

Experimental Physics

Modern Methods

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Experimental Physics

Preface

This text is the result of teaching a full-year, junior-level course in experimental physics over the past six years. The course consists of three hours of lecture per week and a complementary laboratory, and so this book serves as both source material for the lecture and reference for the laboratory. In cases where a lecture course on experimental physics is taught independently of laboratory work, this text should provide enough material for two semesters. In cases where a laboratory course is taught without accompanying lectures, this book should serve as a useful reference. However, it is not intended as a laboratory manual of physics experiments. The purpose of the text is to provide an overview of the physical principles of experimental apparatus and measurement techniques and, for the most part, does not make reference to specific experiments. The text assumes the student has a knowledge of introductory mechanics, electricity, and magnetism, including some background in wave mechanics. Some familiarity with basic quantum mechanics would also be helpful. Most of the discussions on optics and on nuclear, atomic, and solid-state physics are developed from basic principles. Typically, physics majors at the junior level or higher should have sufficient background to follow the presentation.

Experimental physics encompasses a vast number of different areas. It is not possible to provide even a brief description of experimental techniques from all these areas within a single text; nor would this necessarily be desirable. Since this text is designated for use by advanced undergraduate students, it deals with those subjects which these students are most likely to encounter from an experimental point of view. For this reason, the book concentrates on three particular areas of modern physics: solid-state physics, optics, and nuclear physics, though the apparatus and techniques described here are frequently applicable to other areas of physics as well. To understand the operation of modern laboratory apparatus, some knowledge of electronics is necessary. And since it has been assumed that many physics majors do not have any formal background in electronics, the necessary introductory material is also presented. This treatment of electronics emphasizes the physics of electronic devices rather than principles of circuit design.

Specifically, Chapter 1 is an introduction to the band theory of solids. This is necessary for an understanding of semiconducting devices, which first

appear in Chapters 2 and 3, as well as for the discussions on the physics of sensors, which appear throughout the later chapters. Chapter 4 presents an overview of electronic techniques for signal processing and data accumulation. Chapters 5 to 7 deal with producing, controlling, and measuring temperature and pressure.

The remaining material can be divided into three main groups. Chapters 8 to 10, which deal with optics, Chapters 11 and 12, which deal with nuclear physics, and Chapters 13 and 14, which deal with solid-state properties. These three groups may be covered in any order with one exception. The section on photomultiplier tubes, which appears in section 10.1, is important for the discussion of scintillation detectors, which begins in section 12.1.

Finally, the use of nomenclature and units requires some comment. This book deals with topics from several diverse fields of physics. The nomenclature and units commonly used in the different fields are not always consistent. As much as possible, the nomenclature and symbols used for various quantities have been made uniform throughout the book. Also, wherever practical, the SI system of units has been used, although in some specific cases the more customary unit has been retained.

February 1988
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R. A. D.

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Experimental Physics

1

The electrical properties of solids

1.1 The free-electron model

The electrical conductivity of solids covers one of the largest ranges of values of any physical parameter known—more than 25 orders of magnitude. This range is illustrated in Figure 1.1. Materials are grouped roughly into three categories according to electrical properties: conductors, semi-conductors, and insulators. To understand the reasons for these distinctions, it is necessary to gain some insight into the behavior of electrons.

Although in some cases the electron behaves like a particle, it can be shown (e.g., by diffraction experiments) to possess characteristics of a wave as well. The wave-like nature of the electron is described by a wave equation, just as are the displacement of a vibrating string and the density fluctuations in air caused by sound waves. For electrons, the relevant entity is the electron wavefunction. This is a function of the spatial coordinates, $\psi(\mathbf{r})$, and its square, $|\psi(\mathbf{r})|^2 = |\psi(\mathbf{r})\psi(\mathbf{r})^*|$, gives the probability of finding the electron at some particular location at a given time. For simplicity, we consider the one-dimensional case. The derivation of the three-dimensional case is somewhat more complicated but follows along the same lines. The wave equation for an electron is Schrödinger's equation and in one dimension it has the form

$$\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} - V\psi = -\mathcal{E}\psi \quad (1.1)$$

where \hbar is Planck's constant, m is the mass of the electron, \mathcal{E} is its total energy, and V is the potential energy. As the simplest case, we consider a free electron. In this case, the electron does not interact with other electrons or with atoms or ions. This means that, at least for the time being, we assume that there are no perturbing fields (e.g., electric or magnetic fields). Hence $V = 0$, and the energy of the electron is merely the kinetic energy, $\mathcal{E} = \frac{1}{2}mv^2$. (We have ignored relativistic effects here and it will turn out that, in dealing with electrons in solids, this omission is justifiable.)

