RADIOLOGY PHYSICS

JOHN KELLOCK ROBERTSON

THIRD EDITION

RADIOLOGY PHYSICS

AN INTRODUCTORY COURSE FOR RADIOLOGISTS, RADIOGRAPHERS AND MEDICAL STUDENTS

BY

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LONDON
MACMILLAN & CO LTD
NEW YORK · ST MARTIN'S PRESS
1956

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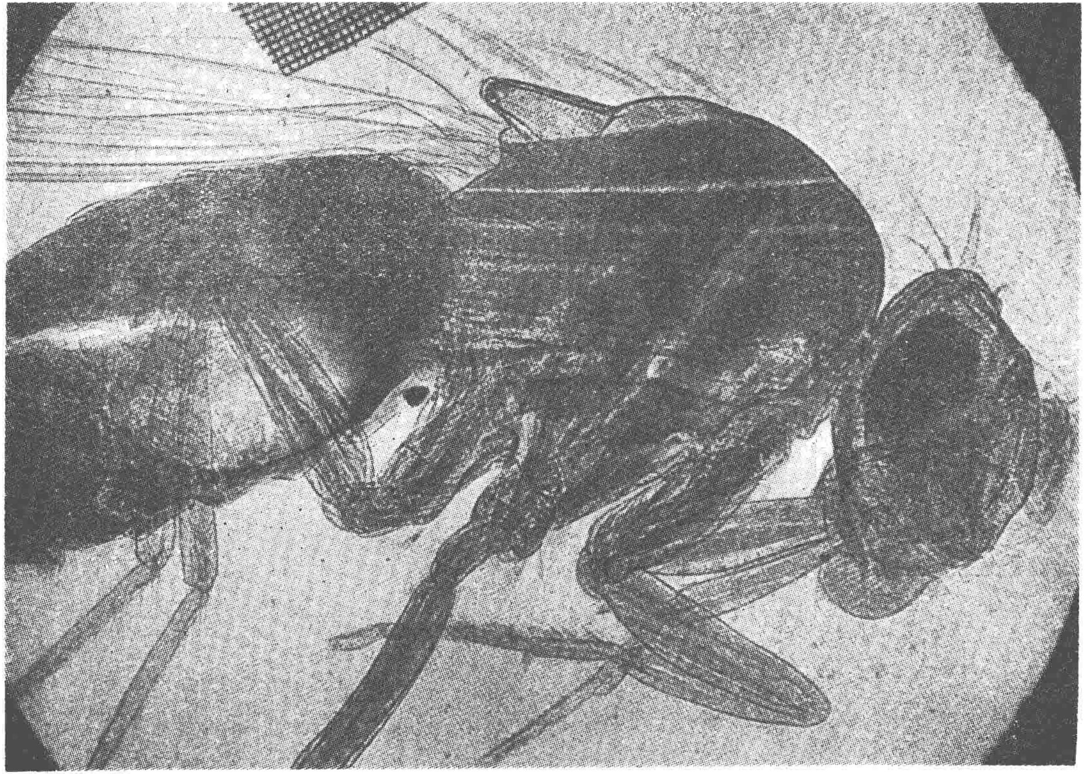

Courtesy Cosslett and Nixon

Microradiograph of *Drosophila melanogaster* (fruit fly), freeze-dried. Primary magnification $\times 20$; enlargement factor $\times 7{\cdot}5$; total magnification $\times 150$. The pattern in the upper left corner is a portion of a silver grid, 1500 meshes per inch.

PREFACE TO THE THIRD EDITION

In this edition much new material has been added and a fair amount considered either obsolete or unnecessary, dropped. The additional work includes a new chapter on Radiography and Microradiography, sections on the oscilloscope, the image intensifier, the scintillation counter, the rad and the rem, the different types of synchrotrons and the linear accelerator, and much new material on the physics necessary for the use of radioactive isotopes. An important Appendix on protection has been added. The revision has made possible also the introduction of many minor changes and the addition of certain topics such as inherent regulation, the meaning of cross-section, average life, secular and transient equilibrium, photoelectric timer, and tomography. It is hoped that this edition will be of enhanced value to students of both therapy and diagnosis.

