Chapter 10

Early Modern Physics

10.1 INTRODUCTION

There is an understandable desire in the physics community for earlier introduction of students to aspects of modern physics. In some quarters these dreams of accelerated learning extend to advocacy of injection of the results of quantum mechanics, nuclear physics, and high energy physics as early as freshman, or even high school, level. In light of what we have been learning in recent years about cognitive development and concept formation, I doubt that genuine learning and understanding of such material is feasible at such early stages. One would only cultivate blind memorization of end results to be used in artificial homework exercises and to be tested for as what Eric Rogers used to call “cheap recall.” Knowledge and understanding do not reside in strings of names such as “quark,” “gluon,” “neutrino,” “charm,” or “wave function.” When the “How do we know . . . ? Why do we believe . . . ?” questions are not being dealt with, no genuine learning or understanding can be achieved. I doubt that it is wise for us to succumb to subject matter pressure (as so many chemists have done, for example) and force our students to memorize end results without understanding.

What seems to me to be feasible and highly desirable in an introductory course is to get to the insights gained in early 20th century physics: Electrons, photons, nuclei, atomic structure, and (perhaps) the first qualitative aspects of relativity. To achieve this, it is impossible to include all the conventional topics of introductory physics. One must leave gaps, however painful this may seem. How does one decide what is to be left out? One powerful way, in my experience, is to define what I call a “story line.” If one wishes, say, to get to the Bohr atom, one should identify the fundamental concepts and subject matter from mechanics, electricity, and magnetism that will make understandable the experiments and reasoning that defined the electron, the atomic nucleus, and the photon. The selected story line would develop the necessary underpinnings and would leave out those topics not essential to understanding the climax. For students continuing in physics, the gaps would have to be recognized, ac-
cepted, kept in mind by the faculty, and closed in subsequent courses. (If the students were given a chance really to learn, understand, and absorb the most basic concepts, they would subsequently close at least some of the seeming gaps on their own.) Some efficiency could be gained by putting certain topics (e.g., elementary dc circuits, geometrical optics) entirely in the laboratory and not devoting them appreciable class time. Such topics are far more effectively developed in a "hands on" context in any case (cf. Sects. 7.4-7.9 and Sects. 9.17-9.18).

If one has carefully thought out the story line to be developed, it is possible to inject, along the way through earlier material, many questions and exercises that prepare the students for thinking and reasoning that will be encountered toward the end. Quite a few textbooks are now attempting to do this, but most of them include so much material that such preparatory exercises get lost in the clutter. Most textbooks that do deal with the early 20th century developments tend to go through the material so rapidly that much opportunity for physical insight and reasoning is extruded; it is the end results that are dwelt on and not the reasoning that yielded them.

It must be kept in mind that all of what we call "modern physics" deals with levels of insight not directly accessible to our senses. Students need time to absorb and comprehend the inferences drawn from the classical experiments that led to the deep insights we now assert so quickly and casually. Furthermore, the classical experiments and the reasoning they entail provide an exceedingly rich and valuable opportunity for the kind of spiralling back that has been advocated throughout this book. Many students begin to show their first reasonably firm mastery of basic concepts such as velocity, acceleration, force, mass, momentum, energy, centripetal force, electric charge, electric field strength, and magnetic B-field when they synthesize them in rich contexts such as those provided by the Thomson experiment and the Bohr atom.

In the light of the issues outlined above, this chapter will concentrate on the intellectual growth students can achieve in the study of early 20th century physics. This happens to be an instance in which at least parts of the historical development (not all the intimate details) are deeply conducive to learning, understanding, and the cultivation of some degree of scientific literacy. Unfortunately, neglect of some of these historical aspects greatly diminishes the effectiveness of many treatments of this area of subject matter. I wish to support these contentions in the following discussion.

10.2 HISTORICAL PRELIMINARIES

The insights we usually associate with the term "modern physics" began with the qualitative study of gaseous discharge and cathode rays in the 1870s and 1880s and rose to something of a crescendo with Roentgen’s discovery of x-rays in December 1895, Becquerel’s discovery of radioactivity in early 1896, and Thomson’s experiment identifying the electron in 1896-97.
10.2. HISTORICAL PRELIMINARIES

Replicas of the tubes that Crookes used in his study of cathode rays are available in most physics preparation rooms, and the demonstrations are invariably of great interest to the students. There is an unfortunate tendency, however, for lecturers to rush through the demonstrations, asserting very quickly what each one implies about the cathode beam. The impact of these demonstrations can be greatly enhanced if time is allowed for contemplation, discussion, and inference. As the demonstration is performed, it is more effective to ask the students what is to be inferred from the observations. For one thing, this helps many students who are still in need of exercise in sharpening their discrimination between observation and inference; for another, it allows articulation of alternative explanations and inferences—which should be tolerated and debated rather than dictatorially suppressed. Such discussion provides a very important underpinning for the study of the Thomson experiment since Thomson was motivated to resolve the debate as to whether the cathode beam consisted of particles, as had been conjectured by Crookes, or of some hitherto unknown radiation, as was being argued by Lenard (see Section 10.3). Students inclined to support a radiative model should be, at least temporarily, encouraged to do so; they would be in good company.

