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Volume 5

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PART A

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FOREWORD TO VOLUME 5A

After a longer delay than originally expected, I am able to present here the next volume in the series of *Methods of Experimental Physics:* the first part of the "Nuclear Physics" Methods. Much thought and work went into this volume and I am in the best position to appreciate all the effort of my fellow editors who devoted so much time in preparing this particular volume. The aims of the publication did not change. The reception of the earlier volumes had proven that it was really useful to concentrate on "a concise, well illustrated presentation of the most important methods, or general principles, needed by the experimenter, complete with basic references for further reading. Indication of limitations of both applicability and accuracy is an important part of the presentation. Information about the interpretation of experiments, about the evaluation of errors, and about the validity of approximations should also be given. The book should not be merely a description of laboratory techniques, nor should it be a catalog of instruments." In these troubled times, when furthering of scientific education is so important, we hope that these volumes can be of real help as well to the educator, as to the research worker.

At the time of writing my foreword, two other volumes are well under way. The manuscripts of the companion volume of the present one, Volume 5B, are accumulating rapidly and printing should follow this one within a few months. In an even more advanced stage is our Volume 3, "Molecular Physics," which, under the very valuable leadership of Professor Dudley Williams, promises to become a perfect companion to the already existing volumes. At the writing of this foreword, Volume 3 is just entering the page-proof stage.

I would like to report also on further development. It has been suggested that, in order to enhance the usefulness of this collection to the graduate student, we supplement the planned six volumes with a seventh devoted to nothing but problems. In discussing this idea with a number of my colleagues I found favorable reaction and at present I am investigating how to organize such a volume.

It is a pleasant duty to thank again all those who have devoted so much time and work to the preparation of this volume. In the first place come the volume editors whose intelligent and devoted handling of the material is beyond praise. One shouldn't, however, forget the authors. They have been most accommodating and I join the volume editors in expressing my appreciation. The publishers deserve our gratitude for being very patient and very helpful during this longer delay than we expected. As in the past, Mrs. Claire Marton has been most helpful in handling many of the problems of the editorial office. To all these people go my heartfelt thanks.

L. MARTON

Washington, D. C.
June, 1961

PREFACE TO VOLUME 5A

The field of experimental nuclear physics has in the last two decades, experienced a tremendous growth of activity in all its branches. The difficulty in performing nuclear physics experiments is also greatly multiplied with the increasing complexities of the problems involved. There are, at present, many articles and books which give excellent reviews on basic principles and details of techniques of various detectors, methods and specific topics in nuclear physics. But it is often hard to obtain comprehensive information on the principal methods and their relative merits for the measurement of a specific physical quantity in the field of nuclear physics. This knowledge is especially desirable when one wishes to make a choice among the various methods on the basis of their feasibility, the accuracies attainable, and the limitations in their application under specific conditions. For any specific method of measurement, the comprehensive procedure of converting the experimental data into the desired physical quantities including the necessary corrections involved is often not explicitly mentioned in the literature. It is the intention of the present volume to try to meet some of the requirements mentioned above. All possible methods that deal with the measurement of each particular physical quantity are grouped together so as to achieve a more coherent presentation. Furthermore, the scope of this book is not limited to the usual treatment of low energy nuclear physics only, but it comprises both the high and low energy regions. We hope that this volume will serve as an informative source and as a reference book for physicists in general and, in particular, as an instructive and useful guide for all those who are interested in doing research in this field.

Every effort has been made to obtain leading experts in each field to prepare contributions on the specific topics involved so that their intimate knowledge and experience can be shared.

Owing to the comprehensive coverage of this book and to the enthusiastic response of a large number of contributors who treated their subject matter so thoroughly, it was found necessary to divide the work into two volumes rather than to publish a single volume as originally planned. For this reason and because an unusually large number of contributors have been involved, there has been some unavoidable delay in the completion of this book.

We wish to take this opportunity to express our deepest appreciation and thanks to all the contributors for their understanding and cooperation, to the publisher and to Dr. L. Marton, the Editor-in-Chief, for their invaluable help and continuous encouragement.

