What Is Matter?

The wave-particle dualism afflicting modern physics is best resolved in favor of waves, believes the author, but there is no clear picture of matter on which physicists can agree

by Erwin Schrödinger

Fifty years ago science seemed on the road to a clear-cut answer to the ancient question which is the title of this article. It looked as if matter would be reduced at last to its ultimate building blocks—to certain submicroscopic but nevertheless tangible and measurable particles. But it proved to be less simple than that. Today a physicist no longer can distinguish significantly between matter and something else. We no longer contrast matter with forces or fields of force as different entities; we know now that these concepts must be merged. It is true that we speak of "empty" space (*i.e.*, space free of matter), but space is never really empty, because even in the remotest voids of the universe there is always starlight—and *that* is matter. Besides, space is filled with gravitational fields, and according to Einstein gravity and inertia cannot very well be separated.

Thus the subject of this article is in fact the total picture of space-time reality as envisaged by physics. We have to admit that our conception of material reality today is more wavering and uncertain than it has been for a long time. We know a great many interesting details, learn new ones every week. But to construct a clear, easily comprehensible picture on which all physicists would agree—that is simply impossible. Physics stands at a grave crisis of ideas. In the face of this crisis, many maintain that no objective picture of reality is possible. However, the optimists among us (of whom I consider myself one) look upon this view as a philosophical extravagance born of despair. We hope that the present fluctuations of thinking are only indications of an upheaval of old beliefs which in the end will lead to something better than the mess of formulas which today surrounds our subject.

Since the picture of matter that I am supposed to draw does not yet exist, since only fragments of it are visible, some parts of this narrative may be inconsistent with others. Like Cervantes' tale of Sancho Panza, who loses his donkey in one chapter but a few chapters later, thanks to the forgetfulness of the author, is riding the dear little animal again, our story has contradictions. We must start with the well-established concept that matter is composed of corpuscles or atoms, whose existence has been quite "tangibly" demonstrated by many beautiful experiments, and with Max Planck's discovery that energy also comes in indivisible units, called quanta, which are supposed to be transferred abruptly from one carrier to another.

But then Sancho Panza's donkey will return. For I shall have to ask you to believe neither in corpuscles as permanent individuals nor in the suddenness of the transfer of an energy quantum. Discreteness is present, but not in the traditional sense of discrete single particles, let alone in the sense of abrupt processes. Discreteness arises merely as a structure from the laws governing the phenomena. These laws are by no means fully understood; a probably correct analogue from the physics of palpable bodies is the way various partial tones of a bell derive from its shape and from the laws of elasticity to which, of themselves, nothing discontinuous adheres.

EDITOR'S NOTE

This article is condensed from a lecture entitled "Our Conception of Matter," given by Professor Schrödinger in 1952 at a conference in Geneva organized by Rencontres Internationales de Genève. The condensation is based on a translation by Sonja Bargmann, and it is published here with the kind permission of Editions de la Baconnière of Neuchâtel, Switzerland, who are publishing the full lecture in a volume called *L'homme devant la science*, presenting the proceedings of the conference.

The idea that matter is made up of ultimate particles was advanced as early as the fifth century B.C. by Leucippus and Democritus, who called these particles atoms. The corpuscular theory of matter was lifted to physical reality in the theory of gases developed during the 19th century by James Clerk Maxwell and Ludwig Boltzmann. The concept of atoms and molecules in violent motion, colliding and rebounding again and again, led to full comprehension of all the properties of gases: their elastic and thermal properties, their viscosity, heat conductivity and diffusion. At the same time it led to a firm foundation of the mechanical theory of heat, namely, that heat is the motion of these ultimate particles, which becomes increasingly violent with rising temperature.

