhonda S. Bogard, Wesley. E. Bolch, Roger J. Cloutier, Darryl J. Downing, Keith F. Eckerman, Joseph D. Eddlemon, Paul W. Frame, Peter Jacob, Cynthia G. Jones, Herwig G. Paretzke, Charles A. Potter, Robert C. Ricks, Joseph Rotunda, Richard E. Toohey, and Vaclav Vylet. Their interest and contributions are much appreciated. I would also like to thank the staff of John Wiley & Sons, particularly Esther Dörring, Anja Tschörtner, and Dagmar Kleemann, for their patience, understanding, and superb work during the production of this volume.

Oak Ridge, Tennessee *James E. Turner*
March 21, 2007

1
About Atomic Physics and Radiation

1.1
Classical Physics

As the nineteenth century drew to a close, man's physical understanding of the world appeared to rest on firm foundations. Newton's three laws accounted for the motion of objects as they exerted forces on one another, exchanging energy and momentum. The movements of the moon, planets, and other celestial bodies were explained by Newton's gravitation law. Classical mechanics was then over 200 years old, and experience showed that it worked well.

Early in the century Dalton's ideas revealed the atomic nature of matter, and in the 1860s Mendeleev proposed the periodic system of the chemical elements. The seemingly endless variety of matter in the world was reduced conceptually to the existence of a finite number of chemical elements, each consisting of identical smallest units, called atoms. Each element emitted and absorbed its own characteristic light, which could be analyzed in a spectrometer as a precise signature of the element.

Maxwell proposed a set of differential equations that explained known electric and magnetic phenomena and also predicted that an accelerated electric charge would radiate energy. In 1888 such radiated electromagnetic waves were generated and detected by Hertz, beautifully confirming Maxwell's theory.

In short, near the end of the nineteenth century man's insight into the nature of space, time, matter, and energy seemed to be fundamentally correct. While much exciting research in physics continued, the basic laws of the universe were generally considered to be known. Not many voices forecasted the complete upheaval in physics that would transform our perception of the universe into something undreamed of as the twentieth century began to unfold.

1.2
Discovery of X Rays

The totally unexpected discovery of X rays by Roentgen on November 8, 1895 in Wuerzburg, Germany, is a convenient point to regard as marking the beginning of

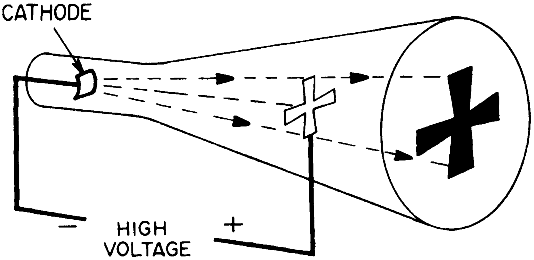

Fig. 1.1 Schematic diagram of an early Crooke's, or cathode-ray, tube. A Maltese cross of mica placed in the path of the rays casts a shadow on the phosphorescent end of the tube.

Fig. 1.2 X-ray picture of the hand of Frau Roentgen made by Roentgen on December 22, 1895, and now on display at the Deutsches Museum. (Figure courtesy of Deutsches Museum, Munich, Germany.)

the story of ionizing radiation in modern physics. Roentgen was conducting experiments with a Crooke's tube—an evacuated glass enclosure, similar to a television picture tube, in which an electric current can be passed from one electrode to another through a high vacuum (Fig. 1.1). The current, which emanated from the cathode and was given the name cathode rays, was regarded by Crooke as a fourth state of matter. When the Crooke's tube was operated, fluorescence was excited in the residual gas inside and in the glass walls of the tube itself.

It was this fluorescence that Roentgen was studying when he made his discovery. By chance, he noticed in a darkened room that a small screen he was using fluoresced when the tube was turned on, even though it was some distance away. He soon recognized that he had discovered some previously unknown agent, to which he gave the name X rays.[1] Within a few days of intense work, Roentgen had observed the basic properties of X rays—their penetrating power in light materials such as paper and wood, their stronger absorption by aluminum and tin foil, and their differential absorption in equal thicknesses of glass that contained different amounts of lead. Figure 1.2 shows a picture that Roentgen made of a hand on December 22, 1895, contrasting the different degrees of absorption in soft tissue and bone. Roentgen demonstrated that, unlike cathode rays, X rays are not deflected by a magnetic field. He also found that the rays affect photographic plates and cause a charged electroscope to lose its charge. Unexplained by Roentgen, the latter phenomenon is due to the ability of X rays to ionize air molecules, leading to the neutralization of the electroscope's charge. He had discovered the first example of ionizing radiation.

