experiments in modern physics

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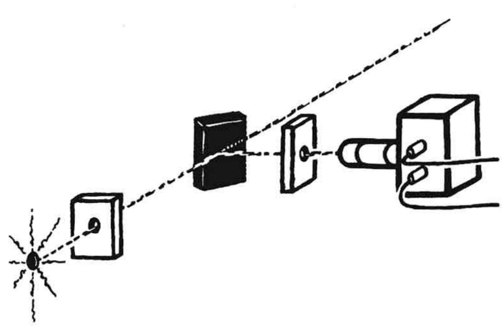

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Preface

THIS BOOK is intended as a guide for a laboratory course in modern physics. Students taking the course are expected to be juniors or seniors in science and engineering who have taken (or are taking concurrently) a course in atomic physics and who are familiar with some elementary quantum theory. The experiments have been chosen to illustrate some of the important basic concepts of modern physics and to familiarize the students with modern laboratory techniques. An effort has also been made to deal with topics having important practical applications so that engineering students will find the material useful.

In any laboratory course, there is always a conflict between the educational content of an experiment and the desire to have it "work" properly. If a laboratory experiment is so designed that it works too well, there is a danger that the student will simply flip all the proper switches, read all the meters he is instructed to read, write an appropriate report, and learn no more than he would have learned from a properly designed lecture demonstration. On the other hand, if too much of the construction and design of the experiment is left to the student, the chances are that he will not be able to perform any significant measurements, and thus will be confused rather than enlightened. The secret in organizing an effective laboratory course lies in avoiding these two pitfalls.

A skillful choice must be made between the equipment supplied and that which the student must construct for himself. The items left for construction by the student should afford the widest possible scope for individual initiative and originality. They should not be trivial things, since the students must learn that experiments never "work" properly the first time. The frustrations encountered in making things work properly are difficult to face for many students. It is exceedingly important to impress upon prospective experimental scientists that patience, care, and thoroughness are absolutely essential if reliable results are to be obtained and that frustrations are an inevitable by-product of creative work.

Although wide latitude should be left to the individual instructor to deal with some of these problems, it might be useful to outline ways in which they have been handled in the past. In the nuclear magnetic resonance experiment, the magnet, its power supply, and a good laboratory oscilloscope are supplied. The student group working on this experiment might be asked to build the resonance head. This would include winding all the necessary coils, building the appropriate mount, and providing the proper leads to the measuring equipment. The student group would also perform all the preliminary calculations to make certain that the important parameters (dimensions, electrical properties of cables, etc.) are properly chosen. Another alternative would be to require the student group to construct the radio frequency oscillator circuit which drives the coil used to excite the sample. Here also, only the basic tools and materials (soldering guns, transistors and other electrical components, etc.) would be supplied. The actual design and construction would be performed by the students themselves. Both these approaches have been successfully employed in this experiment.

If the laboratory course is to be successful, some care must be taken in organizing the student groups. A high faculty-to-student ratio in such a course is clearly desirable. In the course given at the University of California, experienced teaching assistants and interested students who had taken the course previously have been used as section leaders. Laboratory sections are held twice a week for three-hour periods. The students taking the course are divided into groups of three or four in the beginning of the semester. Some care should be taken in organizing the groups. It is highly probable that four or five students in the class have had some experience in working with experimental equipment. These can be found by asking for people who have built model airplanes, hi-fi sets, or hot rods. One of the experienced students should be assigned to each of the experimental groups. He can then act as a guide and help the other students in the group to cope with practical problems that arise.

Eleven different experimental topics are offered in the course given at the University of California. If a reasonable fraction of the construction work is left to the students, it is not possible for them to perform all the available experiments in a sixteen-week semester, and it should not be attempted. In practice, three or four of the experiments are performed by each group. Approximately ten laboratory sessions should be allocated for each experiment.

The laboratory room in which the class is conducted should duplicate conditions usually encountered in research laboratories. Several sturdy benches should be available. All the loose equipment should be stored in cabinets, and a complete tool chest should be assigned to each group. A small stock of electronic equipment and parts should be provided, together with the necessary tools.

When organizing a laboratory course, sufficient equipment must be available for complete instrumentation of the experiments. The following list of equipment is a reasonable sample of what is desirable:

Two vacuum systems
One laboratory magnet
Four DC power supplies
Two pulse amplifiers
Two oscilloscopes
Two pulse counters
Two volt-ohm-amp meters
Optical pyrometer
Ruby laser
Double pulser
Scintillation counter
Polaroid scope camera and accessories
Single or multi-channel pulse height analyzer
Assorted electronic supplies
Assorted tools

The cost of this equipment could be quite substantial if purchased new. However, the figure can be reduced considerably by picking up surplus and second-hand equipment which, although not suitable for the highest quality research, performs adequately for the experiments described in this book.

