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 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

Atoms, Radiation, and Radiation Protection, Fourth Edition.
James S. Bogard, Darryl J. Downing, Robert L. Coleman, Keith F. Eckerman, and James E. Turner.

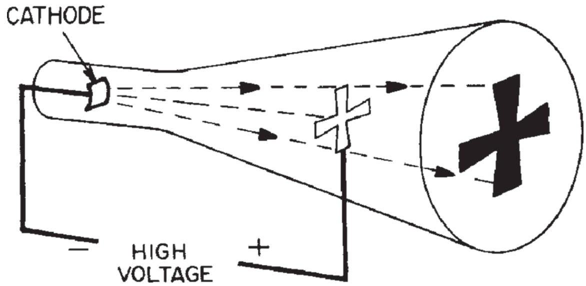

Figure 1.1 Schematic diagram of an early Crooke's, or cathode-ray, tube. A Maltese cross of mica placed in the path of the rays casts a shadow on the phosphorescent end of the tube.

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

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.

Figure 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 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.

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, $\lambda = h/$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 which 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

Figure 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.)

the European Organization for Nuclear Research (CERN) on the border between Switzerland and France, near Geneva, had 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 retired in 2000 to make way for the Large Hadron Collider (LHC) in its place, which began operation in 2008. The LHC is primarily used to collide two beams of nearly 7-TeV protons head-on but also supports Pb ions. The LHC is used to investigate properties of sub-atomic matter and, by extension, our understanding of the universe.

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

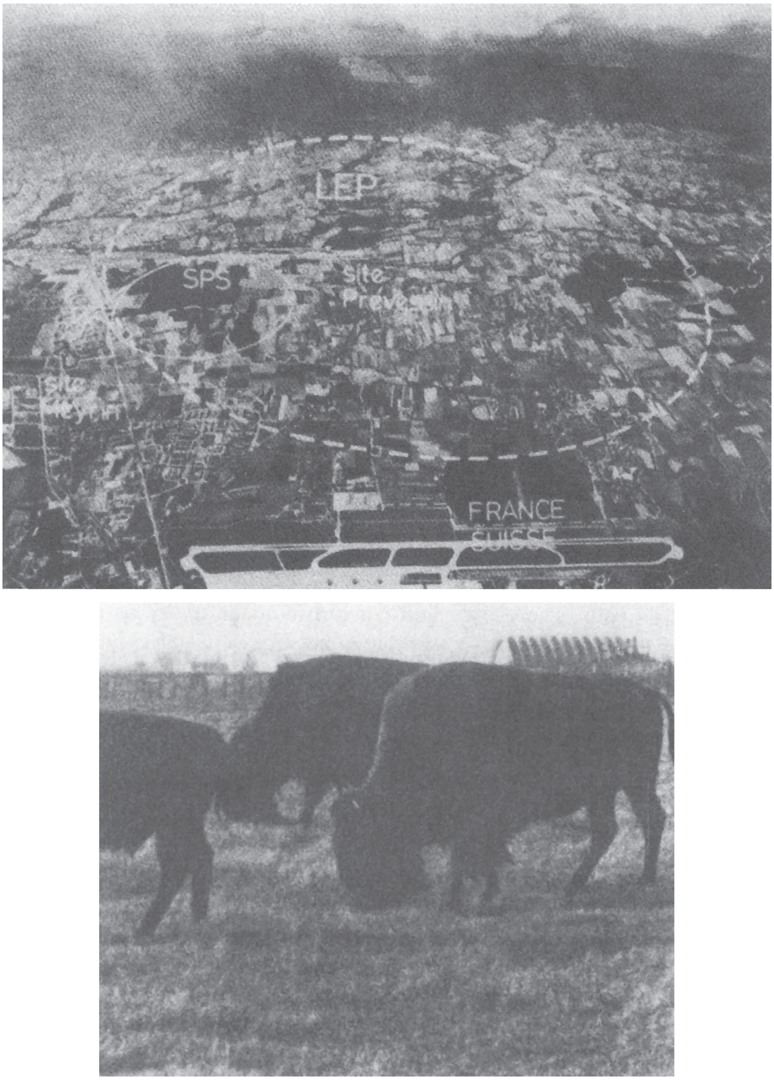

Figure 1.4 Fermi National Accelerator Laboratory, Batavia, Illinois. Buffalo and other wildlife live on the 6800 acre site. The 1000 GeV proton synchrotron (Tevatron) began operation in the late 1980s. (Figure courtesy of Fermi National Accelerator Laboratory. Reprinted with permission from *Physics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

