THE PHYSICS OF RADIOLOGY

FOURTH EDITION

HAROLD ELFORD JOHNS

O.C., Ph.D., F.R.S.C., LL.D., D.Sc.

University Professor Emeritus, University of Toronto
Professor Emeritus, Department of Medical Biophysics and
Department of Radiology, University of Toronto
Former Head of, and now consultant to, the Physics Division,
Ontario Cancer Institute and the Radiological Research Laboratories;
University of Toronto

JOHN ROBERT CUNNINGHAM

B.Eng., M.Sc., Ph.D.

Senior Clinical Physicist, Ontario Cancer Institute
Professor, Department of Medical Biophysics
University of Toronto

Authority, comprehensivity and a consummate manner of presentation have been hallmarks of *The Physics of Radiology* since it first saw publication some three decades past. This Fourth Edition adheres to that tradition but again updates the context. It thoroughly integrates ideas recently advanced and practices lately effected. Students and professionals alike will continue to view it, in essence, as the bible of radiological physics.

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CHARLES C THOMAS • PUBLISHER
Springfield • Illinois • U.S.A.

Published and Distributed Throughout the World by

CHARLES C THOMAS • PUBLISHER
2600 South First Street
Springfield, Illinois 62717 U.S.A.

ISBN 0-398-04669-7

Library of Congress Catalog Card Number: 81-21396

First Edition, 1953
Second Edition, First Printing, 1961
Second Edition, Revised Second Printing, 1964
Second Edition, Third Printing, 1966
Third Edition, First Printing, 1969
Third Edition, Second Printing, 1971
Third Edition, Revised Third Printing, 1974
Third Edition, Fourth Printing, 1977
Third Edition, Fifth Printing, 1978
Fourth Edition, 1983

With THOMAS BOOKS careful attention is given to all details of manufacturing and design. It is the Publisher's desire to present books that are satisfactory as to their physical qualities and artistic possibilities and appropriate for their particular use. THOMAS BOOKS will be true to those laws of quality that assure a good name and good will.

Printed in the United States of America
CB-1

Library of Congress Cataloging in Publication Data

Johns, Harold Elford.
The physics of radiology.

(American lecture series; publication no. 1054)
First published in 1953 under title: The physics of radiation therapy.
"A monograph in the Bannerstone Division of American lectures in radiation therapy"—ser. t.p.
Bibliography: p.
Includes index.
1. Radiology, Medical. 2. Radiology. I. Cunningham, John Robert. II. Title. III. Series. [DNLM: 1. Health physics. WN 110 J65p]
R895.J6 1983 616.07'57 81-21396
ISBN 0-398-04669-7 AACR2

PREFACE

Since the publication of the Third Edition of *The Physics of Radiology,* various international organizations have attempted to introduce SI (système international) units into their fields. Of particular interest to us are the new terms that have been defined for the radiological sciences: the *gray* has replaced the rad as the unit of absorbed dose, and the *becquerel* has replaced the curie as the unit of activity.

We are convinced of the advantages of SI and the new units are used throughout the book. We realize, however, that it will take some time before workers in the field are at ease with them and for this reason the older units are often used in parallel with the new ones.

Committees of the I.C.R.U. are attempting to deemphasize the use of the roentgen as a unit of exposure. In spite of this we have continued to use it, especially in diagnostic radiology. When patients are exposed to soft x rays, as they are in diagnostic radiology, there is no single factor which allows one to go from exposure to dose. The authors feel that the I.C.R.U. has not adequately assessed the impact of their decision on this subject. Because the roentgen remains a practical unit, the chapter on diagnostic radiology still makes extensive use of it.

The use of small electronic calculators has relieved the scientist of many of the boring arithmetical tasks of the past. We believe that all scientists now use calculators, and we have felt at greater liberty to do calculations that involve logarithms or exponentials, a procedure which was previously more difficult. In addition, we have introduced, in the first chapter, exponential growth and decay, since it is common to all aspects of radiation and since, for example, we believe the doubling time for the growth of cells is no more complicated a concept than the determination of the doubling time of invested money, a topic which everyone understands.

The emphasis in radiation therapy has shifted further towards the use of high energy beams. We therefore give less attention to cobalt 60 and more to the higher energy radiation produced by linear accelerators in the 10 to 25 MeV range.

There have been explosive developments in diagnostic radiology with the invention and exploitation of the CT scanner. In addition, other methods of imaging are rapidly becoming available. We have, therefore, more than doubled the size of the chapter on this subject. In addition, because of the general fear of radiation, we have emphasized the idea that for every risk there should be a benefit and have discussed ways of reducing this risk without loss of diagnostic information.

In the chapter on radiobiology we have removed some basic radiation chemistry and replaced it with discussions on survival curves of patients so that the reader will have ways of comparing the results of different modes of treatment.