The authors have been working on this book and on the laboratory course for the past three years. A great many people have made important contributions to this venture. Professor Thomas H. Pigford of the University of California provided the initial stimulation, en-

couragement, and support for the organization of the laboratory course. He was also responsible for developing the experiment on thermionic emission. Much of the equipment required for the development of the course was purchased with funds granted by the Atomic Energy Commission on a special educational equipment grant. Professor Lawrence Ruby, Professor Selig N. Kaplan, and Dr. Robert V. Pyle of the Department of Nuclear Engineering at the University of California (Berkeley) all have participated in giving the course. Aside from spending many hours with the students in class, they also originated many new experiments and contributed important ideas to the book. The laboratory course could not have been organized successfully without the help of Mr. Lee Stollar, who saw to it that the equipment worked in spite of many shortages and difficulties. Professor Norman Rasmussen of the Department of Nuclear Engineering at the Massachusetts Institute of Technology spent much time discussing this project with one of the authors (Hans Mark) and carefully read the final manuscript. Many of the suggestions he made have been incorporated. The final draft of the manuscript was typed by Mrs. Betty J. Dial. She corrected many errors in spelling, punctuation, and grammar. In addition, we are also grateful for the excellent editing job she performed during the preparation of the manuscript. The lucid and instructive illustrations are the work of Robert David Wong. One of us (Hans Mark) owes thanks to his wife for her encouragement—and for countless pots of coffee she provided during the course of the work. Finally, the authors would like to express their thanks to the most important group of contributors to this effort—the students who have taken the course in the past three years.

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Chapter 1

INTRODUCTION TO THE LABORATORY

1.1 GENERAL REMARKS

The art of performing meaningful experiments is the heart of the scientific method. The word *art* is used deliberately because it is not always possible to specify precisely how a given experiment should be performed. Many important discoveries have been made by accident in the course of an experiment originally designed to learn something else. The discovery of penicillin by Sir Alexander Fleming,[1] the discovery of X rays by Wilhelm Roentgen,[2] and the discovery of radioactivity by Henri Becquerel[3] are examples of this. Other crucial results have come from a careful and deliberate attempt to choose between two theoretical alternatives or to verify a theoretical prediction. The Michelson-Morley[4] experiment is perhaps the classic example of the former, and the identification of vacuum polarization effects in the hydrogen spectrum by Willis Lamb[5] (the "Lamb" shift) is an excellent case of the latter type. In contrast, a great many experiments have as their object simply the collection of data and the cataloging of physical properties.

Although no hard and fast prescriptions to ensure success exist, certain very fundamental principles underly a fruitful experimental investigation. For instance, it is important to formulate in some detail the questions to be answered before the experiment is organized. Decisions must be reached about the important and the unimportant parameters. Only one experimental parameter must be varied at a time so that observed effects can be isolated and attributed to the proper cause. Judgments must be made regarding the statistical significance of the measurements, and background effects which could interfere with the measurements must be isolated. Above all, the experimenter must learn to be alert for the unexpected. Even a well-planned experiment may "fail" if the experimenter overlooks a small but unexpected deviation which could lead to an important new discovery.

The best way to become familiar with the principles outlined in the previous paragraph is through experience. The purpose of any laboratory course is to provide this experience. The extent to which the course succeeds depends on the freedom of choice and initiative left to the person performing the experiments. Obviously this freedom will be restricted by the equipment available and the time limits imposed by the academic schedule. Nevertheless, it has been possible to organize laboratory courses in which wide latitude of choice about what to do and how to proceed in a given situation is left to the experimenter. The experiments outlined in this book have been chosen with this approach in mind.

1.2 SUBJECT MATTER

The most important scientific development in the first half of the present century has been the process of understanding—for all practical purposes—the structure of matter. This process began in the latter half of the nineteenth century with the development of the atomic theory, statistical mechanics, and study of the interaction of radiation with matter, and reached a zenith with the advent of quantum mechanics in the first part of this century. It is possible to explain most phenomena dealing with matter in its various forms (atoms, nuclei, solids, liquids, gases, etc.) in terms of these theories. Several crucially important questions remain to be answered, of course, but these seem to border on other fields. Topics dealing with the nature of life processes and the principles of cosmology are in this category. It is probable that the next fifty years will see a large-scale application of our knowledge of the structure of matter to the solution of these problems.

Our understanding of the structure of matter has had far-reaching consequences in engineering and applied science. A great many devices have resulted from the research of the past fifty or sixty years in the field of the structure of matter. Among the best known are lasers, transistors, nuclear reactors, and synthetics such as plastics and fibers. There are, however, many other examples of equal importance but less well publicized.

The topics for the experiments described in the following chapters have been chosen to illustrate the important developments in the understanding of the structure of matter. An effort has also been made to deal in a more thorough manner with those principles likely to have important practical and engineering applications. These include topics in atomic structure, solid-state physics, nucleonics, and several others. In addition, the experiments illustrate new developments in instrumentation. A list of these instruments would include oscilloscopes (see Appendix I), power supplies, signal amplifiers, particle detectors, photomultipliers, magnetic field measuring devices, and others. Wherever possible, instruction manuals should be available and the equipment should be operated in accordance with them.