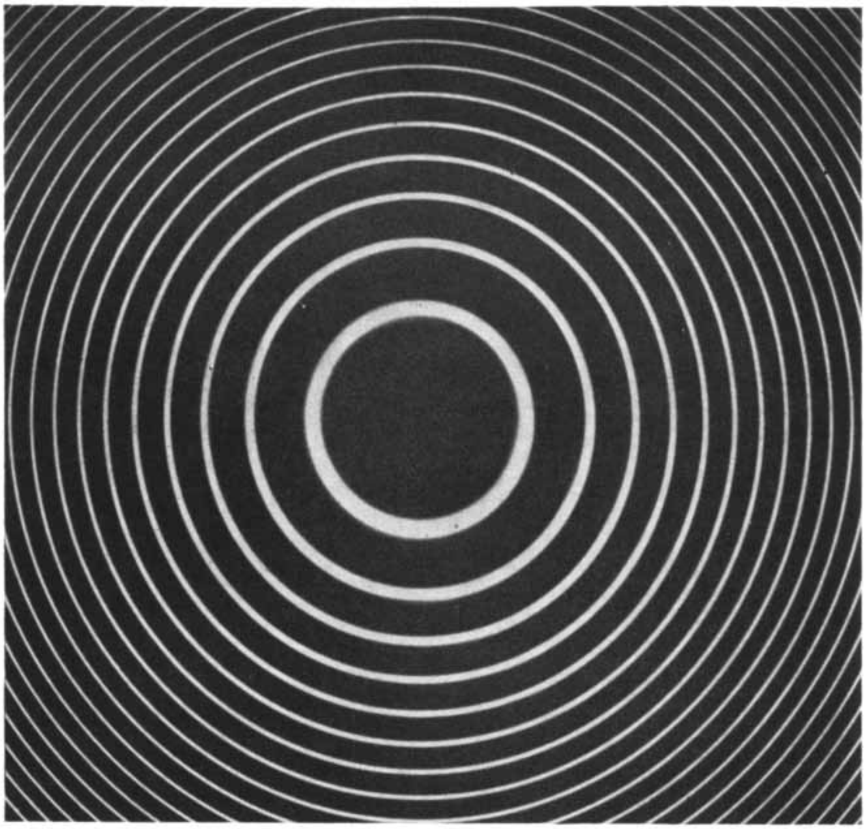
Within one tremendously fertile decade at the turn of the century came the discoveries of X-rays, of electrons, of the emission of streams of particles and other forms of energy from the atomic nucleus by radioactive decay, of the electric charges on the various particles. The masses of these particles, and of the atoms themselves, were later measured very precisely, and from this was discovered the mass defect of the atomic nucleus as a whole. The mass of a nucleus is less than the sum of the masses of its component particles; the lost mass becomes the binding energy holding the nucleus firmly together. This is called the packing effect. The nuclear forces of course are not electrical forces—those are repellent—but are much stronger and act only within very short distances, about 10^{-13} centimeter [*see Hans Bethe's article on page 58*].

Here I am already caught in a contradiction. Didn't I say at the beginning that we no longer assume the existence of force fields apart from matter? I could easily talk myself out of it by saying: Well, the force field of a particle is simply considered a part of it. But that is not the fact. The established view today is rather that everything is at the same time both particle and field. Everything has the continuous structure with which we are familiar in fields, as well as the discrete structure with which we are equally familiar in particles. This concept is supported by innumerable experimental facts and is accepted in general, though opinions differ on details, as we shall see.

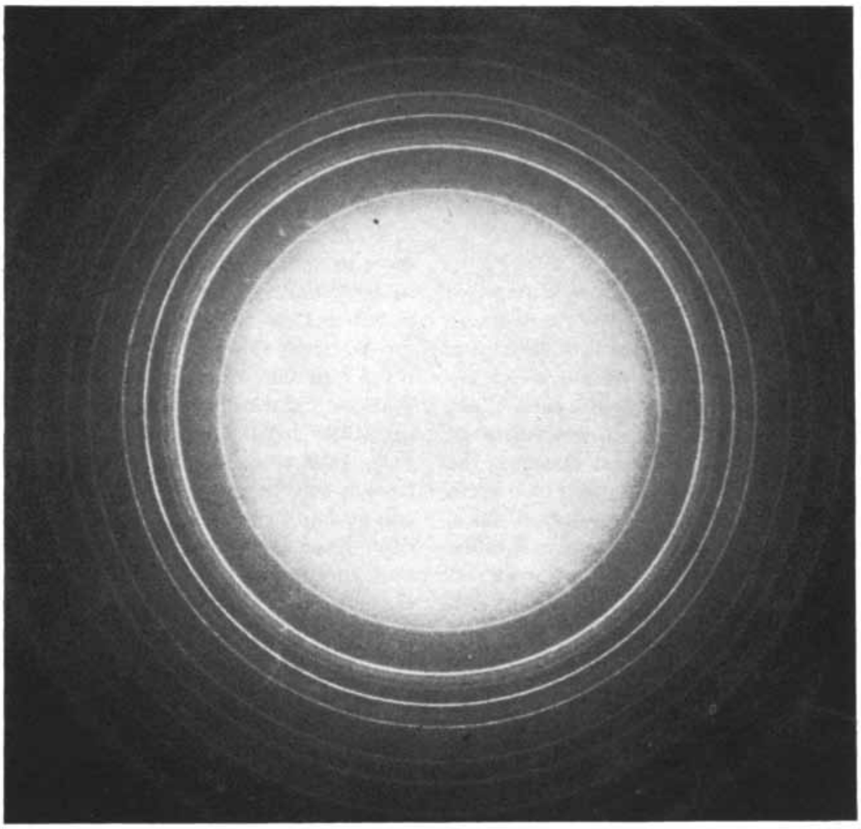
In the particular case of the field of nuclear forces, the particle structure is more or less known. Most likely the continuous force field is represented by the so-called pi mesons. On the other hand, the protons and neutrons, which we think of as discrete particles, indisputably also have a continuous wave structure, as is shown by the interference patterns they form when diffracted by a crystal. The difficulty of combining these two so very different character traits in one mental picture is the main stumbling-block that causes our conception of matter to be so uncertain.

