目　　录

Chapter 1

Introduction

Chapter 1 Introduction

The Scope of Quantum physics

1 In this part of our course we shall study physics in the realm of atoms, nuclei and elementary particles. In so doing we will encounter new aspects of nature: new in the sense that we have not discussed them systematically in the preceding volumes. These aspects of nature are commonly referred to as *quantum phenomena,* and we therefore call the subject matter of this volume *quantum physics.* The currently accepted basic mathematical theory of quantum physics is known as *quantum mechanics.*

Now it should not be thought that "quantum physics" is something which does not concern the macroscopic world. Actually *all* of physics is quantum physics; the laws of quantum physics as we know them today are our most general laws of nature.

An example of a quantum-mechanical system. The behavior of this electric motor (and the flashlight battery used as a power supply) is governed by the laws of quantum mechanics, although the author never suspected this when the motor was given to him about thirty years ago.

The design of an electric motor can, and should, be based on classical electromagnetic theory and classical mechanics, which are limiting forms of quantum mechanics. No engineer in his right mind would attempt to describe a macroscopic system such as this one in terms of the interactions between all the elementary particles which make up the system.

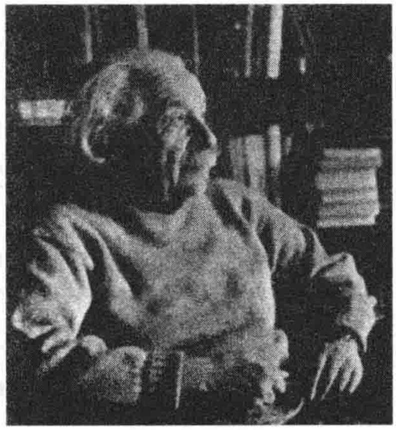
2 In the preceding volumes of the Berkeley Physics Course we have studied physical phenomena in the macroscopic world. The laws of nature which we have discovered are the laws of *classical physics.* Generally we can say that classical physics is concerned with those aspects of nature for which the question of the ultimate constitution of matter is not of *immediate* concern. In this volume, on the other hand, we will specifically study the elementary particles, and we must now try to discover the laws which govern the behavior of these particles. We will naturally focus our attention on physical situations, in which these laws stand out as clearly as possible, and this means that we study situations involving the interactions of only a few particles at a time. Most of the physics studied in this volume could, therefore, be called *microphysics:* we study "small" systems consisting of a small number of elementary particles.

However, if we know the basic laws governing the elementary particles we can also, in principle, predict the behavior of macroscopic physical systems, consisting of a very large number of elementary particles. This means that the laws of classical physics follow from the laws of microphysics, and in this sense quantum mechanics is just as relevant in the macroscopic world as in the microscopic world.

3 When we apply the laws of classical physics to macroscopic systems we try to describe only certain gross features of the behavior of the system. We consider, for instance, the motion of a "rigid body" as a whole, but we do not try to discuss the motions of all the elementary constituents of the body. This is a characteristic feature of classical theories of physics as applied to macroscopic systems; the finer details of the behavior of the system are ignored and no attempt is made to consider all aspects of the situation. In this sense the laws of classical physics are approximate laws of nature. We should regard them as limiting forms of the more basic and comprehensive laws of quantum physics.

The classical theories are, in other words, *phenomenological theories.* A phenomenological theory attempts to describe and summarize experimental facts within some limited domain of physics. It is not intended to describe everything in physics, but if it is a good phenomenological theory it does describe everything within the limited domain very accurately. The philosophically minded reader may want to remark that ultimately *every* physical theory is "phenomenological," and that the difference between a basic theory and a phenomenological theory is only a question of degree. As physicists we recognize, however, a clear difference between the two kinds of theories. Our *basic* laws of nature are distinguished by their great generality; we are not aware of any exceptions to what they state. We regard them as true and exact and universally valid until there is clear experimental evidence to the contrary. In contrast to this, the laws contained in a phenomenological theory are recognized *not* to be of universal validity; we *know* that they are valid (i.e., sufficiently accurate) only in some limited domain of physics, and that outside this domain the phenomenological theory may be completely meaningless.