1.3 MEASUREMENT METHODS AND ERROR ANALYSIS

Certain general rules should be heeded in making measurements if they are to be reliable. The first step is to decide which quantity is to be measured as a function of the variable parameters of the experiment. The data taken should then be recorded in tabular form, preferably in a hard-cover notebook with pages that cannot be removed. *All* data and pertinent events that occur during the course of the experiment should be recorded. If anything subsequently appears to be incorrect, any recorded information may be useful in locating the trouble. It is also advisable to plot the data in graphical form while they are being taken. Often it is possible to spot malfunctions by observing trends in the graphs. In addition, if theoretical predictions are available, it is sometimes very useful to plot these on the same graph so that appropriate comparisons can be made as the data are being taken.

In every measurement, there are always background effects which must be subtracted from measured values. Background effects may come from many different sources. In most experiments involving electronic equipment, the noise level introduced by the various devices may be an important source of background. This "electronic noise" should be determined independently before the experiment is performed. Other background effects may be more difficult to isolate. For instance, in many experiments involving the counting of neutrons, the detector used may also be sensitive to gamma rays. Thus some method must be found to determine the counting rate which must be subtracted from the observed counting rate to obtain the true neutron signal rate. In this case, the objective might be accomplished by placing shields having different transmission characteristics for neutrons and for gamma rays in front of the counter. These examples illustrate the kind of steps which might be taken to isolate certain background effects. It is extremely important that this be done before the experiment is started. For every experiment, a "signal-to-noise ratio" should be calculated from the data available. If this ratio is of the order of 2:1 or larger, then the experiment can probably be performed. If it is less, special measures may be necessary to subtract the background.

No discussion of measurement methods would be complete without some mention of experimental errors. No measurement should ever be reported without also making some statements about the precision of the result. Experimental errors fall into two major categories: those which arise from statistical fluctuations in discrete samples being measured and those which are due to systematic changes in the equipment or errors inherent in reading metering devices. An example of the former might be the fluctuation in the number of counts observed from the decay of a radioactive sample. A typical systematic error might be caused in certain electronic instruments by periodic variation of the electric line voltage. In principle, all systematic errors may be traced and either eliminated or corrected, although this is rarely true in a practical case. Statistical errors, on the other hand, are always present and great care must be exercised to calculate them properly. For background material on this point, the student should consult several excellent texts on the subject (Cohen, Crowe, and DuMond,[6] and Worthing and Geffner[7]).

The practical issues which must usually be decided when experimental errors are assigned to a measurement are how to define the "error" and how errors propagate if the final result is a function of several measured quantities all having different experimental errors.

The definition of a measurement error is always somewhat arbitrary. If a series of measurements of a quantity x_1, x_2, . . . is distributed around a mean value $\bar{x}$ in a normal distribution, the standard deviation from the mean is usually defined as the "experimental error." A normal distribution results if the successive measurements are independent of each other. Since this is the most common circumstance, most of the mathematics of error analysis is based on normal (or Gaussian) distributions. Furthermore, many distributions which are not precisely normal distributions can be approximated with appropriate normal distribution functions so that the analysis may still be used. It is important, however, for the experimenter to recognize when these conditions are fulfilled and when they are not.

The "error" for a normal distribution is usually called the standard deviation, σ, and the experimental result for the measurement of $\bar{x}$ is usually quoted as $\bar{x} \pm \sigma$. The precise meaning of this statement is that the probability that a measurement of the quantity x yields the value x_1 is

$$p(x_1) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-(\bar{x}-x_1)^2/2\sigma^2} \tag{1.1}$$

It can easily be shown that if a set of n measurements are made, the quantity σ is

$$\sigma^2 = \frac{\sum_{k=1}^{n} (\bar{x} - x_k)^2}{n} \tag{1.2}$$

and where

$$\bar{x} = \frac{\sum_{k=1}^{n} x_k}{n} \tag{1.3}$$

The normal distribution function of Eq. (1.1) is illustrated in Fig. 1.1. Further, for a sufficiently large number of measurements, 68.3 percent of the values x_k will lie within $\pm\sigma$ of the mean value $\bar{x}$ and 95.4 percent will lie within $\pm 2\sigma$. It is thus perfectly possible that a repeated measurement x_k may lie outside the "experimental error." This point should be remembered when an experiment is repeated to determine whether the result is "correct."

If the result of an experiment is a function of two or more measured quantities, the experimental errors of all measured quantities must be included in the computation of the standard deviation of the final result. For example, assume that x is a function of two variables y and z so that the mean value $\bar{x}$ is expressed as follows in terms of the mean