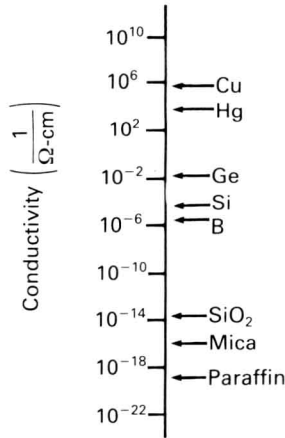


Figure 1.1. Electrical conductivity of some common materials.

Hence, substituting for \mathcal{E} and rearranging, equation (1.1) becomes

$$\frac{\partial^2 \psi}{\partial x^2} = -\frac{m^2 v^2}{\hbar^2} \psi \quad (1.2)$$

We will substitute the nonrelativistic momentum $p = mv$ into subsequent steps of the derivation. Partial differential equations of the form of (1.2) can be solved most easily by guessing at an appropriate function $\psi(x)$, usually with some insight into what the answer should be. In this case, our insight provides the answer

$$\psi(x) = A \sin(px/\hbar) + B \cos(px/\hbar) \quad (1.3)$$

An important observation we can make from equation (1.3) is that the wavefunction of an electron has a wavelength λ that is inversely proportional to the electron momentum by

$$\lambda = \frac{2\pi\hbar}{p} \quad (1.4)$$

that is, the more energetic the electron, the shorter is its wavelength—we recall that the same is true for photons.

Now let us consider the behavior of an electron in a solid. We continue to make the assumption that the electron does not interact with the atoms or with other electrons, so equation (1.2) is still valid inside the material. At room temperature, the electron cannot normally escape from the solid, and the reason for this is simple. If a negatively charged electron were to escape from the surface of the material, it would immediately be attracted back into the material by the positive image charge created by the electron's absence. If an electron gains sufficient energy, as it can in materials at higher temperatures, it can escape from the attraction of its own image

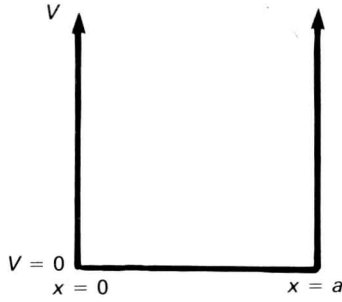


Figure 1.2. Potential energy diagram for an electron in a piece of material in one dimension.

charge. This phenomenon is called thermionic emission, and later we will learn about some of its characteristics. Considering the room-temperature situation, in which this does not occur, we see that there is, in effect, an infinite potential well at the edge of the solid. For a piece of material of length a , the potential energy is described by Figure 1.2. Hence, outside of the material, the wave equation for the electron has the form of equation (1.1) with $V = \infty$. This has only the trivial solution $\psi = 0$. Since ψ must be continuous, we can apply boundary conditions to equation (1.3) at $x = 0$ and $x = a$. The $\psi(0) = 0$ condition requires that $B = 0$, but places no restrictions on A . For $\psi(a) = 0$ we have $pa/\hbar = n\pi$, where n is an integer. Thus, the momentum, and hence the energy, is quantized and this quantization results from the application of the boundary conditions. So we have the momenta

$$p = \frac{n\pi\hbar}{a} \quad (1.5)$$

and the corresponding energy levels

$$\mathcal{E} = \frac{p^2}{2m} \quad (1.6)$$

which are

$$\mathcal{E} = \frac{n^2\pi^2\hbar^2}{2a^2m} \quad (1.7)$$

Thus, the wavefunction for the electron in one dimension has modes of oscillation in the material analogous to the modes of oscillation in a string with both ends fixed. This is shown in Figure 1.3. The square of ψ , which is always a positive quantity, gives the probability of finding the electron at a particular location. Since $\psi = 0$ outside of the material (i.e., for $x < 0$ and $x > a$), the probability of finding the electron outside of the material is, as we expect, zero.