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,

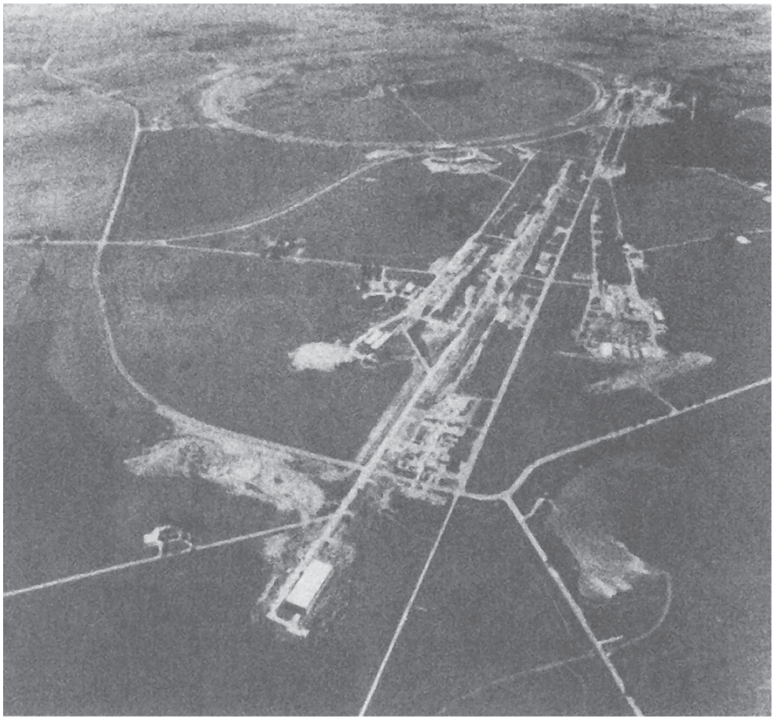

Figure 1.5 Photograph showing location of underground LEP ring with its 27 km circumference. The SPS (super proton synchrotron) is comparable to Fermilab. Geneva airport is in foreground. [Figure courtesy of the European Organization for Nuclear Research (CERN).]

and numerical values for the physical data required. These organizations act as independent bodies composed of specialists in a number of disciplines—physics, medicine, biology, dosimetry, instrumentation, administration, and so forth. They are not government affiliated and they have no legal authority to impose their recommendations. The NCRP today is a nonprofit corporation chartered by the United States Congress.

Some important dates and events in the history of radiation protection follow.

1895	Roentgen discovers ionizing radiation.
1900	American Roentgen Ray Society (ARRS) founded.
1915	British Roentgen Society adopts X-ray protection resolution; believed to be the first organized step toward radiation protection.
1920	ARRS establishes standing committee for radiation protection.
1921	British X-Ray and Radium Protection Committee presents its first radiation protection rules.
1922	ARRS adopts British rules.
1922	American Registry of X-Ray Technicians founded.
1925	Mutscheller's "tolerance dose" for X rays.

1925 First International Congress of Radiology, London, establishes ICRU.

1928 ICRP established under auspices of the Second International Congress of Radiology, Stockholm.

1928 ICRU adopts the roentgen as unit of exposure.

1929 Advisory Committee on X-Ray and Radium Protection (ACXRP) formed in United States (forerunner of NCRP).

1931 The roentgen adopted as unit of X radiation.

1931 ACXRP publishes recommendations (*National Bureau of Standards Handbook* 15).

1934 ICRP recommends daily tolerance dose.

1941 ACXRP recommends first permissible body burden, for radium.

1942 Manhattan District begins to develop atomic bomb; beginning of health physics as a profession.

1946 U.S. Atomic Energy Commission created.

1946 NCRP formed as outgrowth of ACXRP.

1947 U.S. National Academy of Sciences establishes Atomic Bomb Casualty Commission (ABCC) to initiate long-term studies of A-bomb survivors in Hiroshima and Nagasaki.

1949 NCRP publishes recommendations and introduces risk/benefit concept.

1952 Radiation Research Society formed.

1953 ICRU introduces concept of absorbed dose.

1955 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) established.

1956 Health Physics Society founded.

1956 International Atomic Energy Agency organized under United Nations.

1957 NCRP introduces age proration for occupational doses and recommends nonoccupational exposure limits.

1957 U.S. Congressional Joint Committee on Atomic Energy begins series of hearings on radiation hazards, beginning with “The Nature of Radioactive Fallout and Its Effects on Man.”

1958 United Nations Scientific Committee on the Effects of Atomic Radiation publishes study of exposure sources and biological hazards (first UNSCEAR Report).

1958 Society of Nuclear Medicine formed.

1959 ICRP recommends limitation of genetically significant dose to population.

1960 U.S. Congressional Joint Committee on Atomic Energy holds hearings on “Radiation Protection Criteria and Standards: Their Basis and Use.”

