NUCLEAR PHYSICS

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1964.3.2

WADSWORTH PUBLISHING COMPANY, INC.
Belmont, California

503267

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L.C. Cat. Card No.: 62-17901

Printed in the United States of America

Preface

In the study of mechanics, one finds that a very few unifying concepts can be used to explain virtually all observed mechanical phenomena. The same thing can be said of thermodynamics and electricity, except that here there are more basic principles than in mechanics. Nuclear physics, by contrast, is not so neatly structured. Many of the basic laws—laws that might, for example, explain the binding together of nuclear particles—are still lacking. In mechanics, thermodynamics, and electricity it is most efficient, from a pedagogical viewpoint, to state the established laws and then develop their many consequences in an orderly fashion. Such a presentation requires that the student make a separate study of the historical development of the field if he is to gain an insight into the ways in which our present ideas have evolved, and such an insight is indispensable if the student is some day to carry on investigations of his own on the frontiers of scientific knowledge.

Nuclear physics presents a most unusual opportunity to learn the factual matter and its historic setting with little sacrifice in efficiency. The reason is that the field is evolving rapidly, so one must know the background of our present tentative ideas in order to appreciate new theories and developments when they arise. For example, an excellent book published in 1955 stated flatly that the parity of an isolated system is always conserved, thereby leaving the student completely unprepared for the discovery, which soon followed, that parity is *not always* conserved.

In the present book the historical development is followed as much as possible, but whenever this approach seems too cumbersome, ideas are presented in whatever order appears conducive to an understanding of the present status of our concepts.

It has been my observation that beginning graduate students are usually appalled upon discovering their own experiments to be so much more difficult than they had been led to believe by the schematic drawings of equipment and the casual descriptions of procedures given in texts. It is hoped that the occasional lengthy discussions of misinterpreted experiments as well as the detailed descriptions of certain pieces of apparatus will give the student a more realistic background for beginning his own investigations.

Educators are keenly aware of the high degree of compartmentalization of knowledge that is brought about by the methods of teaching presently employed in most colleges and universities, but find it difficult to alter the situation. As a partial solution to this unhappy state of affairs many of the problems in this book have been deliberately constructed to give the student an opportunity to utilize what he has learned in other subject areas.

An attempt has been made to confine the subject matter of this book to the *physics* of nuclear physics. Chapter 4, "Methods of Detecting Nuclear Radiations," was felt to be a necessary digression enabling the reader to understand the experimental techniques used by various investigators and thus to evaluate their conclusions. The complex engineering of charged particle accelerators, although not absolutely essential to an understanding of the experiments in which they are used, is a fascinating subject and one that the student may find is not covered in any other course. For this reason, Appendix A has been devoted to a discussion of these important devices. I have found, in several years of teaching, that although most students have had courses in particle mechanics, they are not as facile in the subject as they need to be to handle the many collision problems arising in nuclear physics. The lack is particularly evident when the collisions must be treated relativistically. For this reason, the subject of collision dynamics is treated in Chapter 10. This chapter could well be read at any time during the course, but has been placed just before the chapter on high energy physics because relativistic collisions are so much a part of the latter subject. Nuclear reactors are not a proper part of nuclear physics but certainly represent the most important commercial application of nuclear physics. The interested reader will find an introduction to the physics of nuclear reactors in Appendix B.

It is assumed that the reader is familiar with quantization concepts from previous courses in modern physics or atomic physics, but that he is not necessarily familiar with the formal methods of wave mechanics. With seeming perversity, relativistic wave mechanics is mentioned in Chapter 7, but only for the purpose of enabling the reader to understand the terms used in the literature of beta decay. For the curious reader, a brief wave-mechanical treatment of barrier penetration is given in Appendix C.

The advisability of using only mks units was seriously considered but finally decided against for two reasons. In the first place, the literature uses a variety of units, with preference given to such quantities as gauss-cm, and ergs per gauss. Secondly, the student at the level for which this text is intended should no longer find conversion of units an obstacle to his understanding. He should view such conversions as are necessary in the problem

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sections not merely as nuisances (which they admittedly are) but also as opportunities to improve his facility in this very necessary process.