The original character of the book has been maintained, its aim being to explain as simply as possible the basic physical principles necessary for the intelligent use of applications of physics in medicine and of radioactive isotopes. Although a knowledge of only elementary mathematics is necessary, wherever possible the work is treated quantitatively, with considerable emphasis on the solution of problems.

In the preparation of the book it is a pleasure for the author to acknowledge his indebtedness to many people and to a number of commercial firms. So many fellow physicists have given help, either directly or indirectly, that it is not possible to give a complete list, but special mention must be made of courtesies shown by Mr. W. J. Meredith, Chief Clinical Physicist of Christie Hospital and Holt Radium Institute, Manchester; Professor J. E. Roberts and Dr. H. F. Cook, of Middlesex Hospital, London; Professor J. Rotblat and Dr. J. W. Boag, of St. Bartholomew's Hospital, London; Professor G. Stead and Professor C. B. Allsopp, of Guy's Hospital Medical School; and Professor F. W. Spiers of the University of Leeds. Most of all, the author is grateful for acts of kindness too numerous to list to Professor W. V. Mayneord and his secretary, Miss Audrey Morrell, of the Royal Marsden Hospital, and to many members of his department, especially Dr. L. F. Lamerton, Dr. G. Spiegler, Dr. N. G. Trott, Miss G. M. Clark, Dr. E. H. Belcher and

Mr. H. J. D. Ireland. It is a pleasure also to thank Sir Edward Bullard and Mr. W. E. Perry of the N.P.L. for literature relating to the standardization of radioactive isotopes in Great Britain ; to Mr. W. E. Schall for the gift of a diagram and for permission to use a diagram from an early edition of his book *X-rays, their Origin, Dosage and Practical Applications* ; to Dr. S. W. Shellshear for the loan of notes ; and to Mr. R. S. Wright for literature relating to stabilizers. The author is greatly indebted to Dr. V. E. Cosslett and Dr. W. C. Nixon both for the gift of the photograph appearing in the frontispiece and for reading, with helpful comments, the chapter on Radiography and Microradiography.

Much of the preparation was done in the library of the British Institute of Radiology, and the help given by Miss G. Davey, General Secretary, Miss M. Powell and Mr. A. E. Atkins is warmly appreciated. Grateful thanks are also due to K. C. Denley, of the Society of Radiographers, for the gift of literature.

Valuable help has been received from a number of commercial firms and their representatives. Special thanks are due to Miss K. C. Clark and Mr. W. Watson of the Ilford Department of Radiography and Medical Photography ; to Isotope Developments Limited for the gift of a photograph of a scintillation counter head ; to Kodak Limited for information about photographic emulsions ; to Mr. R. H. Bull of Atomic Energy of Canada Limited for the gift of a photograph of the theratron ; to the Controller of H.M. Stationery Office for permission to use two photographs of a Harwell reactor ; and, for literature and help, to E.M.I. Research Laboratories Ltd., Marconi Instruments Ltd., and Watson and Sons (Electro-Medical), Ltd. Philips Electrical Ltd. have supplied the author with so much material, much of which has been used, that a word of special thanks is due to them.

Acknowledgement should also be made of the author's use of a *Glossary of Terms used in Radiology*, soon to be published by the British Standards Institution.

J. K. R.

HAMPSTEAD, LONDON
April, 1955

PREFACE TO THE SECOND EDITION

THE developments in nuclear physics which were announced to the world with dramatic suddenness in August 1945 are of great importance in the field of radiology and have made a second edition of *Radiology Physics* desirable. In carrying out the revision, the author has added new work in atomic physics and at the same time has taken the opportunity to overhaul the whole book, rearranging the order and amplifying where necessary. The elementary character of the book has been maintained, for it is essentially an introduction to a vast field whose importance in biology and in medicine is now fully recognized.