We are especially indebted to R.J. Howerton of Lawrence Livermore Laboratory for supplying us with a library of photon interaction coefficients on magnetic tape and to Dr. M.J. Berger of the National Bureau of Standards for supplying us with his latest calculations of electron stopping powers. The helpful discussions we have had with Mr. J.H. Hubbell, Dr. R. Loevinger, and Dr. S. Domen, all of the U.S. National Bureau of Standards, on topics of radiation dosimetry are much appreciated. Similarly, helpful correspondence and discussions on stopping powers with M. Pages of Centre d'Études Nucléaires de Saclay, France, are acknowledged. In addition, our association with members of AAPM Task Group 21 on High Energy Dose Calibrations has helped to clarify many concepts dealt with in this book.

We thank Dr. P. Leung, Mr. A. Rawlinson, Mr. J. Van Dyk, and Dr. P. Shragge for many discussions on clinical radiation physics and Dr. G. Ege and Dr. M. Bronskill for their help with the chapter on Nuclear Medicine.

In preparing Chapter 15 on radiation protection we were helped by Dr. H.O. Wyckoff of the ICRU, Washington; Dr. H. Johnston and Dr. C.L. Greenstock of Atomic Energy of Canada, Whiteshell, Manitoba; Dr. G. Cowper and Dr. A.M. Marko of the Chalk River Laboratories of Atomic Energy of Canada; Dr. M. James of the Atomic Energy Control Board, Ottawa; and Dr. D. Grogan of the Health Protection Bureau, Ottawa.

We are greatly indebted to Dr. K.W. Taylor, of the Radiological Research Laboratory, University of Toronto, who worked with us over a period of three years to create the chapter on diagnostic radiology. Valuable assistance in this task was also provided by Dr. M. Yaffe, Dr. A. Fenster, and Dr. A. Holloway, all of whom are closely associated with us.

The chapter on radiobiology was created in collaboration with Dr. R.P. Hill and valuable discussions on this topic were held with Dr. G. DeBoer, Dr. R.S. Bush, Dr. G.F. Whitmore, Dr. J.W. Hunt, Dr. A.M. Rauth, and Dr. W.D. Rider of our Institute.

We thank Dr. R.S. Bush, Dr. W.D. Rider, and the late Dr. C.L. Ash for their efforts at keeping our writings relevant to clinical problems.

We also acknowledge the help of our radiation oncology residents and radiation physics students who provided criticism and worked many of

the problems. In particular we mention Luis Cabeza, David Hunter, Paul Johns, Gordon Maudsley, Henriette Von Harpe, and John Wong.

The Ontario Cancer Institute continues to be a research facility in which ideas are fully exchanged and discussed and this kind of environment is essential to produce a book of this complexity. We acknowledge the leadership of its director, Dr. R.S. Bush.

We thank Mr. D. McCourt of the Ontario Cancer Institute who drafted over 200 diagrams for the book and Mr. A. Connor and his staff of our photography department who prepared them for publication. We thank Miss C. Morrison, Librarian at OCI, and her staff for helping with the references. We are most deeply indebted to and do sincerely thank our personal secretaries, Mrs. Stellis Robinson and Miss Ann Lake, for all they have done in the preparation of this manuscript.

In the thirty years that Charles C Thomas, Publisher, has been our publisher we have always been able to count on its understanding and support.

The writing of a book of this complexity, spread as it was over the past five years, needed the continuous support and encouragement of our wives and families, and this is gratefully acknowledged.

Harold E. Johns
J.R. Cunningham

CONTENTS

THE PHYSICS OF RADIOLOGY

Chapter **1**

BASIC CONCEPTS

1.01 INTRODUCTION

The sciences of diagnostic radiology, radiotherapy, radiobiology, and nuclear medicine continue to develop and expand. They are all based on an understanding of the underlying physics. This book is written to help a student interested in any of these fields to understand his science and to help the medical physicist who applies the science of physics to these fields of medicine. In this book we will discuss only those physical principles that are absolutely essential to an understanding of these medical applications. Some of the chapters will be of more interest to physicists than to radiologists. For a first reading of this text, the following guidelines are suggested:

- Physicists should read each chapter in order.
- Diagnostic radiologists should read chapters 1, 2, 3, 5, 15, 16, and parts of 7, 8, 9, 10, and 17.
- Radiotherapists should read chapters 1 to 5, 7 to 13, 15, 17, and parts of 14 and 16.
- Specialists in nuclear medicine should read chapters 1, 2, 3, 5, 14, 15, and parts of 7, 8, 9, and 17.
- Radiobiologists should read chapters 1, 2, 3, 5, 15, 17, and parts of 4, 7, 8, 9, and 14.
- For further study all the chapters should then be read in order.

The availability of pocket calculators has freed scientists of much of the drudgery of handling numerical calculations. Each student should therefore obtain a pocket calculator for his own personal use. It should include exponential functions (e^x and y^x) and the ability to manipulate very large or small numbers using powers of ten.

1.02 QUANTITIES AND UNITS

All meaningful measurements require the statement of a numerical value, which is a pure number, and the unit in which the physical quantity is measured, i.e.,

$$(\text{physical quantity}) = (\text{numerical value}) \times (\text{some unit}) \quad (1\text{-}1)$$

For example, one might say the potential across an x ray tube was 80 kilovolts. This involves the pure number 80 and the unit "the kilovolt."