4 We should, of course, not be contemptuous of phenomenological theories. They serve the very useful purpose of summarizing our practical knowledge of the various domains of physics. There are many instances in physics in which we do believe that we have available a basic theory, but where the complexity of the phenomena prevents us from making accurate predictions based on "first principles." In such a case we try a simplified phenomenological theory which is partly based directly on the experimental facts, and partly based on some general features of the basic theory. We let, in other words, "the physical systems do some of our theoretical work." There are, furthermore, many instances in physics where the basic theory is missing. Any phenomenological theory which we can construct (based on some simple model) is then useful as a steppingstone in the search for a more comprehensive theory.



Albert Einstein. Born 1879 in Ulm, Germany; died 1955. Studied at the Institute of Technology (ETH) in Zurich, Switzerland. After receiving his diploma in 1900 he held a position as a patent examiner in the Swiss Patent Office in Bern. During this time he wrote three famous papers, all of which appeared in the 1905 issue of Anna/en der Physik, dealing with the photo-electric effect, Brownian motion, and special relativity. Subsequently he held positions in Bern, Zurich, and Prague, and as director of the Kaiser Wil-helm institute in Berlin. In 1933 he became a member of the Institute for Advanced Study in Princeton, N.J., settling permanently in the United States. He received the Nobel prize in 1921.

Einstein is generally regarded as the most outstanding physicist of this century, and as among the greatest scientists of all time. He possessed to an extraordinary degree the ability to grasp the essence of physical phenomena, and no short summary could do justice to his numerous, always profound contributions on the fundamental problems of physics. His theory of General Relativity stands out as one of the most remarkable intellectual creations of all time. (*Photograph by courtesy of Physics Today.*)

When we try to understand an unfamiliar physical phenomenon it is clearly rational to try the simplest thing first, i.e., to try a theory, or model, which has worked successfully in a seemingly analogous situation. If our model turns out to be successful we have learned something, but if it turns out to be unsuccessful we have *also* learned something.

The important thing to keep in mind is that models are only models and that all of physics need not be described in terms of a single model.

5 People often talk about the "revolution" in physics brought about through the discovery of quantum mechanics. "Revolution" is a dramatic word (with a strange appeal, it seems) which suggests that something has been completely overturned. It should be noted, however, that the laws of classical physics, as applied to those situations which the classical theory was designed to describe, have not been overturned. The motion of a pendulum, for example, is described today in the same way as it was described in the nineteenth century.

It is furthermore the case that classical concepts often can be successfully employed to gain *some* understanding of phenomena in microphysics: they are of approximate validity. It is important that we understand the limits of applicability of classical ideas, and in this chapter we will try to give the reader a *rough* idea of these limits. As we learn more about quantum phenomena in later chapters, the reader will reach a more precise understanding of this important question.

That the classical theories of physics are not of universal validity has been convincingly established through many experiments performed during this century. In this volume we shall present some of the relevant experimental evidence to convince the reader of this fact of life.

6 When we think about the changes that have taken place in physics during this century we should keep in mind that no *comprehensive* classical theory of matter ever existed. The laws of classical physics are good phenomenological laws, but they do not tell us everything about macroscropic bodies. In terms of these laws we can describe the behavior (motion) of a mechanism consisting of springs, levers, flywheels, etc., if we are given some "material constants," such as the density, modulus of elasticity, etc., of the materials of which the mechanism is built. However, if we ask *why* the densities are what they are, *why* the elastic constants have the values they have, *why* a rod will break if the tension in .the rod exceeds a certain limit, and so on, then classical physics is silent. Classical physics does not tell us why copper melts at 1083 °C, why sodium vapor emits yellow light, why hydrogen has the chemical properties it has, why the sun shines, why the uranium nucleus disintegrates spontaneously, why silver conducts electricity, why sulfur is an insulator, nor why permanent magnets can be made of steel. We could go on and on listing everyday observational facts about which classical physics has very little or nothing to tell us.

7 The reader wants to know, do we *now* have a comprehensive theory of matter? The answer is no; we do not have a detailed theory for *everything* taking place in our world. However, our knowledge about nature has expanded enormously during the last sixty years. We have discovered aspects of nature never before dreamed of, and we have succeeded in solving many old problems. It is, for instance, fair to say that we now understand the facts of chemistry and the properties of matter in bulk quite well: in these domains of physics we can answer the questions that could not be discussed within classical theory.