Neither the particle concept nor the wave concept is hypothetical. The tracks in a photographic emulsion or in a Wilson cloud chamber leave no doubt of the behavior of particles as discrete units. The artificial production of nuclear particles is being attempted right now with terrific expenditure, defrayed in the main by the various state ministries of defense. It is true that one cannot kill anybody with one such racing particle, or else we should all be dead by now. But their study promises, indirectly, a hastened realization of the plan for the annihilation of mankind which is so close to all our hearts.

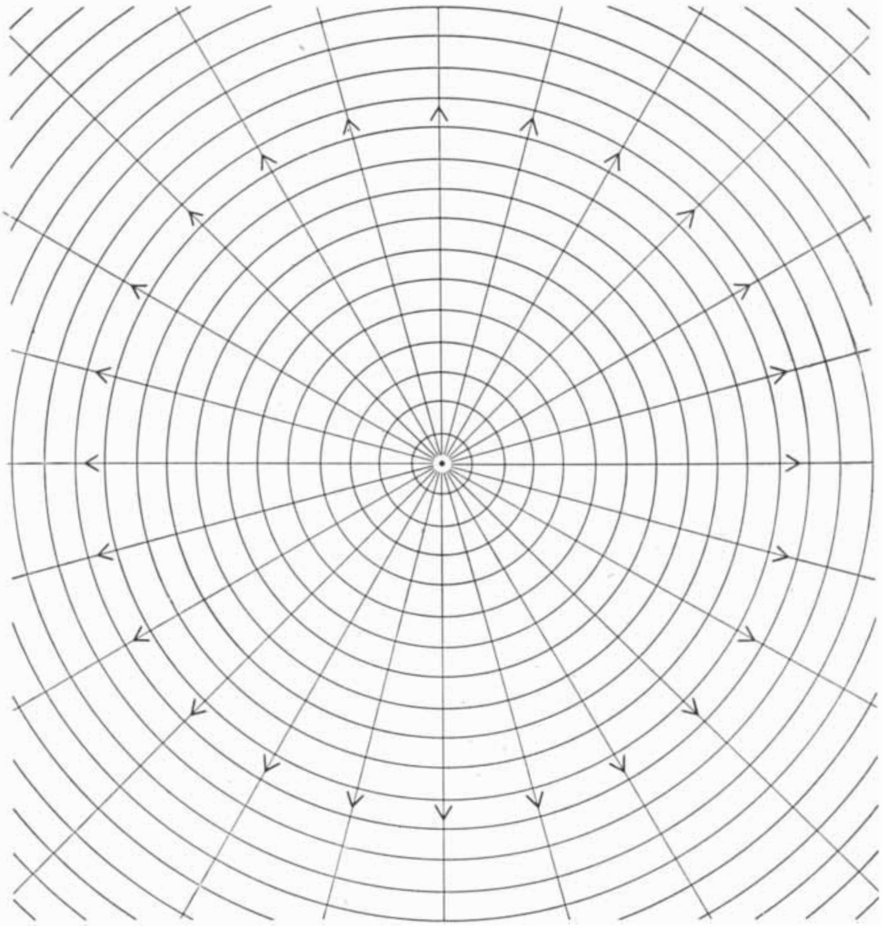
You can easily observe particles yourself by looking at a luminous numeral of your wrist watch in the dark with a magnifying glass. The luminosity surges and undulates, just as a lake sometimes twinkles in the sun. The light consists of sparklets, each produced by a so-called alpha particle (helium nucleus) expelled by a radioactive atom which in this process is transformed into a different atom. A specific device for detecting



LIGHT INTERFERENCE pattern, showing the wave nature of light, was produced at the National Bureau of Standards, using light from mercury vapor and an interferometer.