As each science develops, there is a tendency for each to create its own special units to deal with its own special problems. This has led to confusion when a worker in one field attempts to use work arising from another. In recent years, the Comité International des Poids et Mésures (CIPM) has adopted an international system of units with the abbreviation SI (Système International). These are being officially introduced into most countries of the world.

The International Commission on Radiation Units and Measurements (ICRU) has studied the special problems of units for radiology and has created a number of special units in the past. They now recommend that these special units gradually be phased out and be replaced by SI units. To meet the needs of radiological science, the General Conference of Weights and Measures (CGPM), on the advice of the ICRU, in 1975 established two special SI units, the becquerel and the gray. For further details on these see Wyckoff et al. (W1). In this text we will use the new SI units wherever possible but continually relate these to the earlier ICRU units, which are still in common use.

Fundamental Units

Table 1-1 summarizes some of the important units that are dealt with in this book. Others are introduced as needed. All measurements in science are based on four basic physical quantities: mass, length, time, and electric current. These are shown in the first section of Table 1-1. The corresponding fundamental basic units are the kilogram (kg), the meter (m), the second (s), and the ampere (A), whose *magnitudes* or size are carefully preserved in standardization laboratories throughout the world. They are independent of one another since they represent different ideas and thus cannot be converted from one to another. For example, it would be meaningless to attempt to convert a time in seconds into a length in meters.

Derived Units

The next section of the table introduces a few of the *derived* physical quantities that are relevant to our field. These are based on various combinations of the four fundamental quantities.

Velocity (entry 5) is the ratio of an increment of distance, Δl, to the corresponding increment in time, Δt. It has no special name and can be expressed using *any* unit of distance and *any* unit of time, such as cm per second, meter per second, kilometer per hr, etc. The SI unit of velocity is meter per second (m/s or m s^{-1}).

Acceleration (entry 6) is the ratio of the change in velocity, Δv, to the change in time, Δt, required for this change in velocity. It may be expressed in *any* unit of velocity and *any* unit of time. For example, a car

TABLE 1-1
Fundamental Quantities and Units

	Usual Symbol for Quantity	Defining Equation	SI Unit	Relationships and Special Units
		FUNDAMENTAL UNITS		
1 mass	m	Basic physical units	kilogram (kg)	
2 length	*l*	defined arbitrarily	meter (m)	
3 time	t	and maintained in	second (s)	
4 current	I	standardization laboratories	ampere (A)	
		DERIVED UNITS		
5 velocity	v	$v = \Delta l/\Delta t$	m s^{-1}	
6 acceleration	a	$a = \Delta v/\Delta t$	m s^{-2}	
7 force	F	F = m a	newton (N)	1 N = 1 kg m s ^{2}
8 work or energy	E	$E = F\,l = 1/2\ m\ v^2$	joule (J)	1 J = 1 kg m^2 s ^{2}
9 power or rate of doing work	P	P = E/t	watt (W)	1 W = 1 J/s
10 frequency	f,ν	number per second	hertz (Hz)	1 Hz = 1 s^{-1}
		ELECTRICAL UNITS		
11 charge	Q	Q = I t	coulomb (C)	1 C = 1 A s
12 potential	V	V = E/Q	volt (V)	1 V = 1 J/C
13 capacity	C	C = Q/V	farad (F)	1 F = 1 C/V
14 resistance	R	V = I R	ohm (Ω)	1 Ω = 1 V/A
		RADIATION UNITS		
15 absorbed dose	D	energy absorbed from ionizing radiation per unit mass	gray (Gy)	1 Gy = 1 J kg ^{1} 1 Gy = 100 rads*
16 exposure	X	charge liberated by ionizing radiation per unit mass air	C kg^{-1}	roentgen (R)* 1 R = 2.58 × 10 ^{4} C/kg
17 activity	A	disintegrations of radioactive material per second	becquerel (Bq)	1 Bq = 1 s^{-1} 1 curie* (Ci) = 3.7 × 10^{10} Bq

*The ICRU (W1) recommends that the special units the rad, the roentgen, and the curie be gradually abandoned over the period 1976–1986 and be replaced by the gray (Gy), the coulomb per kg (C/kg), and the becquerel (Bq).

(Useful conversion factors are given in Appendix A-1.)

with a velocity increase of 7.2 km per hour every second would accelerate 7.2 km per hr per second. Acceleration expressed this way involves two different units of time, the hour and the second, and the unit of distance, the km. This acceleration can be expressed in any of the following ways:

$$a = 7.2\ \frac{\text{km}}{\text{hr}} \times \frac{1}{\text{s}} = 7.2 \times 1000\ \frac{\text{m}}{\text{hr}} \times \frac{1}{\text{s}}$$

$$= \frac{7.2 \times 1000\ \text{m}}{3600\ \text{s}} \times \frac{1}{\text{s}} = \frac{2.0\ \text{m}}{\text{s} \times \text{s}} = 2\ \text{m s}^{-2} = 2.0\ \text{m/s}^2$$

It is important that the student understand that numbers (such as 7.2) and units (such as km, hr, etc.) should be carried together in the equation. For example, 1 km is replaced by its equivalent 1000 m. From the above example we see that acceleration involves velocity and time, or distance and time squared. The SI unit of acceleration is meters per s^2 or $m/s^2 = m\ s^{-2}$. It has no special name.