A rather complete list of original papers is given at the end of each chapter. I have found great pleasure in reading these papers and would like to share this pleasure with the readers of this book, for it is inevitable that in the process of condensation necessary to keep the book to a reasonable size, much interesting detail has been omitted. Some of the papers, especially those of Rutherford, are models of scientific clarity. It is hoped that the student will find time to read at least a few of these original papers both for their historical interest and to obtain a better perspective of the developments they report.

My indebtedness extends to many people, but especially to the students who used a preliminary version of this book. A specific acknowledgment is due Albert E. Wilson, who carefully read the appendix on nuclear reactors and made a number of suggestions for the improvement of the presentation. Thanks are also due Professors Harry T. Easterday of Oregon State University, J. A. Jungerman of the University of California at Davis, and William W. Watson of Yale University for their helpful comments and suggestions in the manuscript stage. It would have been impossible to write this book without the sacrifices, the patience, and the understanding of my wife, Jane.

R.A.H.

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1

THE BIRTH OF NUCLEAR PHYSICS

1-1 Early Ideas of Atomism

The idea of atomism—that all matter consists of minute, indivisible particles—began, as far as is known, with the Greeks. Leucippus is credited with founding the Greek School of Atomism at Abdera during the fifth century B.C. His pupil Democritus developed the atomic hypothesis further about 420 B.C., and their ideas were still further developed by Aristotle (384–322 B.C.).

William Higgins, on the basis of determinations of relative combining weights of elements forming chemical compounds, enunciated a theory of combination of definite numbers of atoms, such as two oxygen atoms with one carbon atom to form carbon dioxide. This theory, advanced in 1789, was generally ignored. Not until 1808–10, when John Dalton independently published an almost identical theory, did it receive any serious attention. The experimental fact of combination in definite proportions does not prove that matter consists of atoms, but it is at least in agreement with such a hypothesis, whereas the atoms of Democritus were products of pure speculation, unsupported by experimental evidence of any kind.

In 1815 Prout hypothesized that all the elements were built up of hydrogen atoms. He was led to this conclusion by the fact that most of the known atomic weights were approximately integral multiples of the atomic weight of hydrogen. However, as atomic weights became known more accurately, nonintegral atomic weights such as that of chlorine, 35.5, thoroughly discredited the now famous "Prout's hypothesis."

1-2 Discovery of Radioactivity

Prior to 1895 it was known that some fluorescent bodies, after activation by sunlight, were capable of blackening photographic plates even when the plates were wrapped in black paper. When Roentgen discovered, in 1895, that x-rays could also blacken photographic plates wrapped in black paper, a number of investigators, among them Henri Becquerel, set out to search for some connection between the two phenomena. In February of 1896 several days of cloudy weather prevented Becquerel from exposing a particular fluorescent substance (a double sulfate of potassium and uranium) to the sun's rays. When he placed it near photographic plates wrapped in black paper (1)* he found that the plates were blackened just as they were by fluorescent materials that had been activated by sunlight. He found subsequently that exposure to sunlight had no effect on the phenomenon. It was also observed that the radiation that blackened the plates was capable of penetrating thin sheets of metal and other substances opaque to visible light. Becquerel soon discovered that the penetrating radiation was associated with the uranium, that it was independent of the state of chemical combination of the uranium, and that there was no connection between it and fluorescence. Somewhat later it was found that the radiations were capable of ionizing air and discharging an electroscope, properties which x-rays had also been found to possess.

G. C. Schmidt (24) and Marie Sklodowska Curie† independently observed in 1898 that thorium gave off radiations similar to those emitted by uranium.

Madame Curie (5) made tests on the activities‡ of various compounds of uranium and thorium and found that the activity was independent of the

* Numbers in parentheses refer to the bibliography at the end of the chapter.

† Madame Curie (5) also erroneously concluded that cerium, niobium, and tantalum were slightly radioactive. She observed a high "activity" from yellow phosphorus but correctly suspected that this was not true radioactivity since red phosphorus and phosphates showed no activity whatsoever.

‡ Activity refers to some quantity that measures the intensity of the radiation. In the case of ionization measurements, the rate of discharge of an electroscope is directly proportional to the activity. Activity and photographic blackening are not so simply

state of chemical combination, thus confirming and extending the results of Becquerel. She concluded from this fact that radioactivity, as the phenomenon has come to be called, was an *atomic* phenomenon. She also found that the activity of natural pitchblende $[U(UO_4)_2]$ surpassed that of freshly prepared pure uranium oxide, and that natural chalcolite $[Cu(UO_2)_2(PO_4)_2 \cdot 8H_2O]$ was more active than the same substance prepared in the laboratory. From this she concluded that there must be some extremely radioactive ingredient in natural pitchblende and chalcolite that was not present in pure uranium, and she set herself the task of isolating this unknown substance.