1.3
Some Important Dates in Atomic and Radiation Physics

Events moved rapidly following Roentgen's communication of his discovery and subsequent findings to the Physical–Medical Society at Wuerzburg in December 1895. In France, Becquerel studied a number of fluorescent and phosphorescent materials to see whether they might give rise to Roentgen's radiation, but to no avail. Using photographic plates and examining salts of uranium among other substances, he found that a strong penetrating radiation was given off, independently of whether the salt phosphoresced. The source of the radiation was the uranium metal itself. The radiation was emitted spontaneously in apparently undiminishing intensity and, like X rays, could also discharge an electroscope. Becquerel announced the discovery of radioactivity to the Academy of Sciences at Paris in February 1896.

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[1] That discovery favors the prepared mind is exemplified in the case of X rays. Several persons who noticed the fading of photographic film in the vicinity of a Crooke's tube either considered the film to be defective or sought other storage areas. An interesting account of the discovery and near-discoveries of X rays as well as the early history of radiation is given in the article by R. L. Kathren cited under "Suggested Reading" in Section 1.6.

The following tabulation highlights some of the important historical markers in the development of modern atomic and radiation physics.

1810	Dalton's atomic theory.
1859	Bunsen and Kirchhoff originate spectroscopy.
1869	Mendeleev's periodic system of the elements.
1873	Maxwell's theory of electromagnetic radiation.
1888	Hertz generates and detects electromagnetic waves.
1895	Lorentz theory of the electron.
1895	Roentgen discovers X rays.
1896	Becquerel discovers radioactivity.
1897	Thomson measures charge-to-mass ratio of cathode rays (electrons).
1898	Curies isolate polonium and radium.
1899	Rutherford finds two kinds of radiation, which he names "alpha" and "beta," emitted from uranium.
1900	Villard discovers gamma rays, emitted from radium.
1900	Thomson's "plum pudding" model of the atom.
1900	Planck's constant, $h = 6.63 \times 10^{-34}$ J s.
1901	First Nobel prize in physics awarded to Roentgen.
1902	Curies obtain 0.1 g pure $RaCl_2$ from several tons of pitchblend.
1905	Einstein's special theory of relativity ($E = mc^2$).
1905	Einstein's explanation of photoelectric effect, introducing light quanta (photons of energy $E = h\nu$).
1909	Millikan's oil drop experiment, yielding precise value of electronic charge, $e = 1.60 \times 10^{-19}$ C.
1910	Soddy establishes existence of isotopes.
1911	Rutherford discovers atomic nucleus.
1911	Wilson cloud chamber.
1912	von Laue demonstrates interference (wave nature) of X rays.
1912	Hess discovers cosmic rays.
1913	Bohr's theory of the H atom.
1913	Coolidge X-ray tube.
1914	Franck–Hertz experiment demonstrates discrete atomic energy levels in collisions with electrons.
1917	Rutherford produces first artificial nuclear transformation.
1922	Compton effect.
1924	de Broglie particle wavelength, $\lambda = h/\text{momentum}$.
1925	Uhlenbeck and Goudsmit ascribe electron with intrinsic spin $\hbar/2$.
1925	Pauli exclusion principle.
1925	Heisenberg's first paper on quantum mechanics.
1926	Schroedinger's wave mechanics.
1927	Heisenberg uncertainty principle.
1927	Mueller discovers that ionizing radiation produces genetic mutations.
1927	Birth of quantum electrodynamics, Dirac's paper on "The Quantum Theory of the Emission and Absorption of Radiation."
1928	Dirac's relativistic wave equation of the electron.