The next quantity in the table (entry 7) is force, F, for which everyone has an intuitive feeling. If a ball on the level floor starts to move or accelerate, we know that a force has been applied to it. Likewise, if a car suddenly comes to rest or decelerates we know a force has been applied to it. Force is related to acceleration and is defined by Newton's law of motion, which states that F = m a. Force is measured by the product of mass and acceleration, and since mass and acceleration are already defined, the unit of force is automatically defined as 1 kg m s^{-2}. This unit of force is so important it is given a special name, the newton:

$$1 \text{ newton} = 1 \text{ N} = 1 \text{ kg m s}^{-2} \qquad (1\text{-}2)$$
$$\text{the defining equation is } F = m\ a$$

We now distinguish between mass and force. Suppose you weigh yourself on a hospital balance and obtain the reading 70 kg. This means that you have a mass 70 times the mass of the standard kilogram in Paris. Suppose you now go to the gymnasium and hang from a horizontal bar; what force do you exert on the bar? You know that if the bar breaks you will fall with the acceleration due to gravity of 9.8 m s^{-2}. Hence the pull of the earth on you will give your 70 kg mass an acceleration of 9.8 m s^{-2} and the force exerted by gravity is $F = 70 \text{ kg} \times 9.8 \text{ m s}^{-2} = 686 \text{ kg m s}^{-2} = 686$ newtons. Thus, your mass is 70 kg and the force of attraction of the earth for you is 686 newtons. This force varies slightly from place to place on the earth's surface as the acceleration due to gravity changes,* but your mass is constant.

The next quantity is work or energy (entry 8), which is defined as the product of force times distance. Thus, if while hanging from the gym bar you raise your center of gravity 0.50 m, the work done by you against gravity is 686 N × 0.50 m = 343 newton meters = 343 N m. The newton meter is such an important quantity that it has been given the special name, the joule:

$$1 \text{ joule} = 1 \text{ J} = 1 \text{ newton meter} = 1 \text{ N m} = 1 \text{ kg m}^2 \text{ s}^{-2} \quad (1\text{-}3)$$
$$\text{the defining equation is } E = F\ l$$

It should be emphasized that work in the physical sense described here requires that motion take place. For example, one would get very tired in

*The acceleration due to gravity increases with latitude and decreases with altitude. A few values are Toronto 9.805, London 9.812, North Pole 9.832, Equator 9.780 m s^{-2}.

just hanging from the bar, but one does *not* work until one *raises* oneself.

The next quantity is power (entry 9 in Table 1-1), which is defined as the rate of doing work, or the work done per unit time. The unit of power is the joule per second, but this is so important a unit that it is called a watt:

$$1 \text{ watt} = 1 \text{ W} = \frac{1 \text{ joule}}{1 \text{ second}} = 1 \text{ J/s} = 1 \text{ J s}^{-1} \qquad (1\text{-}4)$$

the defining equation is $P = E/t = E\ t^{-1}$

A related unit widely used in the English speaking parts of the world is the horsepower, which equals 746 watts.

Frequency (entry 10) is used to describe a repetitive event such as the vibration of a violin string or the oscillations of a crystal. It is simply the number of oscillations per unit time and so has dimensions of 1/second = s^{-1}. This is such an important unit that is called the hertz.

$$1 \text{ hertz} = 1 \text{ Hz} = 1 \text{ oscillation per second} = s^{-1} \qquad (1\text{-}5)$$

Power line frequencies are measured in hertz; on the North American continent, for example, this frequency is usually 60 Hz.

Example 1-1. A young scientist of mass 75 kg at the Ontario Cancer Institute, in a foolish trial of endurance, ran from the basement to the seventh floor (height 25.8 m) in 23.6 s. Calculate the work done and the power developed. In Toronto the acceleration due to gravity is 9.8 m s^{-2}.

Force of attraction of the earth for scientist: $F = 75 \text{ kg} \times 9.8 \text{ m s}^{-2} = 735 \text{ newtons}$

Work done: $E = 735 \text{ N} \times 25.8 \text{ m} = 19{,}000 \text{ N m}$
$= 19000 \text{ joules}$

Power developed: $P = \frac{19000 \text{ J}}{23.6 \text{ s}} = 805 \text{ J s}^{-1} = 805 \text{ watts}$
$= 1.08 \text{ hp}$
since 746 watt = 1 horsepower

This is an impressive development of power. The experiment is not recommended, since the subject was not of much value as a scientist for a few days after the experiment.