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August 14, 1961

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1. FUNDAMENTAL PRINCIPLES AND METHODS OF PARTICLE DETECTION

1.1. Interaction of Radiation with Matter* †

1.1.1. Introduction

In this chapter, we shall discuss the various processes which take place when charged particles and γ radiation pass through matter. For any type of charged particle (proton, meson, electron, etc.), there will be a loss of energy as the particle traverses the material, due to the excitation and ionization of the atoms of the medium close to the path of the particle. The loss of energy per cm of path, dE/dx, is generally referred to as the ionization loss. In Section 1.1.2, we give a simplified derivation of the theoretical expression for dE/dx, the well-known Bethe-Bloch formula, including a discussion of the density effect which becomes important at high energies. The ionization loss of a fast charged particle is frequently used as a means of identifying the particle, by observing its track in a cloud chamber, bubble chamber, or in photographic emulsion. The ionization loss dE/dx is a function only of the velocity v of the particle (for a given charge), so that a simultaneous measurement of dE/dx and of the momentum p enables one to determine the mass m of the particle. The ionization loss can also be used to determine approximately the energy of the particle, if its identity has been established by other methods. A further important property of the ionization process is that the energy w required to form an ion pair in a gas is approximately independent of the energy and the charge of the incident particle, so that when a particle is stopped in a gas, a measurement of the total number of ion pairs enables one to obtain the energy of the incident particle, provided that the value of w for the stopping gas is known. This property has been widely used in the operation of ionization chambers.‡ In Section 1.1.2, expressions for dE/dx are given for various cases, together with a discussion of the fluctuations of the ionization loss (Landau effect). The recent experiments on the ionization loss of relativistic charged particles will be discussed in some detail.

For particles heavier than electrons (e.g., protons, K, π, or μ mesons), the ionization loss dE/dx is the most important mechanism of energy loss. As a result, a particle with a given incident kinetic energy T will have a quite well-defined range R, which depends on T, on the mass m and on the

† See also, Vol. 4, B, Parts 6, 7, and 8.

‡ See also this volume, Chapter 1.2.

* Chapter 1.1 is by R. M. Sternheimer.

charge z of the particle, as well as on the stopping substance. The relation between R and T is known as the range-energy relation. Tables of the range-energy relation for protons of energies $T_p = 2$ Mev to 100 Bev have been recently calculated by Sternheimer[1] for the following materials: Be, C, Al, Cu, Pb, and air. These range-energy relations differ from the results of Aron *et al.*[2] in two respects: (1) the density effect correction is included at the higher energies ($T_p \gtrsim 2$ Bev); (2) recent values of the mean excitation potential I (which enters into the Bethe-Bloch formula) have been used, which are somewhat higher than the value $I = 11.5Z$ ev employed by Aron *et al.* The tables of the range-energy relations are given in Section 1.1.3, together with a table of the values of dE/dx which were used in the calculation of $R(T)$. Section 1.1.3 also includes a brief discussion of the range straggling.

Section 1.1.4 gives various formulas pertaining to the scattering of heavy particles (heavier than electrons) by atoms.

When electrons pass through matter, they lose energy by ionization in the same manner as any charged particle (see Section 1.1.2). However, in addition, a high-energy electron will produce electromagnetic radiation (bremsstrahlung) in the field of the atomic nuclei.* For electrons above the critical energy E_c (e.g., 47 Mev for Al, 6.9 Mev for Pb), the energy loss due to radiation exceeds the ionization loss, and constitutes the predominant mechanism for the slowing down process. The γ quanta from the bremsstrahlung can create electron-positron pairs, which in turn can produce additional γ rays. The resulting electromagnetic cascade is called a shower and has been widely observed in cloud-chamber pictures both with incident electrons and γ rays. The theoretical expressions for the bremsstrahlung and a discussion of shower production are presented in Section 1.1.5.

The multiple scattering of charged particles is considered briefly in Section 1.1.6.

The penetration of γ rays through matter is characterized by an absorption coefficient τ which determines the exponential attenuation of the γ ray beam. The processes which contribute to τ are the photoelectric effect, the Compton scattering, and the pair production. A summary of the theoretical expressions for these three processes is given in Section 1.1.7.

The discussion of Sections 1.1.4–1.1.7 follows closely the review article

* See also Vol. 4, A, Section 1.5.2.

[1] R. M. Sternheimer, *Phys. Rev.* **115**, 137 (1959).

[2] W. A. Aron, B. G. Hoffman, and F. C. Williams, University of California Radiation Laboratory Report UCRL-121 (1951); Atomic Energy Commission Report AECU-663 (1951).

by Bethe and Ashkin[3] on the "Passage of Radiations through Matter."