1960 American Association of Physicists in Medicine formed.

1960 American Board of Health Physics begins certification of health physicists.

1964 International Radiation Protection Association (IRPA) formed.

1964 Act of Congress incorporates NCRP.

1969 Radiation in space. Man lands on moon.

1974 U.S. Nuclear Regulatory Commission (NRC) established.

1974	ICRP Publication 23, "Report of Task Group on Reference Man."
1975	ABCC replaced by binational Radiation Effects Research Foundation (RERF) to continue studies of Japanese survivors.
1977	ICRP Publication 26, "Recommendations of the ICRP."
1977	U.S. Department of Energy (DOE) created.
1978	ICRP Publication 30, "Limits for Intakes of Radionuclides by Workers."
1978	ICRP adopts "effective dose equivalent" terminology.
1986	Dosimetry System 1986 (DS86) developed by RERF for A-bomb survivors.
1986	Growing public concern over radon. U.S. Environmental Protection Agency publishes pamphlet, "A Citizen's Guide to Radon."
1987	NCRP Report No. 91, "Recommendations on Limits for Exposure to Ionizing Radiation."
1988	United Nations Scientific Committee on the Effects of Atomic Radiation, "Sources, Effects and Risks of Ionizing Radiation." Report to the General Assembly.
1988	U.S. National Academy of Sciences BEIR IV Report, "Health Risks of Radon and Other Internally Deposited Alpha Emitters—BEIR IV."
1990	U.S. National Academy of Sciences BEIR V Report, "Health Effects of Exposure to Low Levels of Ionizing Radiation—BEIR V."
1991	International Atomic Energy Agency report on health effects from the April 1986 Chernobyl accident.
1991	10 CFR Part 20, NRC.
1991	ICRP Publication 60, "1990 Recommendations of the International Commission on Radiological Protection."
1993	10 CFR Part 835, DOE.
1993	NCRP Report No. 115, "Risk Estimates for Radiation Protection."
1993	NCRP Report No. 116, "Limitation of Exposure to Ionizing Radiation."
1994	Protocols developed for joint U.S., Ukraine, Belarus 20-y study of thyroid disease in 85,000 children exposed to radioiodine following Chernobyl accident in 1986.
1994	ICRP Publication 66, "Human Respiratory Tract Model for Radiological Protection."
2000	UNSCEAR 2000 Report on sources of radiation exposure, radiation-associated cancer, and the Chernobyl accident.
2003	Dosimetry System 2002 (DS02) formally approved.
2005	ICRP proposes system of radiological protection consisting of dose constraints and dose limits, complimented by optimization.
2007	Fundamental recommendations issued (ICRP Publication 103).

1.5 Sources and Levels of Radiation Exposure

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has carried out a comprehensive study and analysis of the presence and effects of ionizing radiation in today's world. The UNSCEAR 2000 Report (see "Suggested Reading" at the end of the chapter) presents a broad review of the various sources and levels of radiation exposure worldwide and an assessment of the radiological consequences of the 1986 Chernobyl reactor accident.

Table 1.1, based on information from the Report, summarizes the contributions that comprise the average annual effective dose of about 2.8 mSv (see Chapter 14) to an individual. They do not necessarily pertain to any particular person, but reflect averages from ranges given in the last column. Natural background radiation contributes the largest portion (~85%), followed by medical (~14%), and then man-made environmental (<1%). As noted in the table, background can vary greatly from place to place, due to amounts of radioactive minerals in soil, water, and rocks and to increased cosmic radiation at higher altitudes. Radon contributes roughly one-half of the average annual effective dose from natural background. Medical uses of radiation, particularly diagnostic X rays, result in the largest average annual effective dose from man-made sources. Depending on the level of healthcare, however, the average annual medical dose is very small in many parts of the world. The last three sources in Table 1.1 represent the relatively small contributions from man-made environmental radiation. Of all man's activities, atmospheric nuclear-weapons testing has resulted in the largest releases of radionuclides into the environment. According to the UNSCEAR Report, the annual effective dose from this source at its maximum

Table 1.1 Annual per Capita Effective Doses in Year 2000 from Natural and Man-Made Sources of Ionizing Radiation Worldwide*

Source	Annual Effective Dose (mSv)	Typical Range (mSv)
Natural Background		
External		
Cosmic rays	0.4	0.3–1.0
Terrestrial gamma rays	0.5	0.3–0.6
Internal		
Inhalation (principally radon)	1.2	0.2–10.
Ingestion	0.3	0.2–0.8
Total	2.4	1–10
Medical (primarily diagnostic X rays)	0.4	0.04–1.0
Man-Made Environmental		
Atmospheric nuclear-weapons tests	0.005	Peak was 0.15 in 1963.
Chernobyl accident	0.002	Highest average was 0.04 in northern hemisphere in 1986.
Nuclear power production	0.0002	See paragraph 34 in Report for basis of estimate.

a) Based on UNSCEAR 2000 Report.

in 1963 was about 7% as large as natural background. The Report also includes an analysis of occupational radiation exposures.