Atoms and Elementary Particles

8 Let us talk about the idea of elementary particles. Some ancient Greek philosophers are credited with being the first to introduce the concept of atoms into the theory of matter. (This does not exclude the possibility that other people might have speculated along similar lines long before.) It should be stated immediately that the "atoms" of the ancients are most certainly not the same things as the atoms of today. It is in fact not an easy matter to understand precisely what the Greek philosophers really meant by the term, but the central problem with which they were concerned was the question of whether matter is, or is not, infinitely divisible. If matter is *not* infinitely divisible, then we must discover, on a sufficiently small scale, elementary constituents of matter, or "atoms." We take a chunk of matter, and we divide it again and again into smaller and smaller pieces. Eventually this splitting comes to an end; we find something which cannot be split further, and that is the "atom" (the word actually means "indivisible").

The Greek atomists believed that all matter is indeed built of "atoms," and presumably they felt that all the extremely varied aspects of matter are somehow explainable in terms of different configurations (and motions?) of "atoms." We believe something

It might well have occurred to some early natural philosopher that the strikingly regular and beautiful shapes of crystals reflect the way in which they are built from small particles, or atoms. Today this seems a very natural idea. It would appear, however, that this idea did not occur early. So far as the author knows there is no indication in the historical record that the Greek atomists speculated about crystals in this manner.

Crystallography as a science began to develop at the end of the eighteenth century. Among early workers we can mention Rom6 de Lisle and Hauy, who made precise measurements of the angles between cleavage planes. Before them both Robert Hooke and Christian Huygens had speculated about how crystals might be built of small (invisible) parts.

vaguely similar today, but there is certainly an enormous difference between our quantitative theories and the nebulous speculations of the ancients.

9 We are not going to discuss the early history of the atomic theory of matter in this book, but the reader is urged to ponder the remarkable understanding of natural phenomena which was achieved during the nineteenth century on the hypothesis that matter is made of atoms. On this assumption we can understand the basic fact of chemistry, namely that a given chemical compound always consists of certain basic chemical elements in fixed, definite proportions, characteristic of the compound. Consider, in particular, the striking fact that we can represent chemical compounds by such simple formulas as H_2O, H_2SO_4, Na_2SO4, and NaOH. What is striking about these formulas is the occurrence of *small* integers which tell us that *two units* of hydrogen combine with *one unit* of oxygen to form *one unit* of water, and so on. If we assume that matter is made of atoms we can immediately understand these empirical facts: Chemical compounds consist of molecules, which in turn are composite systems of a small number of atoms. Two hydrogen atoms combine with one oxygen atom to form one water molecule. Clear and simple.

As further evidence in favor of the atomic hypothesis we point to the successes of the *kinetic theory of gases,* developed in particular by J. C. Maxwell and L. Boltzmann. This theory could explain many properties of gases on the hypothesis that a gas in a container is a swarm of molecules moving randomly inside the container, incessantly colliding with each other and with the walls of the container. The kinetic theory could furthermore be used to estimate Avogadro's number, $N_0 = 6.02 \times 10^{23}$, which is the number of molecules in a mole of any gas. (By a *mole* of any chemical compound is understood a quantity of the substance which has a mass in grams equal to the molecular weight of the compound.) The first crude estimate of N_0 was given by Loschmidt in 1865.

In view of such evidence for the existence of atoms it is hard to understand a certain school of thought, which persisted until the turn of the century, and which rejected the atomic hypothesis on the grounds there was no *direct* (!) evidence that matter is made of atoms.

10 The "atoms" of the Greek philosophers do not correspond to our atoms of today, because our atoms are not indivisible: they are made of protons, neutrons and electrons. It is rather the protons, neutrons, electrons, and a host of other elementary particles which

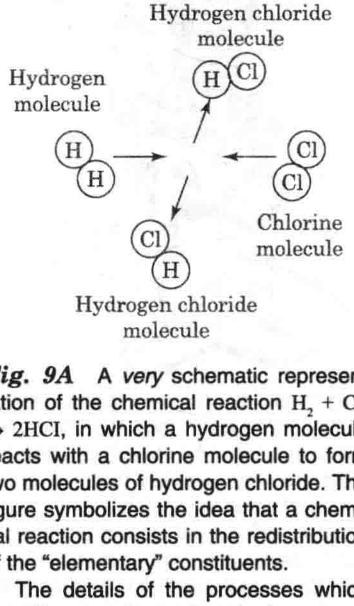


Fig. 9A A *very* schematic representation of the chemical reaction $H_2 + Cl_2 \rightarrow 2HCI$, in which a hydrogen molecule reacts with a chlorine molecule to form two molecules of hydrogen chloride. The figure symbolizes the idea that a chemical reaction consists in the redistribution of the "elementary" constituents.

