SCIENCE

VOL. 73 FRIDAY, JUNE 19, 1931 No. 1903

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

New York City: Grand Central Terminal
Lancaster, Pa. Garrison, N. Y.

Annual Subscription, $6.00 Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary, in the Smithsonian Institution Building, Washington, D. C.

THE UNCERTAINTY PRINCIPLE[1]

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WE have seen that direct experimental evidence pointed to electrons being waves, in the sense that when we send a stream of them through two holes, we can only explain the result by supposing that, like a wave, each electron goes through both holes. We saw, moreover, that if a patch of wave-disturbance in a medium never encounters small obstacles it keeps together as it travels, and behaves in this way like an individual, which is what we think the characteristic of a particle. So we might at first sight be tempted to think that we had got a quite satisfactory and complete view of the character of an electron merely as being a wave of very short wave-length. But a little consideration shows that this will not do.

In the first place we have seen that though a patch of disturbance travels along as an individual with the definite group-velocity, there is always a region round its edges where the disturbance is slowly spreading. There is no way in which a wave can escape this gradual diffusion, and it means that ultimately it will become spread all over space. The rate of diffusion is smaller the larger the volume over which the waves are spread, so that it would be very slow for matter in bulk, and such waves would keep together a considerable time, but still they would not do so forever. Even if we regarded the world as originally created in well-defined "wave-packets," they would certainly by now have spread indefinitely. We may say that the existence of fossils which have preserved their form unchanged for several hundred million years disproves the adequacy of the wave theory.

But the matter is worse than this, since we can do other experiments which seem immediately to disprove the validity of the wave-theory. There exist substances which have the property of *scintillation*

[1] The fourth of the series of lectures on "The New Conceptions of Matter," delivered at the Lowell Institute on March 27, 1931.

when struck by electrons. A scintillating screen is made by lightly powdering a sheet of glass with zinc sulphide crystals; when one of these crystals is struck by an electron it emits a faint spark, which can be seen in the dark with the help of a magnifying lens. When such a screen is exposed to a stream of electrons, scintillations appear irregularly all over it. The natural inference from this experiment is that the stream is like a shower of rain falling on the screen, and each scintillation is produced when a single drop hits the screen. We seem to have a perfect and complete proof that the electrons are little bullets each traveling along a line from source to target.

It looks as though we had arrived at a flat contradiction. This experiment tells us that the electron is a bullet in one part of the stream, while we could not explain Thomson's experiments without supposing that the electron went through two holes at the same time, as only a wave can do. To bring out the contradiction still more strongly we may combine both experiments into one; though this experiment has not actually been done, there is not a shadow of doubt what would be found if it were practically possible. If we sent out a stream of electrons through two small holes close together and then looked for scintillations, we should find these still appearing as isolated sparks, but the sparks would all occur in certain bands, and none at all in between at the places where the diffraction theory predicts darkness. But if we afterwards block one of the two holes, we shall destroy the interference and shall get scintillations everywhere. The crude way of saying what has happened is that the electron stream was a wave when it was going through two holes, but has miraculously turned itself into a particle when it hits the screen. Of course such a description is not to be tolerated, since it would imply foresight on the part of the electron as to what was expected of it. We can imagine, for instance, that we could swindle the electron by pretending we were going to put a shutter with holes, so that it should get ready to be a wave, and then put a scintillating screen instead. Absurdities of this kind show that we have arrived at a very fundamental difficulty.

The elucidation of this contradiction is really the central point of the new quantum theory. The explanation, due to Heisenberg and Bohr, starts by showing that in fact the properties are not contradictory but complementary. Whatever the thing is that we call matter, it can be submitted to various experiments, some of which are devised to show wave properties and some particle properties; but if we devise an experiment which shows the wave properties, that experiment debars us from observing the particle properties at the same time, and *vice versa.* Suppose, for instance, that we wanted to make sure that it really was particles that were going through our holes. We should set a scintillating screen over one of them, and whenever we saw a scintillation we should say that there was a particle coming to that hole. But in doing so we should have prevented the particle going through and so obviously should not get interference on the other side. Next we might try to improve the experiment, by imagining our screen was so thin that the electron could produce a scintillation on it and still get through. Could we not then get interference between this part of the electron wave and the part that went through the other hole unimpeded? We should fail, because, though the electron wave has got through the first hole, the mere act of exciting the scintillation will alter the phase of its wave, and if this phase changes there can be no interference. We have laid a trap for the electron to induce it to tell us which hole it went through, but when the electron answers the question that it went through one hole, it automatically refuses to do the interference which would confess that it went through both.

It is the recognition of this and similar facts that has cleared up the mystery of the quantum theory. A situation arose rather like that in the early days of the discovery of relativity. The great idea which Einstein contributed to scientific philosophy was the principle that if a thing is essentially unobservable then it is not a real thing and our theories must not include it. He showed how the idea of absolute time was of this nature, and the whole beautiful structure of relativity was built up from that basis. But a self-consistent mathematical formulation of the theory is not enough; it is also necessary to convince ourselves by examples that in fact it really is impossible to determine whether two events in different places occur at the same instant. We learn to understand the theory much better by "shamming stupid," trying to lay traps for the theory and seeing how it escapes from them. Much the same state of affairs has arisen in the quantum theory; we have considered one case where we laid a trap for the electron, trying to make it tell us whether it was wave or particle, and we have seen how it avoided the trap. We must convince ourselves that no experiment can be invented which should at the same time require the electron to behave like a particle and like a wave. The guiding principle which establishes this result is called the uncertainty principle, and we shall discuss this and with its help shall see how the conflict between wave and particle is always avoided.