ELECTRON INTERFERENCE pattern from a crystal diffraction experiment at the Radio Corporation of America Laboratories gives convincing evidence that electrons are waves.



WAVE DIAGRAM in two dimensions shows wave fronts (*circles*) and wave "normals" or "rays" (*arrows*). In three dimensions the fronts would be surfaces like layers in an onion.

and recording single particles is the Geiger-Müller counter. In this short résumé I cannot possibly exhaust the many ways in which we can observe single particles.

Now to the continuous field or wave character of matter. Wave structure is studied mainly by means of diffraction and interference—phenomena which occur when wave trains cross each other. For the analysis and measurement of light waves the principal device is the ruled grating, which consists of a great many fine, parallel, equidistant lines, closely engraved on a specular metallic surface. Light impinging from one direction is scattered by them and collected in different directions depending on its wavelength. But even the finest ruled gratings we can produce are too coarse to scatter the very much shorter waves associated with matter. The fine lattices of crystals, however, which Max von Laue first used as gratings to analyze the very short X-rays, will do the same for "matter waves." Directed at the surface of a crystal, high-velocity streams of particles manifest their wave nature. With crystal gratings physicists have diffracted and measured the wavelengths of electrons, neutrons and protons.

What does Planck's quantum theory have to do with all this? Planck told us in 1900 that he could comprehend the radiation from red-hot iron, or from an incandescent star such as the sun, only if this radiation was produced in discrete portions and transferred in such discrete quantities from one carrier to another (*e.g.*, from atom to atom). This was extremely startling, because up to that time energy had been a highly abstract concept. Five years later Einstein told us that energy has mass and mass is energy; in other words, that they are one and the same. Now the scales begin to fall from our eyes: our dear old atoms, corpuscles, particles are Planck's energy quanta. *The carriers of those quanta are themselves quanta.* One gets dizzy. Something quite fundamental must lie at the bottom of this, but it is not surprising that the secret is not yet understood. After all, the scales did not fall suddenly. It took 20 or 30 years. And perhaps they still have not fallen completely.

The next step was not quite so far-reaching, but important enough. By an ingenious and appropriate generalization of Planck's hypothesis Niels Bohr taught us to understand the line spectra of atoms and molecules and how atoms were composed of heavy, positively charged nuclei with light, negatively charged electrons revolving around them. Each small system—atom or molecule—can harbor only definite discrete energy quantities, corresponding to its nature or its constitution. In transition from a higher to a lower "energy level" it emits the excess energy as a radiation quantum of definite wavelength, inversely proportional to the quantum given off. This means that a quantum of given magnitude manifests itself in a periodic process of definite frequency which is directly proportional to the quantum; the frequency equals the energy quantum divided by the famous Planck's constant, h.

According to Einstein a particle has the energy mc^2, m being the mass of the particle and c the velocity of light. In 1925 Louis de Broglie drew the inference, which rather suggests itself, that a particle might have associated with it a wave process of frequency mc^2 divided by h. The particle for which he postulated such a wave was the electron. Within two years the "electron waves" required by his theory were demonstrated by the famous electron diffraction experiment of C. J. Davisson and L. H. Germer. This was the starting point for the cognition that everything—anything at all—is simultaneously particle and wave field. Thus de Broglie's dissertation initiated our uncertainty about the nature of matter. Both the particle picture and the wave picture have truth value, and we cannot give up either one or the other. But we do not know how to combine them.

That the two pictures are connected is known in full generality with great precision and down to amazing details. But concerning the unification to a single, concrete, palpable picture opinions are so strongly divided that a great many deem it altogether impossible. I shall briefly sketch the connection. But do not expect that a uniform, concrete picture will emerge before you; and do not blame the lack of success either on my ineptness in exposition or your own denseness—nobody has yet succeeded.