The details of the processes which actually take place when hydrogen gas burns in an atmosphere of chlorine are very complex. Energy, in the form of light and of kinetic energy of the reaction products, is liberated in the process. The resulting heating of the gases leads to a partial dissociation of the hydrogen and chlorine molecules into atoms, which can "then combine into hydrogen chloride molecules. Other processes, in which the atoms and molecules are excited internally through collisions or by light, also play an important role.

play the role of the Greek "atoms." What do we mean by an "elementary particle"? The *precise* definition of this term is somewhat controversial today, but for our purposes we can give a simple and practical answer to the question: A particle is to be regarded as elementary if it cannot be described as a composite system of other more elementary entities. An elementary particle has no "parts," it is not "built" of anything simpler. Our mental splitting attempts have come to an end. With this definition, the proton, the neutron and the electron are all elementary, but the hydrogen atom or the uranium nucleus is not.

We can say that the essence of the idea that matter is not infinitely divisible is this: We cannot go on forever analyzing things in terms of the parts of which the things are built. Finally this process loses its meaning; we encounter irreducible entities, and these are our elementary particles.

11 How can we assert that the electron is *really* elementary? Might not what is regarded as elementary today be found to be composite tomorrow? After all, the atoms of today were the elementary particles of the nineteenth century: could not history repeat itself?

There are many experimental facts which strongly suggest that history will *not* repeat itself, and that particles such as the electron, the proton or the neutron will never be found to be composite in the same sense as the hydrogen atom was found to be composite. Let us try to describe the nature of this evidence.

If two marbles collide with a sufficiently high relative velocity they will break into smaller fragments. In the same way two hydrogen molecules colliding with a high relative velocity will break into fragments. Unless the velocity is *very* high we will find among the fragments such things as hydrogen atoms, or protons, or electrons; in other words, the components of which hydrogen molecules are built. In both these cases it is fair to describe what has happened as follows: the violence of the collision overcame the cohesive forces which keep the parts together in a marble, or in a hydrogen molecule, and the objects therefore broke apart. A similar interpretation can be given to many nuclear reactions. Nuclei are made of protons and neutrons, and if an energetic proton collides with a nucleus it may happen that a few protons and neutrons are knocked out of the nucleus.

12 However, if we study a violent collision of two elementary particles, such as two protons, we discover phenomena which are *qualitatively different* from the phenomena considered above. For

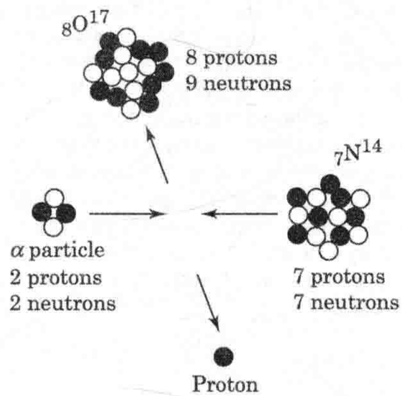


Fig. 11A Schematic representation of a nuclear reaction, in which an alpha particle (helium nucleus) collides with a nitrogen nucleus to produce an oxygen nucleus and a proton. This particular reaction, discovered by Rutherford in 1919, was the first observation of the transmutation of stable nuclei. [E. Rutherford, *Philosophical Magazine* **37**, 581 (1919).] In Rutherford's experiment nitrogen was bombarded by alpha-particles from a radioactive source, and the occurrence of the reaction was established through observation of the emitted protons.

The figure, quite analogous to Fig. 9A, symbolizes the ideas that nuclei are made of protons and neutrons, and that (low-energy) nuclear reactions consist in the rearrangement of these particles among nuclei. It should, of course, not be taken literally: in no sense of the word do nuclei "look" like this.