1930 Bethe quantum-mechanical stopping-power theory.
1930 Lawrence invents cyclotron.
1932 Anderson discovers positron.
1932 Chadwick discovers neutron.
1934 Joliot-Curie and Joliot produce artificial radioisotopes.
1935 Yukawa predicts the existence of mesons, responsible for short-range nuclear force.
1936 Gray's formalization of Bragg-Gray principle.
1937 Mesons found in cosmic radiation.
1938 Hahn and Strassmann observe nuclear fission.
1942 First man-made nuclear chain reaction, under Fermi's direction at University of Chicago.
1945 First atomic bomb.
1948 Transistor invented by Shockley, Bardeen, and Brattain.
1952 Explosion of first fusion device (hydrogen bomb).
1956 Discovery of nonconservation of parity by Lee and Yang.
1956 Reines and Cowen experimentally detect the neutrino.
1958 Discovery of Van Allen radiation belts.
1960 First successful laser.
1964 Gell-Mann and Zweig independently introduce quark model.
1965 Tomonaga, Schwinger, and Feynman receive Nobel Prize for fundamental work on quantum electrodynamics.
1967 Salam and Weinberg independently propose theories that unify weak and electromagnetic interactions.
1972 First beam of 200-GeV protons at Fermilab.
1978 Penzias and Wilson awarded Nobel Prize for 1965 discovery of 2.7 K microwave radiation permeating space, presumably remnant of "big bang" some 10–20 billion years ago.
1981 270 GeV proton–antiproton colliding-beam experiment at European Organization for Nuclear Research (CERN); 540 GeV center-of-mass energy equivalent to laboratory energy of 150,000 GeV.
1983 Electron–positron collisions show continuing validity of radiation theory up to energy exchanges of 100 GeV and more.
1984 Rubbia and van der Meer share Nobel Prize for discovery of field quanta for weak interaction.
1994 Brockhouse and Shull receive Nobel Prize for development of neutron spectroscopy and neutron diffraction.
2001 Cornell, Ketterle, and Wieman awarded Nobel Prize for Bose-Einstein condensation in dilute gases for alkali atoms.
2002 Antihydrogen atoms produced and measured at CERN.
2004 Nobel Prize presented to Gross, Politzer, and Wilczek for discovery of asymptotic freedom in development of quantum chromodynamics as the theory of the strong nuclear force.
2005 World Year of Physics 2005, commemorates Einstein's pioneering contributions of 1905 to relativity, Brownian motion, and the photoelectric effect (for which he won the Nobel Prize).

Figures 1.3 through 1.5 show how the complexity and size of particle accelerators have grown. Lawrence's first cyclotron (1930) measured just 4 in. in diameter. With it he produced an 80-keV beam of protons. The Fermi National Accelerator Laboratory (Fermilab) is large enough to accommodate a herd of buffalo and other wildlife on its grounds. The LEP (large electron-positron) storage ring at the European Organization for Nuclear Research (CERN) on the border between Switzerland and France, near Geneva, has a diameter of 8.6 km. The ring allowed electrons and positrons, circulating in opposite directions, to collide at very high energies for the study of elementary particles and forces in nature. The large size of the ring was needed to reduce the energy emitted as synchrotron radiation by the charged particles as they followed the circular trajectory. The energy loss per turn was made up by an accelerator system in the ring structure. The LEP was recently retired, and the tunnel is being used for the construction of the Large Hadron Collider (LHC), scheduled for completion in 2007. The LHC will collide head-on two beams of 7-TeV protons or other heavy ions.

In Lawrence's day experimental equipment was usually put together by the individual researcher, possibly with the help of one or two associates. The huge machines of today require hundreds of technically trained persons to operate. Earlier radiation-protection practices were much less formalized than today, with little public involvement.

Fig. 1.3 E. O. Lawrence with his first cyclotron. (Photo by Watson Davis, Science Service; figure courtesy of American Institute of Physics Niels Bohr Library. Reprinted with permission from *Physics Today*, November 1981, p. 15. Copyright 1981 by the American Institute of Physics.)