In the preparation of the manuscript the author has consulted freely current literature on nuclear and atomic physics and, in particular, would like to express his indebtedness to *Medical Physics*, edited by Otto Glasser, and to *Lectures in the Physics of Radiotherapy* by M. V. Mayneord, complimentary copies of which were received from the Ontario Institute of Radiotherapy. Acknowledgement is gladly made of helpful suggestions received in conversation with Professor Mayneord, of the Royal Cancer Hospital, London, and with my colleague, Dr. H. M. Cave. A number of new illustrations have been introduced and, for some of them or for permission to use them, my grateful thanks are due Dr. Matthew Luckiesh, Dr. Edith Quimby, Professor Pierre Demers, Professor Serge A. Korff, The Victoreen Instrument Company, Machlett Laboratories, Incorporated, *Radiology* and Dr. J. M. Cork.

The author would like to take this opportunity of expressing his appreciation of helpful comments made by many after the original publication of *Radiology Physics* and, in particular, to thank Dr. Marvin M. D. Williams, of the Mayo Foundation, Rochester, Minn.

J. K. R.

QUEEN'S UNIVERSITY
May 1948

PREFACE TO THE FIRST EDITION

WITH the ever increasing applications of physics in medicine the problem of giving the medical or the premedical student adequate instruction in physics has become one which demands action. To teach in one year the fundamental principles of physics, and at the same time to deal adequately with those applications with which a medical student should be familiar, is well nigh impossible. At Queen's University the problem has been solved and, on the whole, satisfactorily, by giving instruction in two successive years. In the first year, the student is given the usual course in general physics, with the omission of electricity and magnetism. In the second year, lectures and laboratory work in electricity and magnetism lead naturally to a consideration of such topics as X-ray transformers, X-ray tubes, conduction of electricity through gases, radioactivity, nuclear physics, and high frequency currents. *Radiology Physics* covers, with some amplification, the work given by the author in the second half of this course.

It is hoped that this book will prove suitable as a text for similar courses elsewhere, especially for those institutions which agree with the Committee on the Teaching of Physics for Premedical Students* in their opinion " that the American Association of Physics Teachers should go on record as in favour of making the physics prerequisite two years instead of one ". *Radiology Physics* is also commended to all radiologists and radiological technicians who wish, not a handbook, but a simple explanation of the physical principles underlying the use of their apparatus. Although a knowledge of elementary electricity and magnetism is assumed, the mathematical treatment is reduced to a minimum.

In the preparation of the manuscript, the author has made some use of an earlier book on *X-rays and X-ray Apparatus*, and his thanks are due the President of D. Van Nostrand Company, Inc., for permission to use some of the material in the more recent *Atomic Artillery*. Under each illustration due acknowledgment is made where necessary, but my special thanks are due the Philips' Gloeilampenfabrieken, Eindhoven, Holland, the General Electric X-ray Corporation, Dr. J. G. Trump of the Massachusetts Institute of

* *The American Physics Teacher*, 5, 267, 1937.

Technology, and Mrs. Edith Quimby and Dr. G. Failla of the Memorial Hospital, New York, for photographs and other material. Acknowledgment is also made of the kindness of Mr. A. C. Baldwin, Mr. G. E. Simons, and Dr. J. Gross, of the General Electric Corporation, and Mr. Victor Hicks of the Westinghouse X-Ray Company.

It is a pleasure to thank my wife for her valuable asistance throughout the preparation of the book, and my colleagues Dr. B. W. Sargent, who read part of the manuscript, and Dr. H. W. Harkness, who read the chapters on high voltage. With Dr. Sargent the author has had many discussions. My friend and colleague Dean A. L. Clark has again provided clerical and other assistance and it is a pleasant duty to express to him my appreciation.

J. K. R.

QUEEN'S UNIVERSITY
KINGSTON, CANADA
October, 1940

CONTENTS

CHAPTER I
ALTERNATING CURRENTS

THE aim of this text is to present in a systematic way the fundamental physical principles utilized in the field of radiology. It is assumed that the reader has had a general course in physics, but the author does not hesitate to review and to amplify important parts of the elementary course. For example, at the outset the student is asked to recall a few principles in electricity and magnetism, that branch of physics whose applications abound in radiology.