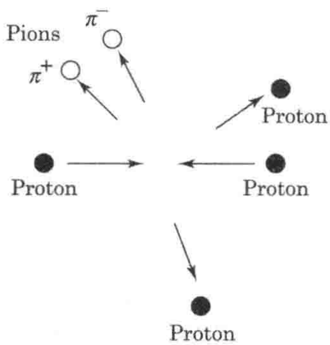


Fig. 12A Schematic representation of the creation of two pi mesons in a high-energy collision of two protons. One pion carries the charge $+e$, and the other the charge $-e$, where e is the magnitude of the electronic charge. The total charge is thus conserved in this event.

Since the two protons remain after the collision and two new particles appear it is strikingly obvious that naive models of the kind shown in Figs. 9A and 11A cannot apply here: the event cannot be thought of as a "rearrangement of the elementary constituents (?) of the two protons."

instance, if a proton of very high energy collides with another proton it may happen that the two protons remain after the collision and that we find in addition one, or several, new elementary particles such as pi mesons, among the reaction products. We say that the pi mesons, also called pions, are *created* in the reaction. This is not the only thing which can happen in a proton-proton collision: the protons may disappear and a number of entirely new particles, known as *K*-mesons and hyperons, may appear instead. Similarly it can happen, in a violent collision of two electrons, that the final reaction products consist of *three* electrons and one positron. (The positron is an elementary particle similar to the electron, except that it carries the opposite charge.) On the other hand, if an electron and a positron collide with each other it can happen that these two particles disappear (we say that they are *annihilated)* and we are left with only electromagnetic radiation in the form of gamma rays.

13 An interesting example of a creation process is the creation of an electron-positron pair when a gamma ray passes through the electric field in an atom. Material particles can thus be created from electromagnetic radiation. Figure 13A, which is a cloud-chamber photograph of so-called cascade showers, "shows" many instances of this phenomenon. The explanation (see also Figs. 13B and C) for what is seen is as follows. If an energetic charged particle, say an electron or a positron, passes through one of the horizontal lead plates seen in the photograph it may be very slightly deflected in the field of one of the atoms in the plate. Such a deflection constitutes accelerated motion, and consequently electromagnetic radiation in the form of an energetic gamma ray is emitted. (The particle may, of course, be deflected by several atoms in a single plate, in which case several gamma quanta will be emitted.) The gamma rays arising in this manner then create electron-positron pairs in the fields of the atoms which they encounter when *they* traverse the plates. These charged particles in turn give rise to more gamma rays as they are deflected in the plates, and the new gamma rays give rise to new pairs, and so on. A single energetic charged particle, or a single gamma ray, can thus give rise to a cascade of gamma rays, electrons and positrons. The charged particles leave visible tracks in the cloud chamber; these are the tracks we see in Fig. 13A. The gamma rays are not visible in the figure.

The cascade shower in the right part of the photograph appears to have been initiated by a gamma ray, incident from above. The energy of this gamma ray was probably about 20 BeV. The