The relationship between \mathcal{E} and p is known as a dispersion relation and

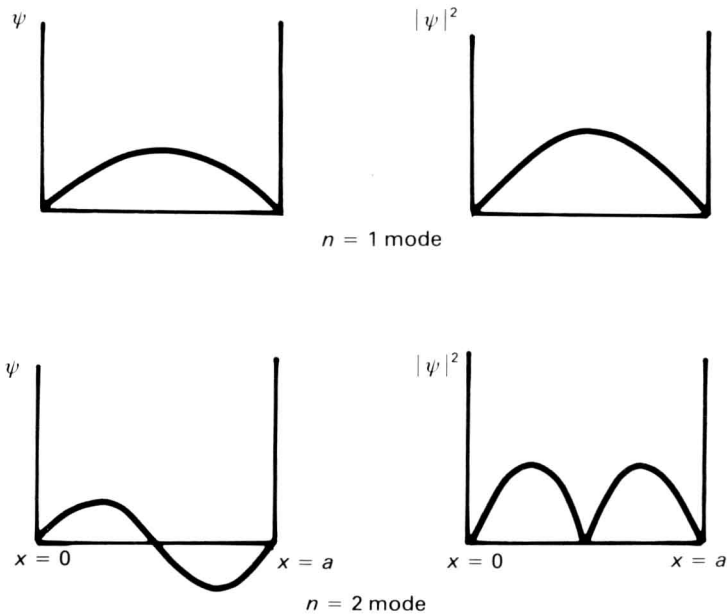


Figure 1.3. Modes of oscillation for a free electron in a piece of material of length a .

for the free electron it is seen from equation (1.6) to be parabolic (see Figure 1.4). The allowed energy (or momentum) states, as given by equation (1.7), are shown in the figure. We see from equation (1.6) that the dispersion relation for all free electrons is the same, but it is clear from equation (1.7) that the spacing in energy between the allowable states depends on a , the size of the piece of material. The number of states per unit energy is referred to as the “density of states.” The larger the sample, the greater the density of states.

Let us now consider which states will be occupied. When the temperature is very low and there are no perturbing forces, the system will be in its ground state. For electrons, which are fermions, there are restrictions on how the energy states can be filled. This restriction is called the Pauli exclusion principle. Basically, it states that any given energy level can contain *at most* two electrons, one with spin up and one with spin down.

Let us look again at the dispersion relation in Figure 1.4. We see that each energy has *two* corresponding momenta, one positive and one negative. This is because energy is a scalar quantity and momentum is a vector. In one dimension the electron can have the same energy by travelling at a particular speed in one direction or the other. These two cases correspond to momenta of opposite signs. An electron can reverse its direction and hence the sign of its momentum without a change in energy by scattering elastically from the potential wall at either end of the piece of material. These two momenta [(+) and (-)] for a given energy are *not*

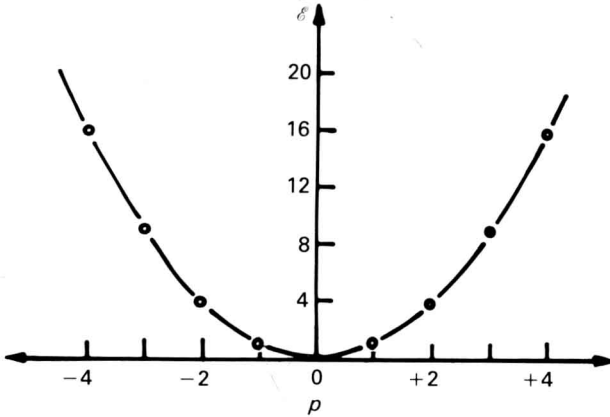


Figure 1.4. Dispersion relation for free electrons showing allowed energy states. The energy is given in units of $\pi^2 \hbar^2 / 2ma^2$ and the momentum is given in units of $\pi \hbar / a$.

analogous to the two spin states! For simplicity, we redraw the dispersion relation for $|p|$ rather than for p . This is illustrated in Figure 1.5.