1.1. Electromagnetism. All students are familiar with the fact that when a bar magnet is placed beneath a sheet of paper on which iron filings are sprinkled, the filings arrange themselves along regular lines. This simple experiment indicates that in the region around the magnet there is a *magnetic field of force*. To visualize this field we say that it is traversed by magnetic lines or that there is a *magnetic flux* through the medium. At any given place a magnetizing force* acts, producing a *magnetic induction*, which is measured by the *flux density*, that is, by the number of lines of magnetic induction per cm^2, the area being at right angles to the lines. The unit of magnetic induction, that is, 1 line per cm^2 is called the *gauss*. It is invariably the lines of magnetic induction with which we are concerned and usually we speak of a field of either so many lines per cm^2 or so many gauss.

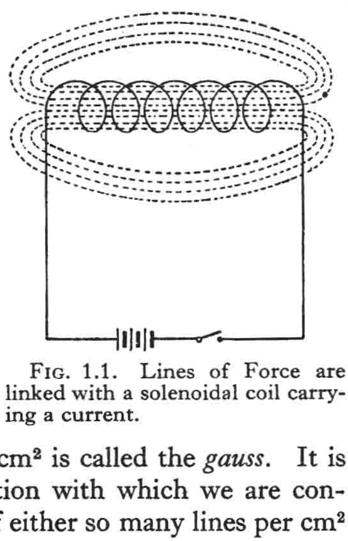

FIG. 1.1. Lines of Force are linked with a solenoidal coil carrying a current.

Elementary experiments with electric currents prove that a magnetic field surrounds a wire carrying a current and show that, if the wire is bent into a solenoidal coil, as in Fig. 1.1, one end of the solenoid is a north pole, the other a south. Moreover, if the air inside the solenoid is replaced by a core of soft iron, the iron becomes strongly magnetized under the influence of the magnetic field due to

* The value of this force is expressed in oersteds, 1 oersted corresponding to a force of 1 dyne acting on a unit magnetic pole, in a vacuum.

the current, and a powerful electromagnet may be created. We can have magnetic fields, therefore, subject to the control of an electric circuit. When the circuit is closed, the magnetic lines are said to be *linked* with the turns of the circuit, the number of *linkages* being equal to the product of the total magnetic flux times the number of turns of the circuit with which they are linked. When the circuit is broken, the lines disappear, with a consequent change in the number of linkages.

1.2. Electromagnetic Induction. Suppose a wire *AB*, Fig. 1.2., which forms part of a simple closed circuit containing a galvanometer *G but no battery*, is free to be moved between the poles of an electromagnet whose circuit is closed. If *AB* is moved from position I across the lines of force to position II, (indicated by *A'B'*) a momentary current is indicated by the galvanometer. If the wire *AB* is moved back again, a momentary current in the opposite direction is recorded. In general, it is found that as long as the wire is moving with respect to the lines of force, a current is developed. This and many other similar experiments prove that *whenever a portion of any circuit is moving with respect to magnetic lines of force, an induced electromotive force (e.m.f.) is developed, and if the circuit is closed, an induced current results.* This is the very important principle of electromagnetic induction, discovered in 1832 by Faraday in England, and simultaneously by Henry in the United States.

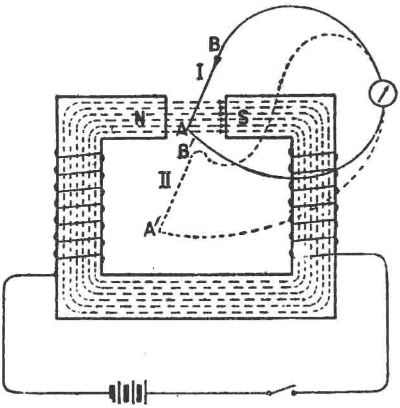

FIG. 1.2. When the wire *AB* is moved across the magnetic field, an induced electromotive force is developed in the wire.