Electrical Units

The next section of Table 1-1 involves electrical units (all items involve the fundamental unit of current, the ampere, in combination with other fundamental or derived units). Charge (entry 11) is the product of current times time and has dimensions ampere seconds (A s). Because of its fundamental importance it is given a special name, the coulomb:

$$1 \text{ coulomb} = 1 \text{ C} = 1 \text{ ampere second} = 1 \text{ A s} \qquad (1\text{-}6)$$

the defining equation is $Q = I\ t$

Potential, or potential difference (entry 12), is a difficult concept that deals with the electrical pressure that causes a current to flow in a circuit. If we connect a dry cell to a light bulb, a current flows through the bulb producing heat and light. Work is being done by the battery, and the amount of work is proportional to the charge, Q, which passes through the bulb. Potential difference is defined by

$$\text{potential difference} = \frac{\text{work done in electrical circuit}}{\text{charge passing through circuit}} \qquad (1\text{-}7)$$

Since our unit of work is the joule and unit of charge is the coulomb, potential difference is measured in joules per coulomb. This is such an important unit it is called the volt:

$$1 \text{ volt} = 1 \text{ V} = \frac{1 \text{ joule}}{1 \text{ coulomb}} = 1 \text{ J/C} \qquad (1\text{-}8)$$

By rearranging equation 1-7 we see that the work done in an electrical circuit is

$$\text{work done} = Q\ V = I\ t\ V \qquad (1\text{-}9)$$

This leads us to a special unit of energy, the electron volt (eV), which is the energy acquired when an electron of charge $e = 1.602 \times 10^{-19}$ C falls through 1 volt. Thus,

$$\mathbf{1\ eV} \text{ (a unit of energy)} = 1.602 \times 10^{-19} \text{ C} \times 1 \text{ volt} \qquad (1\text{-}10)$$
$$= \mathbf{1.602 \times 10^{-19}\ J}$$
$$\mathbf{1\ MeV} = 10^6 \text{ eV} = 10^6 \times 1.602 \times 10^{-19} \text{ J} = \mathbf{1.602 \times 10^{-13}\ J}$$

The electron volt and its multiples are extensively used in radiological science.

Capacity (entry 13) describes the ability of an insulated conductor to store charge. Such an insulated conductor is called a condenser or capacitor. When a charge Q is placed on such a conductor, its potential is raised to V and the capacity C is defined by

$$\text{capacity } C = \frac{\text{charge Q stored on conductor}}{\text{potential V to which conductor is raised}} \qquad (1\text{-}11)$$

or $Q = C\ V$

Since charge is measured in coulombs and potential in volts, the unit of capacity is coulombs per volt. This is such an important unit it is called the farad:

$$1 \text{ farad} = 1 \text{ F} = \frac{1 \text{ coulomb}}{\text{volt}} = 1 \text{ C/V} \qquad (1\text{-}12)$$

The farad is an enormous capacity, and one usually deals with capacities some 10^6 to 10^{12} times smaller.

The final electrical quantity in which we are interested is resistance (entry 14). Suppose a potential difference V is applied to the ends of a wire causing a current I to flow. The size of the current will be proportional to the applied potential and will depend on the nature of the wire—its area, its length, and the material from which it is made. The resistance of the wire, R, is defined as the ratio of V to I and so is measured in volts per ampere. This unit is given a special name, the ohm:

$$1 \text{ ohm} = 1\ \Omega = \frac{1 \text{ volt}}{1 \text{ ampere}} = 1 \text{ V/A} = 1 \text{ V A}^{-1} \qquad (1\text{-}13)$$

the defining equation is $V = IR$

Example 1-2. A potential of 12 volts placed across a heating coil produces a current of 1.5 amperes. Find the resistance of the coil, the charge which passes through the coil in 1.0 min, the energy dissipated, and power developed.

Resistance $R = \frac{V}{I} = (\text{eq. 1-13}) = \frac{12 \text{ volts}}{1.5 \text{ amperes}} = 8 \text{ ohms} = 8\ \Omega$

Charge $Q = I\,t = 1.5 \text{ A} \times 1 \text{ min} = 1.5 \text{ A} \times 60 \text{ s} = 90 \text{ A s} = 90 \text{ C}$

Work done (eq. 1-8) $E = Q\,V = 90 \text{ C} \times 12 \text{ V} = 1080 \text{ C V} = 1080 \text{ J}$

Power $P = \frac{E}{t} = \frac{1080 \text{ J}}{60 \text{ s}} = 18 \text{ J s}^{-1} = 18 \text{ W}$

or, by rearranging equation 1-9 we obtain

$$P = \frac{\text{work done}}{t} = I\,V = 1.5 \text{ A} \times 12 \text{ V} = 18 \text{ W}$$

Example 1-3. A current of 2.5×10^{-6} A flows into a 20.0×10^{-6} F condenser for 20 seconds. Find the potential to which the condenser is charged.

Charge placed on condenser (eq. 1-6) $Q = I\,t = 2.5 \times 10^{-6} \text{A} \times 20 \text{ s} = 10^{-6} \text{ C}$

Potential difference between plates of condenser (eq. 1-11) $V = \frac{Q}{C} = \frac{50 \times 10^{-6}\ C}{20.0 \times 10^{-6}\ F} = 2.5\,C\,F^{-1} = 2.5\ \text{volts}$

Radiation Units

We now discuss a few of the quantities and units that are used in the field of ionizing radiation.