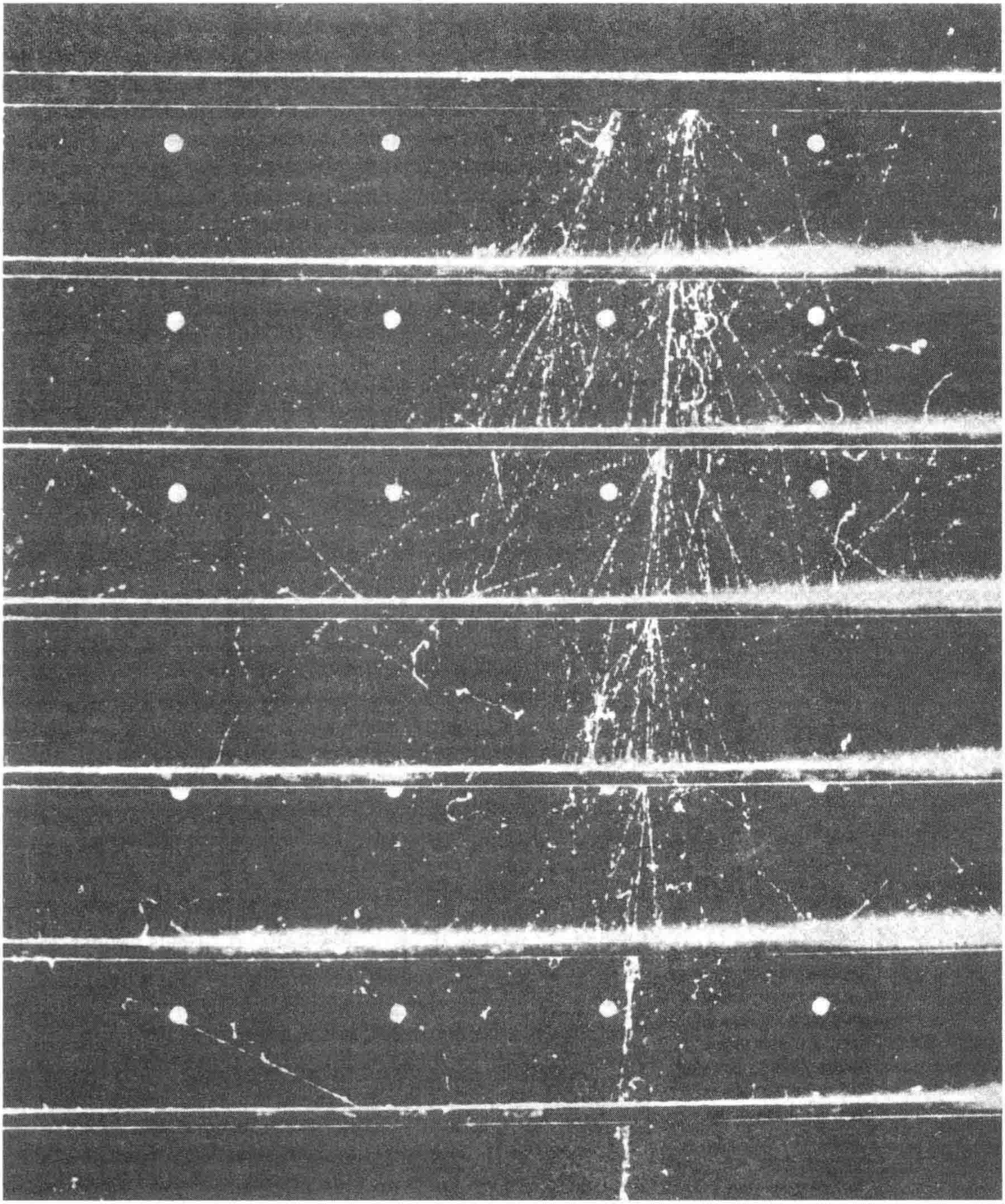


Fig. 13A Cloud chamber photograph showing cascade showers. Most of the visible tracks are due to electrons and positrons, which generally move toward bottom of picture. The particle entering at the top right and penetrating three plates before stopping in the fourth may be a pion. See text for further comments. (Courtesy of *Professor W. B. Fretter, Berkeley.)*

shower at the left appears to have been initiated by a charged particle, of somewhat lower energy. Both showers probably originated from some event which took place in the wall of the chamber, outside the field of view. Most of the particles seen in the showers moved in the downward direction. It is a characteristic feature of these processes that the most energetic particles tend to be emitted in the direction of the incident particle, whereas less energetic particles can be emitted in other directions. If we look closely at the photograph we notice that the secondary showers due to particles emitted in directions other than those of the principal showers soon "die out." A cascade shower naturally stops when the original energy has been distributed among so many charged particles and photons that none of them has enough energy for the creation of additional pairs. The low-energy particles are then absorbed by the lead plates.

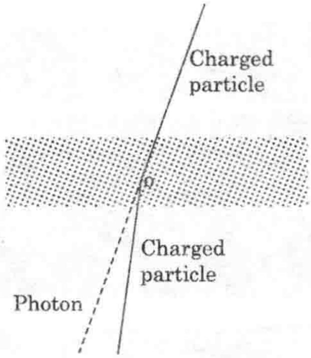


Fig. 13B An energetic charged particle (say a positron or an electron) is deflected by the electric field within an atom, and as a result of this accelerated motion a gamma ray (i.e., an energetic photon) is emitted. This is the physical phenomenon of brems-strahlung. The shaded part of the figure represents matter in bulk, say a portion of a lead plate in a cloud chamber. (The size of the atom is slightly exaggerated for clarity.)