Working with her husband, Pierre Curie (6), Madame Curie found that a bismuth sulfide (Bi_2S_3) could be separated from pitchblende which showed an activity 400 times that of the same quantity of pure uranium, while ordinary bismuth sulfide showed no activity whatever. They assumed that this precipitate contained a new radioactive element, which they named polonium. In collaboration with G. Bemont (7) they found that a barium sulfate precipitate from pitchblende carried down a substance which could be converted to the chloride and then separated from barium chloride by fractional crystallization. The separated crystals darkened a photographic plate in half a minute, whereas several hours' exposure was required to obtain the same degree of blackening with pure uranium or thorium. It was assumed that yet another new element had been discovered, and it was given the name radium. The atomic weight of radium was found to be greater than that of barium.

1-3 Separation of Rays into α, β, and γ Components

After numerous erroneous results had been published by various investigators it was found by F. O. Giesel (9) and by S. Meyer and E. von Schweidler (10) that the radiations could be partially resolved by a magnetic field perpendicular to the beam of radiation. Rutherford (15) suggested the names α rays for the easily absorbed undeviated component, and β rays for the deviated rays. P. Villard (26) showed that the undeflected portion of the beam could be partially absorbed by thin layers of material but that the remainder of the beam was capable of penetrating thick layers of matter. He suggested the name γ rays for the penetrating component of the undeviated rays. He found that the deflected portion of the beam was negatively charged and behaved like a beam of electrons.

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related, but the activity can be obtained from the blackening by the same methods used to interpret blackening in terms of light intensity. One such method makes use of the fact that blackening is (to a good approximation) a function of the product of intensity and exposure time, so that if it takes twice as long to produce a given amount of blackening with one source as it does with another source, one infers that the first source is only half as active as the second.

It was suggested by both Strutt (25) and Sir William Crookes (4) that since the β rays were negatively charged it was likely the α rays were positively charged. Rutherford (16) was led to the same conclusion by the following facts:

1. The decrease in intensity (as measured for example by the rate of discharge of an electroscope) is approximately proportional to the density of the material traversed by the rays. Since this was known to be true for β rays, it seemed reasonable to assume that α rays too were charged.

2. The decrease in intensity per unit thickness of traversed material increases with the thickness of material previously passed through. Since this is not characteristic of x-rays, it seemed doubtful that the rays could be electromagnetic waves.

3. Although the failure of the rays to be deflected by a magnetic field would seem to rule out the possibility of charged particles, he pointed out that q/M (the ratio of charge to mass) for H^+ ions is about 10^4 emu/gm, some thousand times smaller than the estimated value for electrons, so that if the "particles" were as massive or more massive than H^+ ions their deviation would be minute compared with that of an electron moving with the same velocity.

Rutherford (17) verified his theory by use of the apparatus shown schematically in Fig. 1-1. The radium salt was placed at the bottom of the lower box, which also contained the collimating plates. The top of the box was covered by an aluminum foil 0.00034 cm thick, and dry electrolytic hydrogen gas was forced slowly through this foil to prevent any radium emanation (a radioactive substance coming from radium, now called *radon*) from entering the ionization chamber above. A magnetic field applied perpendicular to the paper in the figure deflected the negatively charged radiation sideward, thus preventing it from passing through the collimating plates. Since a part of the undeviated radiation was known to be easily absorbed, it was advantageous to use a light gas such as hydrogen rather than air in the collimating chamber in order to reduce the absorption of the undeviated radiation. The smaller absorption by hydrogen in the ionization chamber was compensated for by making the chamber quite tall. The magnetic field was produced by the field magnet of an Edison dynamo whose pole faces were each 1.90×2.50 cm. The magnetic flux density at the pole faces was 8370 gauss and the fringing field was 2460 gauss near the bottom of the radium container.