Absorbed dose (entry 15) is defined as the energy deposited by ionizing radiation per unit mass of material and is expressed in J/kg. This is such an important quantity in radiological science that a special SI unit, the gray (Gy) has been created (W1)*, to represent 1 J/kg. Another unit that has been used for some 20 years and will now slowly be abandoned is the rad, which is smaller by a factor of 100 (1 Gy = 100 rads = 1 J/kg).

Exposure (entry 16) is the quantity that is used to describe the output of an x ray generator. It is the charge liberated by ionizing radiation per unit mass of air and in SI units is expressed in C kg^{-1}. For many years exposure has been expressed in roentgens, where 1 roentgen = 2.58×10^{-4} C kg^{-1}. There is no doubt that the roentgen will continue to be used for a few years in spite of the fact that it is not accepted as an SI unit by CGPM. In this book we will often express exposures in roentgens as well as in C/kg.

Activity (entry 17) describes the number of disintegrations per unit time of a radioactive isotope. Since disintegrations have no dimensions, activity is measured in reciprocal seconds, or s^{-1}. The special unit of activity is the becquerel (Bq) = s^{-1}. For many years activities have been measured in curies (Ci); 1 Ci = 3.70×10^{10} Bq. The introduction of the becquerel may create some problems so throughout the book we will use the curie as well.

It should be noted that the becquerel is measured in the same fundamental unit, s^{-1}, as the hertz. This is unfortunate but will probably not create too serious a problem since the fields of radioactivity in which the becquerel is used should not often be confused with electrical engineering, where the hertz is used. One would certainly not measure activity in hertz or an electrical frequency in becquerels. There is one important distinction between the two concepts: in radioactivity disintegrations are at random, while frequencies in hertz are periodic functions with pulses evenly spaced in time.

PREFIXES: All of these units can be altered by various factors of 10 through the use of appropriate prefixes. These are summarized in Table 1-2.

*References are found at the end of the book.

TABLE 1-2
Prefixes to be Used to Alter Units by Powers of 10

deci (d) = 10^{-1}	deka (da) = 10^{1}
centi (c) = 10^{-2}	hecto (h) = 10^{2}
milli (m) = 10^{-3}	kilo (k) = 10^{3}
micro (μ) = 10^{-6}	mega (M) = 10^{6}
nano (n) = 10^{-9}	giga (G) = 10^{9}
pico (p) = 10^{-12}	tera (T) = 10^{12}
femto (f) = 10^{-15}	peta (P) = 10^{15}
atto (a) = 10^{-18}	exa (E) = 10^{18}

For example, one might refer to the capacity of a particular condenser as being 100 picofarads (100 pF) or 0.1 nF or 10^{-10} F. In addition the use of a double prefix should be avoided. For example, although 1 mμs = $10^{-3} \times 10^{-6}$ s = 10^{-9} s = 1 ns is correct, the use of the double prefix, mμ (milli micro), is not recommended. When a prefix is used before the symbol of a unit the combination of prefix and symbol should be considered as one new symbol. For example, cm^3 means $(cm)^3$ not $c(m)^3$. Thus, $cm^3 = (0.01\ m)^3 = 10^{-6}\ m^3$, not $0.01\ m^3$.

The reader may well wonder why numbers such as 2.58×10^{-4} C/kg should appear in a so-called logical science and why some numbers should be so large and others so small. The answer is that once the fundamental units of mass (kg), length (m), time (s), and current (A) are defined all others follow. The coulomb is logically an ampere second and is a useful unit to measure charge in an electrical circuit, but it is far too large a unit to be useful in describing the charges liberated in an ion chamber by ionizing radiation. Now we require a unit some 10^{12} times smaller, such as the picocoulomb (pC). The curious numbers involved in the definition of the roentgen = 2.58×10^{-4} C/kg arise from the fact that roentgen was defined as the radiation required to liberate 1 electrostatic unit of charge in 1 cm^3 of air, a logical definition. To use it, however, in relation to other SI units requires a knowledge of a troublesome conversion factor between the electrostatic unit and the coulomb and more confusion results. Similarly, the curie = $3.7 \times 10^{10}\ s^{-1}$ needs comment. This unit of activity was originally defined as the activity of 1 gm of radium, a logical but troublesome definition as with each improved measurement of the emissions of radium, a redefinition of the unit of activity would be required.

Often it is required to convert a measurement from one unit to another. For example, since 1 gray (Gy) = 100 rad, a dose of 50 Gy could be expressed:

$$\text{Dose} = 50\ \text{Gy} = 50 \times 100\ \text{rad} = 5000\ \text{rad}$$

Observe that one carries the unit along in the calculation with the numerical value; in this case we replace 1 Gy by its equivalent 100 rad. Note that the rad is a *smaller* unit of dose than the gray, hence to describe a given dose in rads, one requires a *larger* numerical value. Mistakes can often be avoided by asking if the answer seems reasonable. If the new unit is smaller, a larger number is required to describe a given quantity and vice versa.

Example 1-4. A patient is given an x ray exposure X, of 5.16×10^{-5} coulombs per kg. Convert this exposure into roentgens (R), given that $1\text{R} = 2.58 \times 10^{-4}$ coulombs per kg.