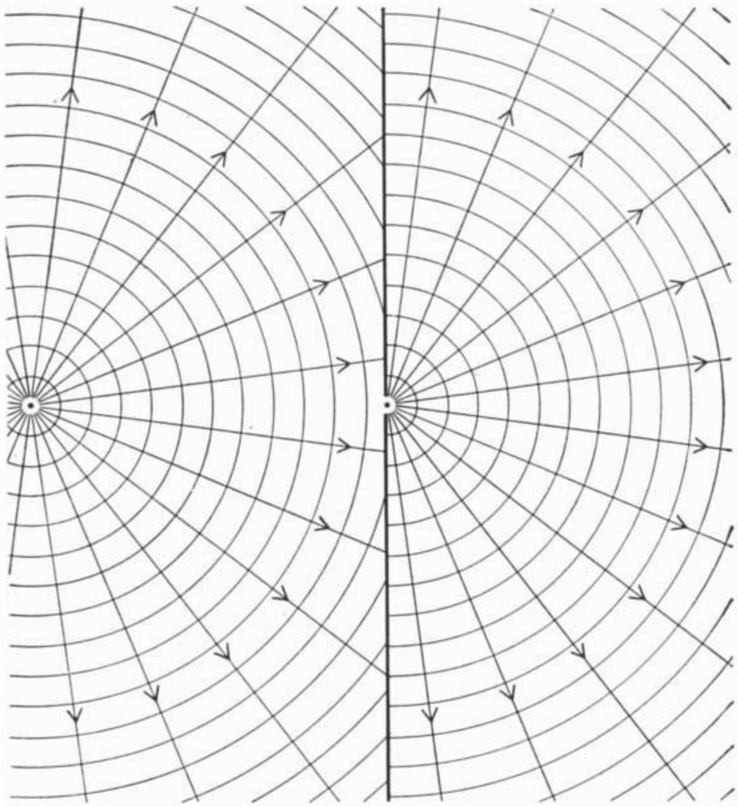
One distinguishes two things in a wave. First of all, a wave has a front, and a succession of wave fronts forms a system of surfaces like the layers of an onion. You are familiar with the two-dimensional analogue of the beautiful wave circles that form on the smooth surface of a pond when a stone is thrown in. The second characteristic of a wave, less intuitive, is the path along which it travels—a system of imagined lines perpendicular to the wave fronts. These lines are known as the wave "normals" or "rays."

We can make the provisional assertion that these rays correspond to the trajectories of particles. Indeed, if you cut a small piece out of a wave, approximately 10 or 20 wavelengths along the direction of propagation and about as much across, such a "wave packet" would actually move along a ray with exactly the same velocity and change of velocity as we might expect from a particle of this particular kind at this particular place, taking into account any force fields acting on the particle.

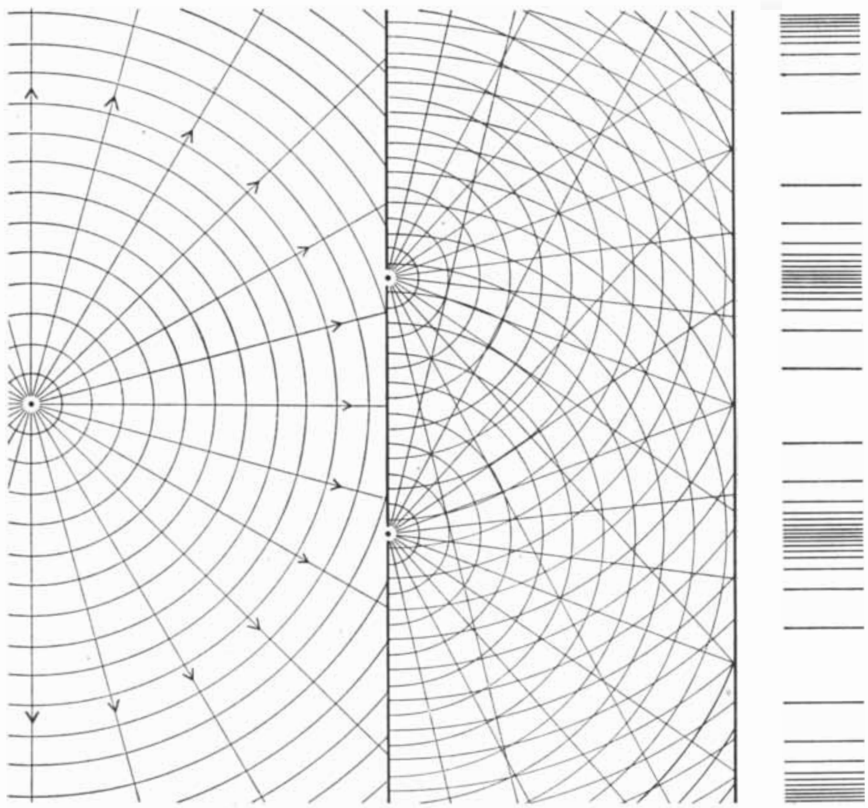
Here I falter. For what I must say now, though correct, almost contradicts this provisional assertion. Although the behavior of the wave packet gives us a more or less intuitive picture of a particle, which can be worked out in detail (*e.g.*, the momentum of a particle increases as the wavelength decreases; the two are inversely proportional), yet for many reasons we cannot take this intuitive picture quite seriously. For one thing, it is, after all, somewhat vague, the more so the greater the wavelength. For another, quite often we are dealing not with a small packet but with an extended wave. For still another, we must also deal with the important special case of very small "packelets" which form a kind of "standing wave" which can have no wave fronts or wave normals.