The radium was placed 1.4 cm below the 25 collimator plates, each of which was 3.70 cm long by 0.7 cm wide. The results shown in Table 1-1 were obtained. These results prove that the α rays, which are not easily deflected by a magnetic field, are nevertheless deflected slightly by a *strong* magnetic field. The experiment, while presumably proving that the α rays consist of charged particles, gives no information as to whether they are positively or negatively charged.

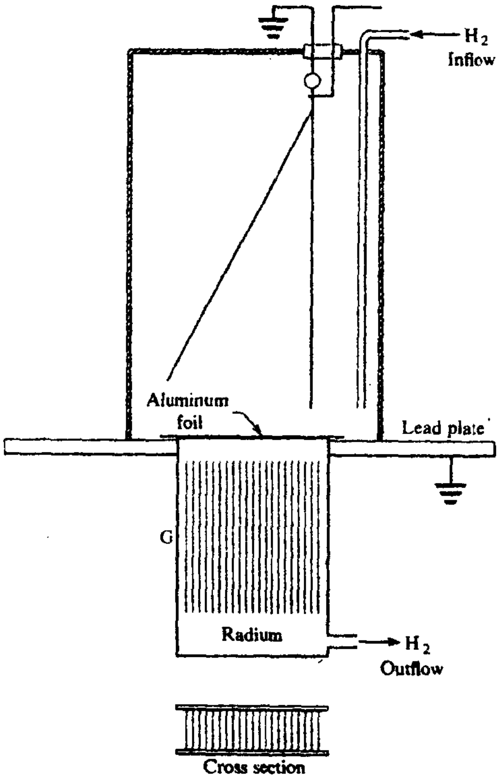

Fig. 1-1. Apparatus by means of which Rutherford proved that alpha rays are charged particles. A magnetic field perpendicular to the page was applied to the right of *G*.

Table 1-1

Condition	Electroscope discharge rate (volts/min)
Without magnetic field (residual magnetic field believed to deflect β rays)	8.33
With magnetic field	1.72
With magnetic field but radium covered with 0.01 cm thick mica plate to absorb α rays	0.93
Without magnetic field but radium covered with 0.01 cm thick mica plate to absorb α rays	0.92

Rutherford was able to determine the sign of the charge by a slight modification of the experiment. As shown in Fig. 1-2, a grid was placed over the collimating plates, thus partially blocking the openings between them.

The plates were spaced 1 mm apart and the unblocked openings were about 0.5 mm wide. When a magnetic field somewhat less than enough to deflect all the charged particles from the beam was applied in such a direction as to deflect positively charged particles toward the right, no noticeable change in ionization took place in the chamber. When a field of the same strength was

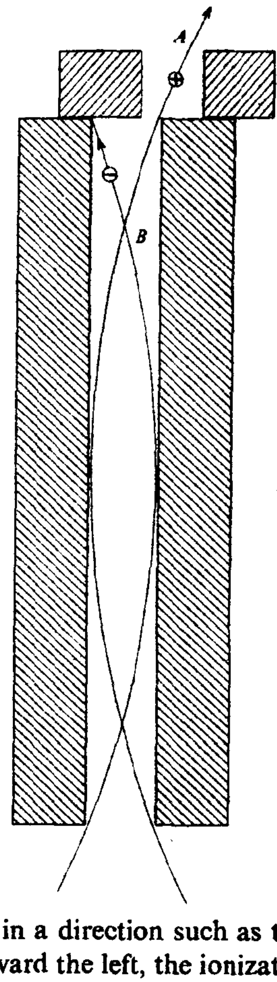

Fig. 1-2. Details of the modification made in the collimating plates of Fig. 1-1 to determine the sign of the charge borne by alpha particles. *A* is the trajectory of a positively charged particle with just sufficient energy to pass through the collimator under deflection produced by a given magnetic field. *B* is the trajectory of a negatively charged particle with the same magnitude of q/m and the same momentum as the positively charged particle whose trajectory is labeled *A*.

established in the opposite direction, that is, in a direction such as to cause positively charged particles to be deflected toward the left, the ionization was reduced to about one-fourth of its original value. This confirmed the suspicions of Crookes, Strutt, and Rutherford that the α rays were positively charged particles.

1-4 Determination of q/M for Alpha Particles

Rutherford next investigated electrostatic deflection of the α rays by insulating the collimating plates from each other and applying a potential difference of 600 volts between each pair of plates. This produced a 7%

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