Now we can begin to fill up the available states, placing up to two electrons in each, as indicated in Figure 1.5. Ultimately what we would like to determine is the *maximum* energy an electron can have in the ground state. To find this qualitatively, we consider a material with a density n_0 of electrons. In one dimension this is the number of electrons per unit length. A length a of material then contains $N = n_0 a$ electrons. Since there can be two electrons per state, we require $an_0/2$ states to accommodate all of the electrons. The energy of the highest filled state is obtained from equation

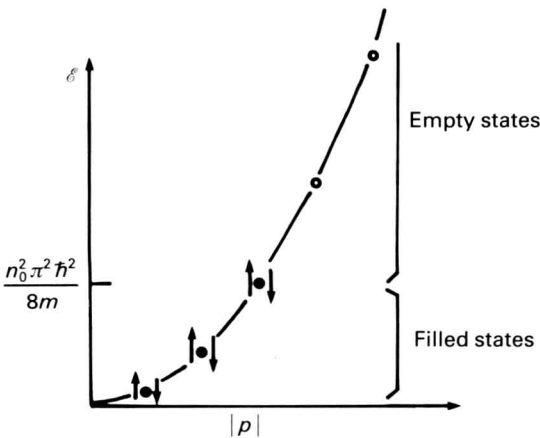


Figure 1.5. Population of the energy levels of a one-dimensional system of fermions in the ground state.

(1.7) by substituting $n = an_0/2$ and is called the Fermi energy. This is found to be

$$\mathcal{E}_F = \frac{n_0^2 \pi^2 \hbar^2}{8m} \quad (1.8)$$

We note that this energy depends on the *density* of the electrons in the material but not on the overall dimensions of the piece of material. We should emphasize that the *number* of energy states below \mathcal{E}_F does depend on the size of the material since, the larger this is, the more electrons must be accommodated. Figure 1.5 shows how the electrons are arranged in the energy levels, one with spin up and one with spin down to each level. If we had proceeded with this derivation in three dimensions, we would have obtained the Fermi energy as

$$\mathcal{E}_F = \frac{\hbar^2}{2m} (3\pi^2 n_0)^{2/3} \quad (1.9)$$

where n_0 is the electron density per unit volume.

The above calculation applies at zero temperature. At finite temperature, the probability that an energy state is occupied is a function of energy and of temperature. This probability function is the Fermi–Dirac distribution and it is illustrated in Figure 1.6. These curves should, in fact, be a series of dots equally spaced in momentum, as the allowed states are quantized. If the sample is large and contains a large number of electrons, the dots are closely spaced and, as in the figure, appear as a solid line. The mathematical form of the Fermi–Dirac distribution is given by

$$f(\mathcal{E}) = \frac{2}{e^{(\mathcal{E} - \mathcal{E}_F)/k_B T} + 1} \quad (1.10)$$

where k_B is Boltzmann’s constant. The 2 in the numerator comes from the

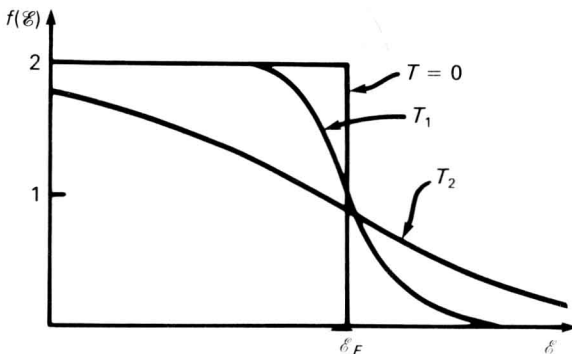


Figure 1.6. Fermi–Dirac distribution for electrons ($0 < T_1 < T_2$).