The principle may be stated in another and possibly more useful way. When the movable wire *AB* is in position I there are no lines of force linked with the galvanometer circuit, but when it is in position II, all the lines are linked or interlocked with that circuit. Frequently, then, we state that an induced e.m f. is developed in a circuit wherever there is any *change* in the number of lines linked with it. If, for example, the wire is left in position *A'B'* and the electromagnet circuit (the *primary* circuit) is *broken*, there is a momentary induced current in the movable wire circuit (the *secondary*). Again, when the primary circuit is *made*, a momentary induced current results in the secondary. In this experiment, the secondary circuit is not moved, but the magnetic lines appear on make of the primary, disappear on break, and so on both make and break there is relative motion of lines and a portion of a circuit. Or, stating it the other way, on *break* of the primary, there is a decrease in the number of lines linked with the secondary ; on *make*, an increase —in both a change, and hence an induced e.m.f. is developed.

The magnitude of the induced e.m.f. is found by experiment to depend on the *rate* at which the lines are cut or on the rate at which the number of linkages is changing. Large e.m.f. may be obtained, therefore, when numerous electric conductors rapidly cut the lines of strong magnetic fields, or when such fields are linked and "unlinked" with many turns of an electric circuit. This, in fact, is the basic principle utilized in dynamos, in transformers and in induction coils.

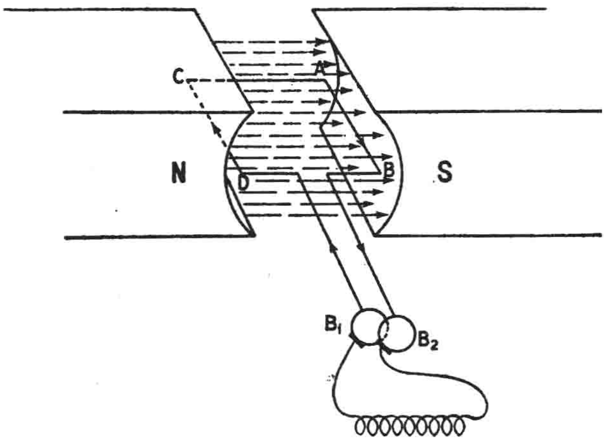

FIG. 1.3. A simple arrangement to generate an alternating current.

1.3. Alternating Currents (a.c.). Suppose a single loop of wire *ABCD*, Fig. 1.3, is rotated in the region between two magnetic poles *N* and *S*. As the wire *AB* goes down it cuts lines of force and in it we have an induced e.m.f. in the direction of the arrow. At the same time *CD*, the other side of the loop, goes up, thus cutting the lines in the opposite direction and so developing in *CD* an induced e.m.f. in the opposite direction. If the ends of the loop are connected to two slip rings upon which rest brushes B_1 and B_2 and these brushes are connected by an external conductor, the circuit is complete and a current flows. Evidently all the time *AB* is going down and *CD* up, that is, for half a revolution, a current flows in the direction indicated by the arrows. After AB has reached its lowest position, however, it begins to move up, thus cutting lines in the opposite direction, and the direction of the induced e.m.f. and of the resulting current reverses. At the same time the wire CD reverses its direction from up to down, and in it, too, the induced e.m.f. changes direction. It follows, therefore, that with this simple arrangement, for one half of a revolution a current is flowing in one direction, for the other half, in the opposite.

Not only, however, is there a reversal of current (or, if you like, of polarity between the brushes B_1 and B_2) but the *strength* of the current is continually changing. This will be evident if it is realized that when the wire AB is passing through its highest position and the wire CD through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As AB goes down (and CD up) the lines are cut more and more quickly until after one quarter of a revolution both AB and CD are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the biggest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until AB reaches the bottom (CD the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero, from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Fig. 1.4. This is called a sine curve, because, as is explained more fully in section 1.11, the changes in current values follow a sine law.

A current of this type is an *alternating* one (a.c.) as well as *sinusoidal*. Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual " smooth " changes in intensity.

It is well to note that while a sinusoidal current is always a.c., it is possible to have alternating currents which are not sinusoidal.

Two or three important terms should be noted.

A *cycle* refers to the complete change from zero to a maximum in one direction, down through zero to a maximum in the other direction and back again to zero. In Fig. 1.4, OA represents a cycle.