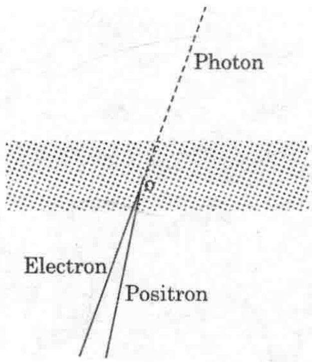


Fig. 13C An energetic gamma ray colliding with the electric field inside an atom gives rise to an electron-positron pair: this is the physical phenomenon of *pair production.* The two basic processes shown in the above two figures are responsible for the development of the cascade shower shown in Fig. 13A.

The energy of the particle initiating a shower can be estimated from the number of charged secondary particles which are produced,

14 The creation and annihilation processes which we have mentioned are important aspects of nature. It is obvious that these phenomena are in no way analogous either to the shattering of marbles or to chemical reactions. We can describe a chemical reaction by saying that new molecules are formed from the elementary constituents of other molecules, and for the purpose of such a description the *atoms* are the elementary constituents of molecules. Consider, in contrast to this, a collision event in which the two particles originally present remain after the collision, along with a number of new particles created in the event. Clearly we cannot describe such an event in terms of a rearrangement of the elementary constituents of the original particles into new composite systems. Nor can this description be applied to events in which some of the original particles disappear. A striking example of the latter phenomenon is the annihilation of an electron-positron pair, in which the material particles originally present disappear completely and we are left with gamma rays.

15 To decide experimentally whether a particle is elementary or composite we try to shatter it by letting it collide with another particle and observe the reaction products. In this way we can shatter molecules into atoms, and atoms into electrons and nuclei, and it is fair to say that molecules are built of atoms, which in turn are built of electrons and nuclei. The nineteenth century physicists were really mistaken when they thought that atoms are indestructible and indivisible:

atoms can in fact be shattered readily. In the same way nuclei can be shattered, and it is fair to say that nuclei are built of protons and neutrons. To shatter a nucleus, however, requires much more energy than to shatter an atom, and in this sense nuclei are much less "destructible" than atoms.

With modern particle accelerators we can produce beams of very energetic particles, and we thus have the means for shattering such particles as protons if they could indeed be shattered. But protons do not shatter like atoms and nuclei: something quite different happens. We must conclude that when we study electrons, protons, neutrons, etc., we have reached a limit: it does not appear to be sensible and useful to regard these particles as made up of other more elementary particles.

16 Nobody would attempt today to create a comprehensive theory of matter based on the proposition that matter is infinitely divisible: such an undertaking would be futile. Let us, however, speculate a bit on what features such a theory *might* have. If we take a chunk of copper, and divide it into smaller and smaller pieces, we never get anything but small chunks of copper. No matter how small the pieces are, they are still recognizable as chunks of copper. What does this mean? It means that the physical laws governing the behavior of *small* chunks of copper are the same as the laws governing the behavior of *large* chunks of copper; physical systems can be "scaled down" indefinitely. Now it must be admitted that our theory need not *necessarily* have this feature, but it would be a very natural feature of a theory describing matter which is infinitely divisible. We note that in many respects our classical theories of physics do have this feature. The laws of physics which we use to describe some machine weighing a ton are not qualitatively different from the laws we use to describe a wrist watch. Macroscopic physical systems can be scaled over a considerable range.

This "preservation of the form of physical laws" which might appear natural if matter were infinitely divisible is certainly totally implausible if matter is made of elementary particles. An *atom* of copper is in no way like a macroscopic chunk of copper; it is something entirely different. We have absolutely no a priori reasons to believe that the laws of physics which describe macroscopic systems sufficiently accurately would also be adequate to describe the structure of atoms and elementary particles.