Many textbooks give adequate and sufficient, albeit abbreviated, discussions of the discoveries of x-rays and radioactivity. (Although there is much good physics to be learned in considering these stories in greater detail, there are limits to the time one can devote.) A few aspects, important for subsequent study, are, however, insufficiently emphasized, and students tend to lose sight of their significance. One of these aspects is the fact that both x-rays and radioactive emanations were quickly discovered to ionize air, the conductivity being observed and recognized through the discharge of electroscopes. Becquerel, in fact, initially surmised that the rays from uranium were weak x-rays. Thomson was studying x-ray induced conductivity in gases just before undertaking his classic study of the cathode beam, and his awareness of the ionization played a very important role in making the cathode beam experiments possible.

The conceptual importance of the discovery of ionization of gases is underlined by Millikan (1917):

\[ \ldots \text{up to this time the only type of ionization known was that observed in solution, and here it is always some compound molecule like sodium chloride which splits up spontaneously into a positively charged sodium ion and a negatively charged chlorine ion. But the ionization produced in gases by x-rays was of a wholly different} \]

Many students are exceedingly weak on such discrimination. Unless guided by questioning, they do not ask themselves what were the facts and evidence on the one hand and the inferences drawn from the facts on the other. They fail to make similar discriminations in other disciplines (history, for example). Yet such discrimination underlies, together with other processes, the intellectual behavior one would characterize as "critical thinking." (See Sect. 2.19 and Chapter 13 for additional discussion.)
sort, for it was observable in pure gases like nitrogen and oxygen, or even in monatomic gases like argon and helium.\textsuperscript{2} Plainly, then, the neutral atom even of a monatomic substance must possess minute electrical charges as constituents. Here was the first direct evidence (1) that an atom is a complex structure, and (2) that electrical charges enter into its makeup. With this discovery, due directly to the use of the new agency, x-rays, the atom as an ultimate, indivisible thing was gone, and the era of the constituents of the atom began.

A second aspect, either not mentioned at all or too quickly glossed over, is the discovery by the Curies that a vial of radium compounds maintains itself permanently above room temperature and that, when placed in a calorimeter, "each gram of radium gives off 80 calories per hour ... sufficient heat ... to melt its own weight of ice." Thus a serious question was raised, from the very beginning, about the origin of all this energy and the validity of the energy conservation law.

Furthermore, both $\alpha$ and $\beta$ radiations were shown to have mass. How could one account for the continuous emission of material particles in the apparent absence of chemical change (the work of Rutherford and Soddy on the transformation of the elements was still to come) or other alteration in the state of the radioactive material? How, in particular, could one account for material emission from elements (pure metallic uranium and radium) without interaction with atoms of other substances? Thus the law of conservation of mass was also being called into question.\textsuperscript{3}

As part of awareness of their own intellectual history, it is desirable that students face and appreciate these initial questions and that the story that unfolds eventually show how they were explicitly resolved. It is through such experience that scientific literacy is enhanced, not through glossing over of the questions and rapid assertion of names and end results.

A question, which frequently arises when one elects to use elements of the historical sequence in teaching an introduction to modern physics, concerns what was known about (what we now call) Avogadro's number $N_0$ and about the sizes of atoms and molecules prior to Millikan's determination of the quantum of electrical charge and the advent of x-ray diffraction. (This is a question I am asked from time to time by my own physics colleagues.) The facts are as follows.

\textsuperscript{2}It was, of course, well known that flames rendered gases conducting, but flames involved chemical reactions, introduced new products into an initially pure gas, caused convection currents and extraneous effects due to temperature differences. A steady, controlled, reproducible electrical process could not be achieved under these circumstances.