One interpretation of wave phenomena which is extensively supported by experiments is this: At each position of a uniformly propagating wave train there is a twofold structural connection of interactions, which may be distinguished as "longitudinal" and "transversal." The transversal structure is that of the wave fronts and manifests itself in diffraction and interference experiments; the longitudinal structure is that of the wave normals and manifests itself in the observation of single particles. However, these concepts of longitudinal and transversal structures are not sharply defined and absolute, since the concepts of wave front and wave normal are not, either.

The interpretation breaks down completely in the special case of the standing



DIFFRACTION is characteristic of waves. When a wave (*left*) comes to a barrier perforated with a small hole, it diffracts around the edges of the hole to form a new wave (*right*).



INTERFERENCE is also evidence of waves. Its characteristic pattern is formed when rays interact. For light waves the pattern shows up as bright and dark bands on a screen (*right*).

waves mentioned above. Here the whole wave phenomenon is reduced to a small region of the dimensions of a single or very few wavelengths. You can produce standing water waves of a similar nature in a small basin if you dabble with your finger rather uniformly in its center, or else just give it a little push so that the water surface undulates. In this situation we are not dealing with uniform wave propagation; what catches the interest are the normal frequencies of these standing waves. The water waves in the basin are an analogue of a wave phenomenon associated with electrons, which occurs in a region just about the size of the atom. The normal frequencies of the wave group washing around the atomic nucleus are universally found to be exactly equal to Bohr's atomic "energy levels" divided by Planck's constant *h*. Thus the ingenious yet somewhat artificial assumptions of Bohr's model of the atom, as well as of the older quantum theory in general, are superseded by the far more natural idea of de Broglie's wave phenomenon. The wave phenomenon forms the "body" proper of the atom. It takes the place of the individual pointlike electrons which in Bohr's model are supposed to swarm around the nucleus. Such pointlike single particles are completely out of the question within the atom, and if one still thinks of the nucleus itself in this way one does so quite consciously for reasons of expediency.

What seems to me particularly important about the discovery that "energy levels" are virtually nothing but the frequencies of normal modes of vibration is that now one can do without the assumption of sudden transitions, or quantum jumps, since two or more normal modes may very well be excited simultaneously. The discreteness of the normal frequencies fully suffices—so I believe—to support the considerations from which Planck started and many similar and just as important ones—I mean, in short, to support all of quantum thermodynamics.

The theory of quantum jumps is becoming more and more inacceptable, at least to me personally, as the years go on. Its abandonment has, however, far-reaching consequences. It means that one must give up entirely the idea of the exchange of energy in well-defined quanta and replace it with the concept of resonance between vibrational frequencies. Yet we have seen that because of the identity of mass and energy, we must consider the particles themselves as Planck's energy quanta. This is at first frightening. For the substituted theory implies that we can no longer consider the individual particle as a well-defined permanent entity.

That it is, in fact, no such thing can be reasoned in other ways. For one thing, there is Werner Heisenberg's famous uncertainty principle, according to which a particle cannot simultaneously have a well-defined position and a sharply defined velocity. This uncertainty implies that we cannot be sure that the same particle could ever be observed twice. Another conclusive reason for not attributing identifiable sameness to individual particles is that we must obliterate their individualities whenever we consider two or more interacting particles of the same kind, *e.g.*, the two electrons of a helium atom. Two situations which are distinguished only by the interchange of the two electrons must be counted as one and the same; if they are counted as *two* equal situations, nonsense obtains. This circumstance holds for any kind of particle in arbitrary numbers without exception.

Most theoreticians will probably accept the foregoing reasoning and admit that the individual particle is not a well-defined permanent entity of detectable identity or sameness. Nevertheless this inadmissible concept of the individual particle continues to play a large role in their ideas and discussions. Even deeper rooted is the belief in "quantum jumps," which is now surrounded with a highly abstruse terminology whose common-sense meaning is often difficult to grasp. For instance, an important word in the standing vocabulary of quantum theory is "probability," referring to transition from one level to another. But, after all, one can speak of the probability of an event only assuming that, occasionally, it actually occurs. If it does occur, the transition must indeed be sudden, since intermediate stages are disclaimed. Moreover, if it takes time, it might conceivably be interrupted halfway by an unforeseen disturbance. This possibility leaves one completely at sea.