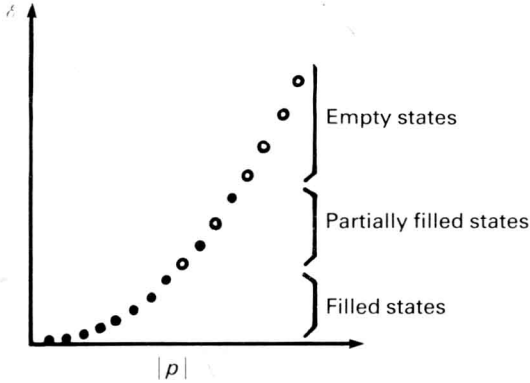


Figure 1.7. Dispersion relation for free electrons at $T > 0$.

two allowed spin states per energy state. By inspection of equation (1.10) we can see that $f(\mathcal{E})$ for $T = 0$ is a step function with a value of 2 for $\mathcal{E} > \mathcal{E}_F$ and a value of 0 for $\mathcal{E} < \mathcal{E}_F$. This represents the ground-state situation we have previously described. As T increases, the curve smears out around \mathcal{E}_F . This corresponds to the electrons near the Fermi energy jumping up into unoccupied higher-energy states. The lower-energy electrons cannot gain any additional energy unless there is a unoccupied energy state above them and they have sufficient energy to jump up into that empty state. At some intermediate temperature, the situation is as shown in Figure 1.7. Hence, the states can be divided into three regions; filled, partially filled, and vacant. The integral of $f(\mathcal{E})$ must be independent of temperature, as the number of electrons is conserved. You can see this for yourself by integrating equation (1.10) over energy.

Materials contain a lot of electrons, many of which are unimportant (more or less) in determining the electronic properties. It turns out that the electrons that are of importance are the valence electrons. The core electrons remain localized around particular atoms and, at least to first order, are not important to the electronic properties. In the general sense, the valence electrons are those that have “orbits” that encompass more than one atom. So, when we look back at equations like (1.8), it is only the valence electrons that we have to consider in determining n_0 .

Now let us use what we have learned to calculate some measurable properties of a material. Consider a sample of cross section A and of length l . We attach leads to each end and supply a voltage V . Free electrons can gain energy via interaction of their charge with the electric field E produced by the applied voltage. We perform the experiment as shown in Figure 1.8. At some time (defined as $t = 0$) we close the switch and apply the electric field. The motion of an electron at the Fermi energy can be considered as that of an entirely free electron, because there are unlimited empty energy states above it. Hence we can write down the equation of motion for this

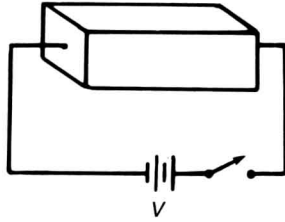


Figure 1.8. Experiment for measuring the electrical conductivity of a sample.

electron in terms of the Lorentz force:

$$\mathbf{F} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (1.11)$$

where e is the electron charge, \mathbf{v} is the electron velocity, \mathbf{E} is the applied electric field, and \mathbf{B} is the applied magnetic flux density. Since, in our experiment, $\mathbf{B} = 0$, equation (1.11) is immediately separable and we can integrate it to obtain

$$\int_{p_0}^p dp = -eE \int_0^t dt \quad (1.12)$$

or

$$p = p_0 - eEt \quad (1.13)$$

where p_0 is the momentum of the electron before the electric field was applied. Since p_0 is small, the (nonrelativistic) energy of the electron at time t after the switch is closed is

$$\mathcal{E} = \frac{e^2 E^2 t^2}{2m} \quad (1.14)$$

To find the conductivity of a material, let us write the well-known form of Ohm's law

$$V = IR \quad (1.15)$$

Dividing each side of this equation by the length of the material to give

$$\frac{V}{l} = \frac{I}{A} \frac{RA}{l} \quad (1.16)$$

we see that the left-hand side is just the electric field inside the material. The first factor on the right-hand side is the current density j , and the second factor on the right-hand side is the resistivity ρ , or the inverse of the conductivity σ . Thus Ohm's law may be written in the form

$$E = \frac{j}{\sigma} \quad (1.17)$$