Suggested Reading

1. Cropper, William H., *Great Physicists,* Oxford University Press, Oxford (2001). [Portrays the lives, personalities, and contributions of 29 scientists from Galileo to Stephen Hawkin.]
2. Glasstone, S., *Sourcebook on Atomic Energy,* 3d ed., D. Van Nostrand, Princeton, NJ (1967).
3. Kathren, R. L., "Historical Development of Radiation Measurement and Protection," pp. 13–52 in *Handbook of Radiation Protection and Measurement,* Section A, Vol. I, A. B. Brodsky, ed., CRC Press, Boca Raton, FL (1978). [An interesting and readable account of important discoveries and experience with radiation exposures, measurements, and protection. Contains bibliography.]
4. Kathren, R. L., and Ziemer, P. L., eds., *Health Physics: A Backward Glance,* Pergamon Press, Elmsford, NY (1980). [Thirteen original papers on the history of radiation protection.]
5. Meinhold, Charles B., "Lauriston S. Taylor Lecture: The Evolution of Radiation protection—from Erythema to Genetic Risks to Risks of Cancer to …?," *Health Phys*. 87, 241–248 (2004). [President Emeritus of the NCRP describes the evolution of radiation protection through the present-day ICRP, NCRP, and other organizations. This issue (Vol. 87, No. 3) contains the proceedings of the 2003 annual meeting of the NCRP, on the subject of radiation protection at the beginning of the 21st century.]
6. Moeller, Dade W., "Environmental Health Physics—50 Years of Progress," *Health Phys*. 87, 337–357 (2004). [Review article, discussing sources of environmental radiation and the transport and monitoring of radioactive materials in the biosphere. Extensive bibliography.]
7. Morgan, K. Z., "History of Damage and Protection from Ionizing Radiation," Chapter 1 in *Principles of Radiation Protection,* K. Z. Morgan and J. E. Turner, eds., Wiley, New York (1967). [Morgan is one of the original eight health physicists of the Manhattan Project at the University of Chicago (1942) and the first president of the Health Physics Society.]
8. National Research Council, *Health Effects of Exposures to Low Levels of Ionizing Radiation—BEIR V,* National Academy Press, Washington, DC (1990).
9. NCRP Report No. 93, *Ionizing Radiation Exposure of the Population of the United States,* National Council on Radiation Protection and Measurements, Bethesda, MD (1987).
10. Pais, Abraham, *Inward Bound,* Oxford University Press, Oxford (1986). [Subtitled *Of Matter and Forces in the Physical World,* this is a very readable account of what happened between 1895 and 1983 and the persons and personalities that played a role during that time.]

11 *Physics Today,* Vol. 34, No. 11 (Nov. 1981). [Fiftieth anniversary of the American Institute of Physics. Special issue devoted to "50 Years of Physics in America."]

12 *Physics Today,* Vol. 36, No. 7 (July 1983). [This issue features articles on physics in medicine to commemorate the twenty-fifth anniversary of the founding of the American Association of Physicists in Medicine.]

13 Ryan, Michael T., "Happy 100th Birthday to Dr. Lauriston S. Taylor," *Health Phys*. 82, 773 (2002). [The many contributions of Taylor (1902–2004), the first President of the NCRP, are honored in this issue (Vol. 82, No. 6) of the journal.]

14 Segrè, Emilio, *From X-Rays to Quarks,* W. H. Freeman, San Francisco (1980). [Describes physicists and their discoveries from 1895 to the present. Segrè received the Nobel Prize for the discovery of the antiproton.]

15 Stannard, J. N., *Radioactivity and Health,* National Technical Information Service, Springfield, VA (1988). [A comprehensive, detailed history (1963 pp.) of the age.]

16 Taylor, L. S., *Radiation Protection Standards,* CRC Press, Boca Raton, FL (1971). [The history of radiation protection as written by one of its leading international participants.]

17 Taylor, L. S., "Who Is the Father of Health Physics?" *Health Phys.* 42, 91 (1982).

18 United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2000 Report to the General Assembly, with scientific annexes, Vol. I Sources, Vol. II Effects, United Nations Publications, New York, NY and Geneva, Switzerland (2000).

19 Weart, Spencer R. and Phillips, Melba, Eds., *History of Physics,* American Institute of Physics, New York, NY (1985). [Forty-seven articles of historical significance are reprinted from *Physics Today*. Included are personal accounts of scientific discoveries and developments in modern physics. One section, devoted to social issues in physics, deals with effects of the great depression in the 1930s, science and secrecy, development of the atomic bomb in World War II, federal funding, women in physics, and other subjects.]

The following Internet sources are available:

www.hps.org
www.icrp.org
www.icru.org
www.ncrponline.org
www.nobelprize.org/physics/laureates