In equations and in conversion factors, rather than use "per," it is simpler and better to use a fraction or a reciprocal:

$$X = 5.16 \times 10^{-5}\,\frac{\text{C}}{\text{kg}} \qquad \text{or} \qquad X = 5.16 \times 10^{-5}\ \text{C kg}^{-1}$$

$$1\ \text{R} = 2.58 \times 10^{\;4}\ \text{C kg}^{-1} \qquad \text{or} \qquad 1\ \text{C kg}^{-1} = \frac{1\ \text{R}}{2.58 \times 10^{-4}}$$

Replacing 1 C kg^{-1} by its equivalent

$$X = 5.16 \times 10^{-5}\ \text{C kg}^{-1}$$

$$= 5.16 \times 10^{-5} \times \frac{1\ \text{R}}{2.58 \times 10^{-4}} = .200\ \text{R}$$

By carrying the units along with the numbers we obtain our answer with its units. We then ask, is the answer reasonable? In this case, the roentgen is a much smaller unit than the C/kg, hence our answer must be a much larger number (0.2) than the original number of 5.16×10^{-5}.

1.03 ATOMS

All matter is composed of atoms. Each atom consists of a small dense nucleus with a radius of about 10^{-14}m, and a surrounding "cloud" of moving planetary electrons that travel in orbits with radii of about 10^{-10} m. The electrons have a small mass compared to the nucleus but, because of their diffuse nature, occupy a great deal of space. A group of atoms then consists of a few dense spots (nuclei) while the rest of the space occupied by the electrons is virtually empty. As an illustration, if an atom were increased in size to "occupy" a room, the nucleus would occupy a space the size of a pin point placed at the center of the room. Because of this emptiness of so-called solid matter, a high energy electron or nucleus from one atom may readily penetrate many atoms before a collision results between the moving particle and any part of the atom.

Atoms differ from one another in the constitution of their nuclei and in the number and arrangement of their electrons. *The number of electrons in the atom is referred to as the atomic number and is represented by Z.* Z ranges from one for the simplest atom (hydrogen) to 105 for the most complex atom as yet discovered (hahnium). The chemical properties of an atom are determined by the atomic number. The properties of the lighter atomic species are given in Table 1-3. The first column gives the element, the second column the symbol used to represent this element, and the third column the atomic number, Z. To understand the rest of the table, we must inquire into the structure of the nucleus.

TABLE 1-3
Atomic Numbers, Atomic Weights, and Mass Numbers of a Few of the Lighter Elements

Element	Symbol	Atomic Number (Z)	Atomic Weight (amu)	Mass Numbers of Stable Isotopes (A)	Mass Numbers of Unstable Isotopes (A)
Hydrogen	H	1	1.00797	1, 2	3
Helium	He	2	4.0026	3, 4	5, 6, 8
Lithium	Li	3	6.941	6, 7	5, 8, 9, 11
Beryllium	Be	4	9.0122	9	6, 7, 8, 10, 11, 12
Boron	B	5	10.811	10, 11	8, 9, 12, 13
Carbon	C	6	12.011	12, 13	9, 10, 11, 14, 15, 16
Nitrogen	N	7	14.0067	14, 15	12, 13, 16, 17, 18
Oxygen	O	8	15.9999	16, 17, 18	13, 14, 15, 19, 20

1.04 THE NUCLEUS

A nucleus can be broken up into its constituent parts by bombarding with high speed particles. When this occurs, it becomes evident that there are two important, fundamental particles within the nucleus: *protons and neutrons.* Either particle may be referred to as a *nucleon.* Protons carry a positive charge, equal in size but opposite in sign to that carried by the electrons, while neutrons have no charge. Protons and neutrons have nearly the same mass, some 1900 times that of the electron. Since the atom as a whole is electrically neutral, there must be one proton in the nucleus for every electron outside the nucleus. Hence Z, which represents the number of electrons outside the nucleus, also represents the number of protons in the nucleus.

MASS NUMBER, A: The total number of nucleons in the nucleus (protons plus neutrons) is called the mass number and range from 1 for hydrogen to about 250 for the heaviest nuclei. Since Z represents the number of protons in the nucleus, (A − Z) gives the number of neutrons.

ISOTOPES: Most elements consist of a mixture of several atomic species with the *same* extranuclear structure but *different* nuclear masses, that is, different mass numbers. *Atoms composed of nuclei with the same number of protons but different number of neutrons are called isotopes.* Isotopes may be stable or unstable and a few of both types are given in Table 1-3. For example, hydrogen has two stable isotopes with mass numbers 1 and 2, and an unstable one with mass number 3. Helium has two stable isotopes, mass numbers 3 and 4, and three unstable isotopes, mass numbers 5, 6, and 8. Lithium consists of two stable isotopes, mass numbers 6 and 7, and four unstable isotopes, mass numbers 5, 8, 9, and 11. The stability of an isotope depends upon there being the right mixture of protons and neutrons. If there is an unbalance in this mixture, a particle will be ejected; this process will continue until a stable configuration is achieved. The ejection of a particle is called a disintegration and the isotope is said to be radioactive. This will be dealt with in later sections of this book.