17 To admit, as a matter of abstract principle, that classical ideas might not be appropriate to atoms, and that the electron is really an elementary particle is one thing, but to live up to such principles fully in one's thinking is quite a different thing. Experience shows that our thinking tends to be prejudiced, and that we do not easily give up ideas which we have once absorbed. Since our first conscious observations of physical phenomena concern macroscopic systems, we acquire a set of "classical prejudices" which have to be overcome when we wish to study quantum physics.† Let us try to illustrate the meaning of these remarks by considering two closely related problems which have been the objects of much speculation in this century.

18 Let us ask the following: What are the forces which keep an electron together? What fraction of the mass of an electron is of an *intrinsic* nature and what fraction is due to the energy of the electrostatic field of the electron? To try to deal with these questions we assume a not unreasonable model according to which the electron is a small uniformly charged sphere of radius r. The different parts of this sphere repel each other electrostatically, and there must therefore be some other kind of force which keeps the sphere together. What is the nature of this force?

In Volume II of this series‡ we have learned how to compute the total energy "residing" in an electrostatic field: we integrate $(1/8\pi)\mathbf{E}^2$ over all space, where $\mathbf{E}$ is the local electric field. For our model we obtain the expression $W = 3/5(e^2/r)$ for the electrostatic energy, § where e is the electronic charge. (The coefficient in front of the expression e^2/r depends on the details of the model: for a uniformly charged sphere it happens to have the value 3/5. What is important here is not the value of this coefficient but the proportionality of W to the expression e^2/r. That W depends in this way on e and r is immediately obvious on dimensional grounds.) We can now write the mass of the electron in the form $m = m_e + m_i$ where $m_e = W/c^2$ is the electromagnetic contribution and m_i is the "intrinsic" part. The problem is: How large is m_e? Could it perhaps be that $m = m_e$, in which case the entire mass would be of electromagnetic origin? If we make this assumption we can

† It is not only the beginning physics student who has such prejudices, the senior physicist has them too. Since rigidity of mind appears to increase with age it is plausible that the senior physicist actually suffers more from his "classical prejudices" than the beginning student does.

‡ Berkeley Physics Course, Vol. II, *Electricity and Magnetism,* Chap. 2, p. 51.

§ This holds for the egs-system of units. In the MKS system we have

$$W = \frac{3}{5}\left(\frac{e^2}{4\pi\varepsilon_0 r}\right).$$

compute the radius r and we find $r = 1.7 \times 10^{-15}$ m. There are many experimental facts which suggest that the electron must be very "small," and it is therefore comforting that we did obtain something small. Note that we cannot make r much smaller, unless we wish to contemplate the possibility that m_i is negative.

Since the electron is supposed to be elementary it might appear particularly tempting to try a model with $r = 0$, in which case the electron would be a "point-particle" with no extent and no structure. This, however, would lead to an infinite electromagnetic self-energy W, and to a negative infinite intrinsic mass m_i, which hardly makes sense. (This circumstance, which raises an insurmountable obstacle in the way of the *mathematically* simple and attractive model of a point-electron, is referred to in the literature as "the difficulty of the infinite self-energy of the electron.")

19 Let us now think critically about the above speculations: do they really make any sense? In asking our questions we have clearly made many assumptions which reflect our prejudices. We have assumed that the electron is a small charged sphere, and we have assumed that Coulomb's law can be applied to the "parts" of this sphere. How do we know that Coulomb's law applies to this situation? And what about the idea that a force has to hold together the "parts" of the electron against the electrostatic forces of repulsion? We have said earlier that the electron has no "parts"; *it is an elementary particle.* To ask what holds the electron together means we contemplate the possibility that it could break into parts, but this is a very questionable idea. Note that the electrostatic self-energy of the particle is the work which we could obtain by letting the "parts" of the particle disperse completely; this is how we originally derived the result that the electrostatic energy of any system of charges equals the integral of the square of the electric field strength over all space. If the particle *cannot* be dispersed, then the electrostatic self-energy is a doubtful concept. This is particularly true of the nonsensical infinite self-energy of the "point-electron."

Most physicists have realized by now that attempting to create some kind of classical model for the electron is meaningless. The electron does not behave like a charged sphere, and all discussions about what would keep it together if it were like a charged sphere or what its classical self-energy might be, are irrelevant in physics. Our classical prejudices led us to ask questions to which no sensible answers can be expected.