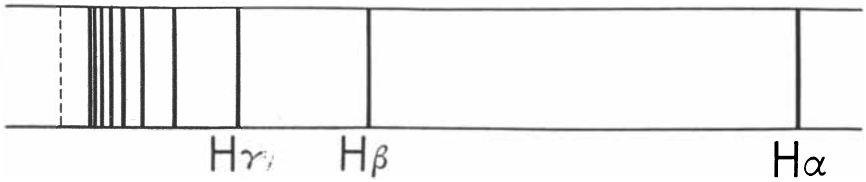
The wave *v.* corpuscle dilemma is supposed to be resolved by asserting that the wave field merely serves for the computation of the probability of finding a particle of given properties at a given position if one looks for it there. But once one deprives the waves of reality and assigns them only a kind of informative role, it becomes very difficult to understand the phenomena of interference and diffraction on the basis of the combined action of discrete single particles. It certainly seems easier to explain particle tracks in terms of waves than to explain the wave phenomenon in terms of corpuscles.

"Real existence" is, to be sure, an expression which has been virtually chased to death by many philosophical hounds. Its simple, naive meaning has almost become lost to us. Therefore I want to recall something else. I spoke of a corpuscle's not being an individual. Properly speaking, one never observes the same particle a second time—very much as Heraclitus says of the river. You cannot mark an electron, you cannot paint it red. Indeed, you must not even *think* of it as marked; if you do, your "counting" will be false and you will get wrong results at every step—for the structure of line spectra, in thermodynamics and elsewhere. A wave, on the other hand, can easily be imprinted with an individual structure by which it can be recognized beyond doubt. Think of the beacon fires that guide ships at sea. The light shines according to a definite code; for example: three seconds light, five seconds dark, one second light, another pause of five seconds, and again light for three seconds—the skipper knows that is San Sebastian. Or you talk by wireless telephone with a friend across the Atlantic; as soon as he says, "Hello there, Edward Meier speaking," you know that his voice has imprinted on the radio wave a structure which can be distinguished from any other. But one does not have to go that far. If your wife calls, "Francis!" from the garden, it is exactly the same thing, except that the structure is printed on sound waves and the trip is shorter (though it takes somewhat longer than the journey of radio waves across the Atlantic). All our verbal communication is based on imprinted individual wave structures. And, according to the same principle, what a wealth of details is transmitted to us in rapid succession by the movie or the television picture!

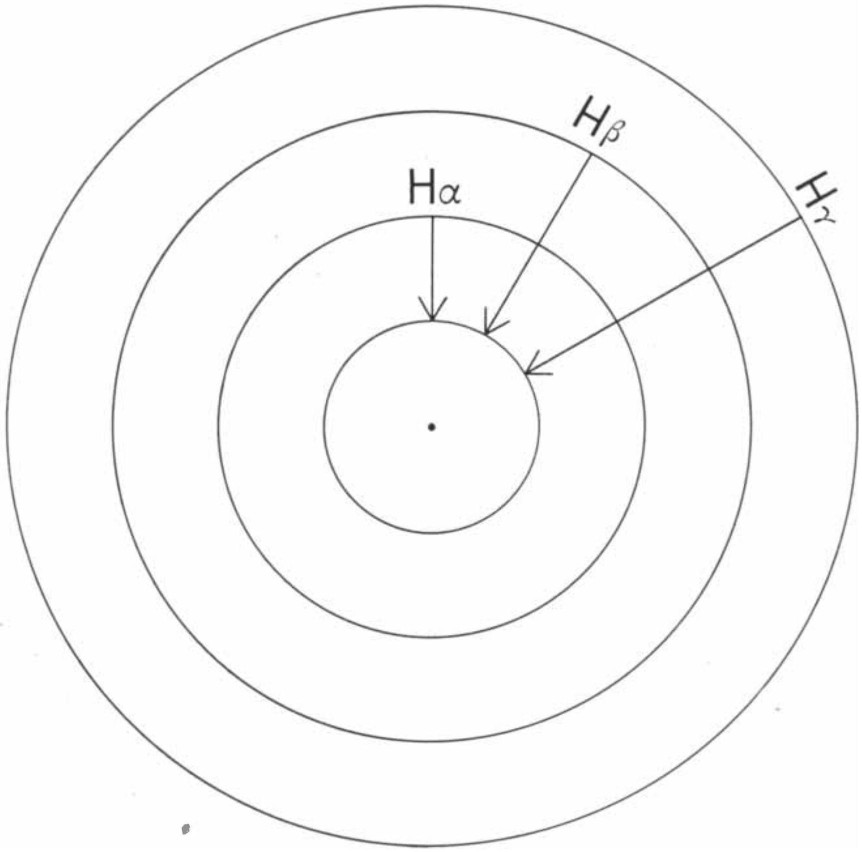
This characteristic, the individuality of the wave phenomenon, has already been found to a remarkable extent in the very much finer waves of particles. One example must suffice. A limited volume of gas, say helium, can be thought of either as a collection of many helium atoms or as a superposition of elementary wave trains of matter waves. Both views lead to the same theoretical results as to the behavior of the gas upon heating, compression, and so on. But when you attempt to apply certain somewhat involved enumerations to the gas, you must carry them out in different ways according to the mental picture with which you approach it. If you treat the gas as consisting of particles, then no individuality must be ascribed to them, as I said. If, however, you concentrate on the matter wave trains instead of on the particles, every one of the wave trains has a well-defined structure which is different from that of any other. It is true that there are many pairs of waves which are so similar to each other that they could change roles without any noticeable effect on the gas. But if you should count the very many similar states formed in this way as merely a single one, the result would be quite wrong.