In 1956, in order to solve certain difficulties connected with the decay of the strange particles (particularly the K meson), Lee and Yang[4] discussed the consequences of a possible nonconservation of parity in the weak interactions (beta decay, strange particle decay, π- and μ-meson decay). They suggested a number of experiments to test this hypothesis. These experiments[5–7] were performed soon after the publication of their paper, and have shown very clearly that parity is not conserved in the weak (decay) interactions, in contrast to the strong interactions which conserve parity to a high accuracy. An important consequence of parity nonconservation is that the electrons (or positrons) from the beta decay of unpolarized nuclei should be strongly longitudinally polarized, i.e., the electron spin should be aligned predominantly antiparallel to the electron direction of motion, while for positron decays, the positron spin should be aligned predominantly parallel to the positron direction of motion. The magnitude of the polarization P is predicted to be v/c in each case, where v is the velocity of the particle (electron or positron). Thus for relativistic electrons or positrons, P should be essentially 100%. It should be noted that the prediction that $P = v/c$ follows only from a particularly simple theory of parity nonconservation, namely the two-component theory of the neutrino. In a separate article,[8] we have given a discussion of the proposals of Lee and Yang[4] concerning parity nonconservation in weak interactions. This article also contains a description of the crucial experiments of Wu *et al.*[5] on the beta decay of oriented nuclei (Co^{60}), and of Garwin and co-workers[6] on the polarization of the μ^+ from π^+ decay, which together with the work of Friedman and Telegdi,[7] were the first experiments that demonstrated the violation of parity conservation in weak interactions. We have also summarized[8] the two-component theory of the neutrino, which was proposed independently by Lee and Yang,[9] Landau,[10] and Salam.[11]

A large number of experiments have been performed to establish the longitudinal polarization of the electrons and positrons from beta decay.

[3] H. A. Bethe and J. Ashkin, Passage of radiations through matter. *In* "Experimental Nuclear Physics" (E. Segrè, ed.), Vol. 1, p. 166. Wiley, New York, 1953.

[4] T. D. Lee and C. N. Yang, *Phys. Rev.* **104**, 254 (1956).

[5] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.* **105**, 1413 (1957).

[6] R. L. Garwin, L. M. Lederman, and M. Weinrich, *Phys. Rev.* **105**, 1415 (1957).

[7] J. I. Friedman and V. L. Telegdi, *Phys. Rev.* **105**, 1681 (1957).

[8] R. M. Sternheimer, *Advances in Electronics and Electron Phys.* **11**, 31 (1959).

[9] T. D. Lee and C. N. Yang, *Phys. Rev.* **105**, 1671 (1957).

[10] L. D. Landau, *Nuclear Phys.* **3**, 127 (1957).

[11] A. Salam, *Nuovo cimento* [10] **5**, 299 (1957).

These investigations involve a variety of methods to determine the longitudinal polarization: scattering of the polarized electrons on nuclei (Mott scattering); scattering on polarized electrons (ferromagnetic 3*d* electrons of iron in a magnetic field), which is often referred to as Møller scattering; circular polarization of the bremsstrahlung emitted by the polarized electrons; and annihilation of the polarized positrons in various materials. The experiments have in turn led to important developments of the theories presented in Sections 1.1.4 and 1.1.5 on the scattering and interaction of electrons in matter. These new theoretical results, as well as a review of the experiments on the longitudinal polarization, are presented in the latter part of the article on parity nonconservation.*[8]

1.1.2. The Ionization Loss dE/dx of Charged Particles

1.1.2.1. The Bethe-Bloch Formula. The theoretical expression for dE/dx is based on the Bethe-Bloch formula, which has been derived from the work of Bohr,[12] Bethe,[13] Bloch,[14] and others. The Bethe-Bloch formula for particles heavier than electrons is given by

$$-\frac{dE}{dx} = \frac{2\pi nz^2e^4}{mv^2}\left[\ln\frac{2mv^2W_{max}}{I^2(1-\beta^2)} - 2\beta^2 - \delta - U\right] \tag{1.1.1}$$

where n = number of electrons per cm^3 in the stopping substance, m = electron mass, $\beta = v/c$, where v = velocity of the particle, z = charge of the particle, I = mean excitation potential of the atoms of the substance, W_{max} = maximum energy transfer from the incident particle to the atomic electrons, δ is the correction for the density effect, which is due to the polarization of the medium, as will be discussed below, and U is a term due to the nonparticipation of the inner shells (K, L, . . .) for very low velocities of the incident particle. This term is generally called the shell correction term, and will be discussed below [see Eq. (1.1.34)]. The maximum energy transfer W_{max} is given by

$$W_{max} = 2mv^2/(1-\beta^2) \tag{1.1.2}$$

for energies $E \ll (m_i^2/2m)c^2$, where m_i is the mass of the incident particle. Throughout this chapter, m (without subscript) denotes the mass of the electron.

The Bethe-Bloch formula (1.1.1) is obtained in the following manner. The electromagnetic field of the passing particle will excite the

* Other aspects of electron polarization are discussed in Vol. IV, A, Chapter 3.5; this volume, Chapter 2.5.

[12] N. Bohr, *Phil. Mag.* [6] **25**, 10 (1913); [6] **30**, 581 (1915).

[13] H. A. Bethe, *Ann. Physik* [7] **5**, 325 (1930).

[14] F. Bloch, *Z. Physik* **81**, 363 (1933).