Since *isotopes* have the same number of protons, and hence the same number of electrons, they *have the same chemical properties.* For this reason they cannot be separated chemically. They can, however, be separated in the mass spectrometer, which exploits the mass differences between the nuclei.

Atomic masses are related to the mass of one of the isotopes of carbon (mass number 12), which is arbitrarily assigned the value 12.0000. Since carbon 12 has 6 protons and 6 neutrons, and since protons and neutrons have nearly the same mass, each particle on this scale has a mass of nearly 1. This means that atomic masses are very nearly whole numbers and equal to the mass number. For example, the two isotopes of hydrogen have atomic masses of 1.007825 and 2.014102, which are very nearly equal to the mass numbers 1 and 2.

Atomic masses as used in chemistry (and usually called atomic weights) and represented by A are generally different from atomic masses since usually there are a number of isotopes involved in a naturally occurring element. For example, boron as found in nature consists of a mixture of two isotopes of mass numbers 10 and 11 in the proportions 19.8% and 80.2%, giving an atomic weight of 10.811 (see Table 1-3). Sometimes atomic masses are nearly whole numbers because one of the isotopes may be much more abundant than any of the others. For example, hydrogen in nature exists as a mixture of mass number 1 (99.985%) and mass number 2 (0.015%), giving an atomic mass of nearly 1 (1.00797).

NOTATION FOR ATOMIC SPECIES: It is usual to represent atomic species using subscripts and superscripts preceding the chemical symbol. For example, the three isotopes of hydrogen (see Table 1-4) are represented by ${}^{1}_{1}H$, ${}^{2}_{1}H$, and ${}^{3}_{1}H$. The subscript gives Z, the number of protons in the nucleus, while the superscript gives the mass number, A. There is some redundancy in this notation, the subscript really being unnecessary because the chemical symbol tells the chemist the atomic number. Often then one could refer to the isotopes of hydrogen as simply ${}^{1}H$, ${}^{2}H$, and ${}^{3}H$. In speaking, these are referred to as hydrogen 1, hydrogen 2, and hydrogen 3.

ISOTOPES OF HYDROGEN: The nucleus ${}^{2}H$, containing one proton and one neutron, is important in nuclear disintegration experiments. It is called a *deuteron.* An atom composed of one deuteron and an electron is

TABLE 1-4
Isotopes of Hydrogen and Helium

Element	Symbol	Number Protons	Number Neu- trons	Mass Number (A)	Properties	Name of Nucleus	Name of Corresponding Atom
Hydrogen Z = 1	$^{1}_{1}H$	1	0	1	Stable	Proton	Hydrogen
	$^{2}_{1}H$	1	1	2	Stable	Deuteron	Deuterium
	$^{3}_{1}H$	1	2	3	Radioactive		Tritium
Helium Z = 2	$^{3}_{2}He$	2	1	3	Stable		
	$^{4}_{2}He$	2	2	4	Stable	Alpha	
	$^{5}_{2}He$	2	3	5	Radioactive		
	$^{6}_{2}He$	2	4	6	Radioactive		
	$^{8}_{2}He$	2	6	8	Radioactive		

called heavy hydrogen or deuterium. The nucleus ^{3}H, consisting of one proton and two neutrons, is radioactive and decays into an isotope of helium ($^{3}_{2}He$). The atom formed from ^{3}H is called *tritium.*

Isotopes of Helium: There are five known isotopes of helium, $^{3}_{2}He$, $^{4}_{2}He$, $^{5}_{2}He$, $^{6}_{2}He$, and $^{8}_{2}He$, of which the first two are stable and the latter three radioactive. $^{4}_{2}He$ is the major constituent of helium and is widely used in nuclear disintegration experiments. It is known as an *alpha* particle. Helium 5, 6, and 8 decay into isotopes of lithium.

Isotopes of Cobalt: ($^{54}_{27}Co$, $^{55}_{27}Co$, $^{56}_{27}Co$, $^{57}_{27}Co$, $^{58}_{27}Co$, $^{59}_{27}Co$, $^{60}_{27}Co$, $^{61}_{27}Co$, $^{62}_{27}Co$, $^{63}_{27}Co$, $^{64}_{27}Co$.) $^{59}_{27}Co$ is the only stable isotope of cobalt, containing 27 protons and 32 neutrons. The others disintegrate in a variety of ways to form isotopes of iron and nickel. Cobalt 60 is used as the source of radiation in many therapy units.

In general, as the atomic number is increased, the number of isotopes and the number of stable isotopes increase. For example, naturally occurring tin consists of a mixture of 10 stable isotopes and at least 15 radioactive ones may be produced artificially.

1.05 ELEMENTAL PARTICLES

In the last section, we saw that the nucleus consists of protons and neutrons. However, in nuclear disintegration experiments, a host of other "particles" have been discovered. A few of these of interest to us are briefly described in Table 1-5. In this table masses are expressed in terms of the mass of one of the isotopes of carbon = 12.0000, and charges in terms of the charge on the proton = 1.602×10^{-19} C.

1.06 EXTRANUCLEAR STRUCTURE

In discussing x rays and their effects on atoms, we are interested in their extranuclear structure, that is, the arrangement of the planetary electrons outside the nucleus.