In spite of everything we cannot completely banish the concepts of quantum jump and individual corpuscle from the vocabulary of physics. We still require them to describe many details of the structure of matter. How can one ever determine the weight of a carbon nucleus and of a hydrogen nucleus, each to the precision of several decimals, and detect that the former is somewhat lighter than the 12 hydrogen nuclei combined in it, without accepting for the time being the view that these particles are something quite concrete and real? This view is so much more convenient than the roundabout consideration of wave trains that we cannot do without it, just as the chemist does not discard his valence-bond formulas, although he fully realizes that they represent a drastic simplification of a rather involved wave-mechanical situation.

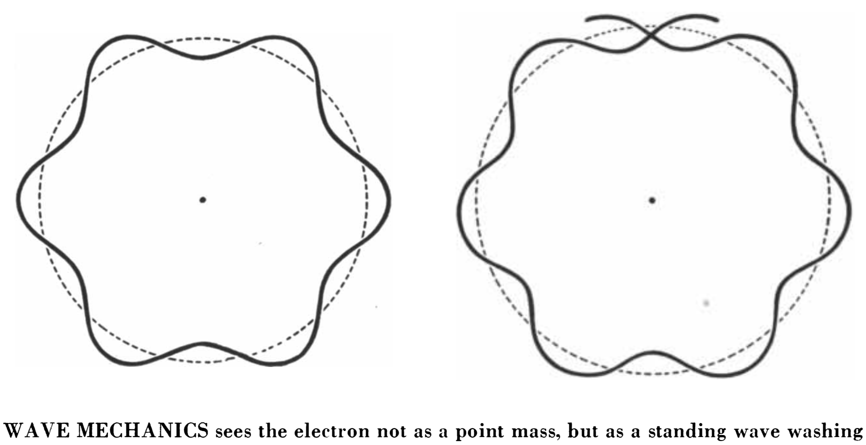
If you finally ask me: "Well, what *are* these corpuscles, really?" I ought to confess honestly that I am almost as little prepared to answer that as to tell where Sancho Panza's second donkey came from. At the most, it may be permissible to say that one can think of particles as more or less temporary entities within the wave field whose form and general behavior are nevertheless so clearly and sharply determined by the laws of waves that many processes take place *as if* these temporary entities were substantial permanent beings. The mass and the charge of particles, defined with such precision, must then be counted among the structural elements determined by the wave laws. The conservation of charge and mass in the large must be considered as a statistical effect, based on the "law of large numbers."



HYDROGEN SPECTRUM expresses the behavior of a fundamental constituent of matter, the electron. Shown above is a part of the Balmer series of spectral lines, which are in the visible light range. Each line is the result of a change in energy of the atom's electron.



BOHR THEORY explained spectral lines of hydrogen by postulating a pointlike electron revolving around the nucleus in any of a number of possible orbits. In falling from one to another, the electron emits light energy whose wavelength is that of one of the spectral lines.



WAVE MECHANICS sees the electron not as a point mass, but as a standing wave washing to and fro in the atom. Some modes of vibration are possible (*left*), while others are not (*right*). The possible modes correspond exactly to the Bohr theory's possible energy levels.