\textsuperscript{3}It might be noted that it was during this period of convulsion in physical science that Henry Adams (1918) made (in The Education) his oft quoted remark "Chaos is the law of Nature; order is the dream of Man."
The orders of magnitude of these quantities were firmly established well before the end of the 19th century and were used in guiding both experimental work and theoretical analysis, but the values were far from precise. The sources of information were the kinetic theory of gases on the one hand and experimental data on the transport phenomena (viscosity, thermal conductivity, diffusivity) and on departures from ideal gas behavior on the other. The story began with the theoretical foundations laid by Clausius in 1857 and 1858 and by Maxwell in 1860 [see Brush (1965) for translations and reprints.]. These works established the mean free path and its connection to the transport coefficients. In modern notation, for example:

\[ \lambda = \frac{1}{\sqrt{2\pi n a^2}} \]  

and

\[ \eta = \frac{1}{3} n m \lambda \bar{v} \]

where \( \lambda \) denotes the mean free path; \( n \) the number of atoms or molecules per unit volume; \( \sigma \) the atomic or molecular diameter (assuming spherical shape); \( \eta \) the coefficient of viscosity; \( m \) the mass of one atom or molecule; and \( \bar{v} \) the mean atomic or molecular velocity. From the Maxwellian distribution, \( \bar{v} \) is given by

\[ \bar{v} = \sqrt{\frac{8RT}{\pi M}} \]

where \( R \) is the universal gas constant; \( T \) the absolute temperature; and \( M \) the relative atomic or molecular mass. In this notation

\[ m = \frac{M}{N_0} \]

Combining Eqs. 10.2.1 and 10.2.2 gives

\[ \eta = \frac{m \bar{v}}{3\sqrt{2\pi a^2}} \]

Equation 10.2.5 implicitly relates the experimentally measurable quantity \( \eta \) to the two unknowns \( N_0 \) and \( \sigma \). It also contains the prediction, since \( n \) has dropped out, that the viscosity coefficient of an ideal gas is independent of the pressure—an intuitively unanticipated prediction, the confirmation of which helped provide powerful reinforcement for the newborn theory.

In 1865, Loschmidt made what appears to be the first calculation of molecular size by taking the intrinsic volume excluded by the molecules in the gas to be equal to the volume occupied by the substance in the solid or liquid state, that is, the very low compressibility of liquids and solids justifies the
assumption that the atoms or molecules are exceedingly close together in these states. If \( \rho \) denotes the density of the solid or liquid, the volume of one mole of molecules \( \frac{M}{\rho} \) is given by

\[
\frac{M}{\rho} = \frac{1}{6} N_o \pi \sigma^3
\]  

(10.2.6)

Combining Eqs. 10.2.5 and 10.2.6, Loschmidt obtained a value of molecular diameter. He could readily have obtained the value of \( n \), which has come to be called the “Loschmidt number,” but did not actually do so. One can also calculate what came to be called Avogadro’s number, \( N_o \).

After van der Waals, in 1873, put forth his modified equation of state for departure from ideal gas behavior,

\[
(p + \frac{a}{v^2})(v - b) = RT
\]

recognition that the constant \( b \) must be approximately equal to four times the volume excluded by one mole of molecules in the gas phase made possible an improved calculation based on modification of Eq. 10.2.6:

\[
\frac{b}{4} = \frac{1}{6} N_o \pi \sigma^3
\]  

(10.2.7)

If one takes modern values for nitrogen, for example, of \( \eta = 178 \) micropoise at 27°C and \( b = 0.03913 \) liters per mole (l/mol), one obtains, from the van der Waals approach, combining Eqs. 10.2.5 and 10.2.7: \( \sigma = 3.1 \) Angstroms and \( N_o = 5.1 \times 10^{23} \).

The experimental values were considerably less accurate in the 19th century, but the preceding calculation illustrates that the orders of magnitude were right and provided reliable guidance. That the estimates were deemed important is indicated by the fact that figures such as Stoney, Lothar Meyer, and Kelvin participated in their development. More accurate determinations did not come until those of Perrin (in 1908), based on Einstein’s 1905 paper on Brownian motion, combined with experimental observation of gravitational stratification and Brownian motion of particles in colloidal suspension. Further refinement of the value of \( N_o \) awaited Millikan’s (1909, 1911) determination of the corpuscle of charge and the advent of x-ray diffraction.

Unfortunately, this story does not lend itself to use in an introductory physics course, the kinetic theory base being far beyond what is realistic at that level. I include the story here, not to advocate its use in teaching, but because it might enhance the perspective of others, as it did my own, when I first explored it. One can tell students about it qualitatively if one wishes to do so and ask them to take the assertions on faith. (Although I see strong objections to asking students to take assertions on faith in early portions of the course, when, because of past inexperience, they only feebly discriminate what is fully substantiated and what is not, I see no objection to doing so occasionally after their ability to discriminate has been strengthened.)