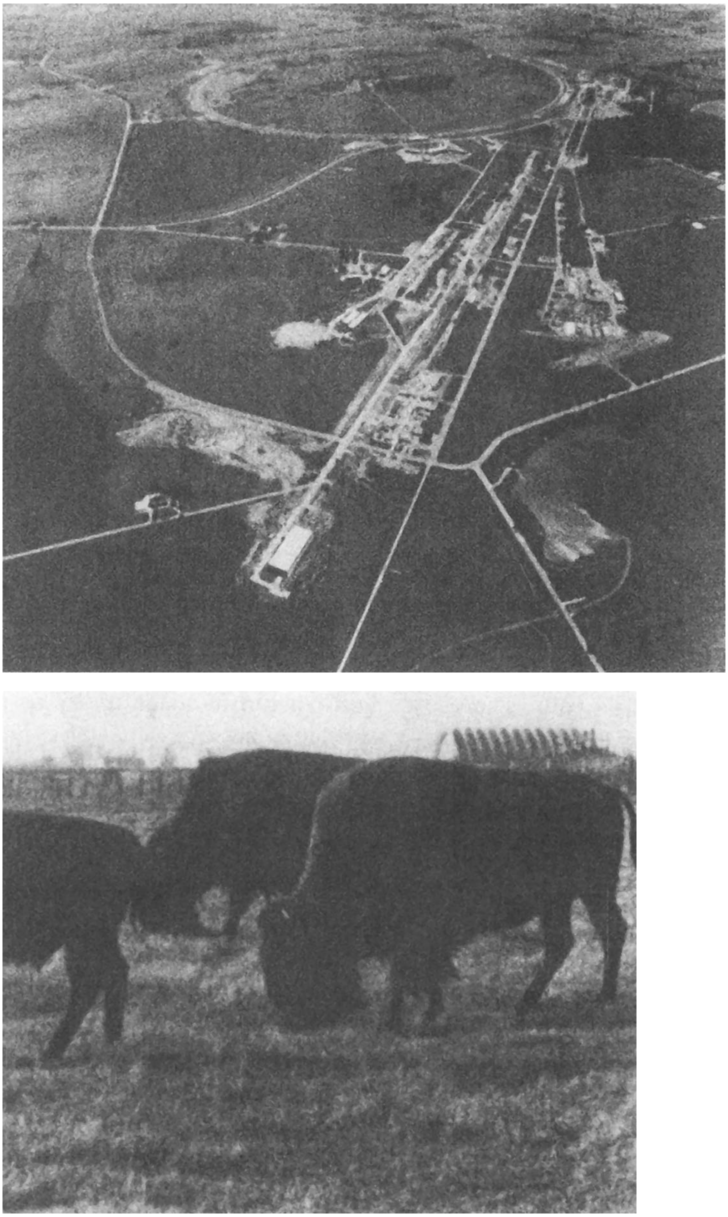

Fig. 1.4 Fermi National Accelerator Laboratory, Batavia, Illinois. Buffalo and other wildlife live on the 6800 acre site. The 1000 GeV proton synchrotron (Tevatron) began operation in the late 1980s. (Figure courtesy of Fermi National Accelerator Laboratory. Reprinted with permission from *Physics Today*, November 1981, p. 23. Copyright 1981 by the American Institute of Physics.)

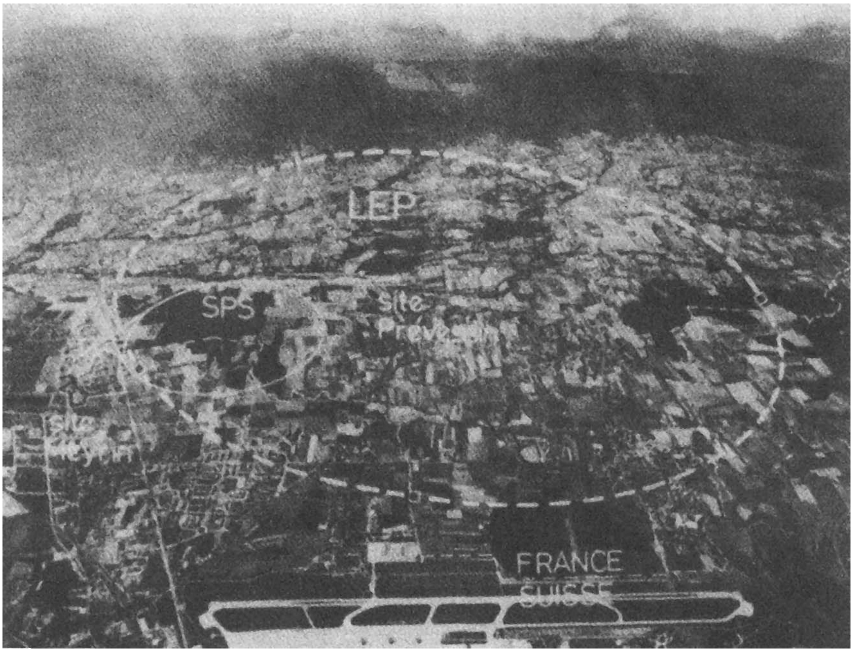

Fig. 1.5 Photograph showing location of underground LEP ring with its 27 km circumference. The SPS (super proton synchrotron) is comparable to Fermilab. Geneva airport is in foreground. [Figure courtesy of the European Organization for Nuclear Research (CERN).]

1.4
Important Dates in Radiation Protection

X rays quickly came into widespread medical use following their discovery. Although it was not immediately clear that large or repeated exposures might be harmful, mounting evidence during the first few years showed unequivocally that they could be. Reports of skin burns among X-ray dispensers and patients, for example, became common. Recognition of the need for measures and devices to protect patients and operators from unnecessary exposure represented the beginning of radiation health protection.

Early criteria for limiting exposures both to X rays and to radiation from radioactive sources were proposed by a number of individuals and groups. In time, organizations were founded to consider radiation problems and issue formal recommendations. Today, on the international scene, this role is fulfilled by the International Commission on Radiological Protection (ICRP) and, in the United States, by the National Council on Radiation Protection and Measurements (NCRP). The International Commission on Radiation Units and Measurements (ICRU) recommends radiation quantities and units, suitable measuring procedures, and numerical values for the physical data required. These organizations act as independent bodies