As we have seen, some experiments with electrons exhibit their particle characters and some their wave characters. We can not avoid thinking about both, and it is a very confusing thing to have to do. In one picture the electron is a little speck of dust, or a bullet, and in the other it is, shall we say, like a stormy sea, and it is not easy to see much resemblance between the two. There have been attempts to regard it as a speck of dust *in* a stormy sea, but it can definitely be said that they are of no use at all. Perhaps the best description can be made by the use of a commercial expression; an electron is a particle "and/or" a wave. We must be ready all the time to think of it as either or both, but we must not mix the ideas. There are two half-worlds, each of which gives a partial view of the whole world; they are related to one another and interdependent, but they are expressed in different languages. We call the two half-worlds the particle aspect and the wave aspect. There is nothing of the same kind anywhere else in scientific thought, but the absolute separation, yet interdependence, can perhaps be compared to a similar separation in metaphysics. There is a close interdependence between the objective thing that we see or hear and our subjective sensation of sight or hearing, and yet the two use wholly different languages. When a string on the piano vibrates 256 times a second, we hear "middle C" without any conception that there is anything happening 256 times; and when an ether vibration with twenty thousand waves in each centimeter strikes our eye, we see yellow, an ultimate sensation giving no hint of a wave motion. In the same way, when we burn a finger in the objective world it is because the atoms of the fire are moving about a little faster than those in ourselves, but actually all we feel is that it is too hot. There is the same kind of interrelation without identity between the wave and particle aspects of matter. It is tempting to carry the analogy a little further, and to decide which way round it is to be taken. I think that it is best to regard the wave aspect as analogous to the objective world, and the particle to the subjective; for example, we have a very direct and intimate perception of what a particle means if we are hit by a bullet, and, on the other hand, we have no intuitive knowledge whatever that light and sound have anything to do with waves. But I do not in the least want to insist on this; the whole thing is only an analogy, and perhaps some will say a fanciful one. I am too bad a metaphysician to judge of this.

We must consider a little more closely the interdependence of the two aspects. In the last lecture we saw that it had been shown that under certain conditions the wave of an electron would have wave-length about the same as that of x-rays, that is about a hundred millionth of a centimeter. Thomson and others have experimented with electrons which, regarded from the particle aspect, have various speeds, and have found that the wave-length is inversely proportional to the speed; but the limitations of experimental technique prevent the investigation of any very wide range of speeds. Theory, however, clearly indicates what the relation will be between speed and wave-length; indeed the experimental work was really only a verification of the theory. The relationship was first given by de Broglie, and involves the *quantum* itself. The quantum is a certain universal constant which is always turning up in atomic theory. That it is a perfectly genuine quantity is shown by the fact that it has with some precision the value 6.545×10^{-27} gr. sq. cm per sec., but this does not really help any one to understand it. Its nature is best described by saying that it is the single universal connecting link between the particle and wave aspects. The rule for finding the wave-length of any particle is to divide the quantum by the momentum of the particle, and this gives the ultimate meaning of the quantum. The rule is true not only for electrons, but also for protons, atoms, molecules, photons and even bodies of ordinary large size.

In order to observe the wave aspect easily, we want to get long waves, and that means small momentum, and small momentum can be got either by having low velocity or else very light particles. For this reason most experiments on the diffraction of particles have made use of electrons, the lightest particles that exist. It is interesting, however, to note that recently the diffraction of whole atoms has also been observed. We will consider a few of the associated values for electrons of speed and wave-length, but in doing so, it must be strongly emphasized that we are describing the two irreconcilable aspects of matter as though they could be mixed together. When I say that such and such a speed implies such and such a wave-length, it is only to be taken formally. It means that if we have a suitable grating, lateral spectra will be found corresponding in position to that wave-length.

In Thomson's experiments the electrons were set in motion by an electric field of about 20,000 volts. This gives them the high speed of 8.5×10^9 cm per sec., more than a quarter of the speed of light, which would carry them right round the earth in half a second. The associated wave-length is 0.8×10^{-9} cm, about a twentieth of the distance between the atoms in the analyzing crystal. In Davisson's experiments much lower voltages were used. With 200 volts the speed would be a tenth as great and the wave-length ten times as much, nearly as great as the size of the atoms of the crystal. For much lower voltages the experiments would become very difficult both because the electrons produce hardly any observable effect, and also because they will not be diffracted when their wave-length is greater than the interatomic distance. It is very probable that these difficulties will be overcome in time; indeed a beginning has already been made in that it has been found possible to observe the diffraction of electrons, though still rather fast ones, with an ordinary optical grating instead of a crystal. Though experiments are lacking, theory predicts with confidence the wave-lengths associated with slower electrons. An electron moving at the speed of a rifle bullet has wave-length about a thousandth of a millimeter, a length visible in a microscope. An electron moving at the rate of ordinary human walking would have wave-length of a size just visible to the naked eye, and one moving at the rate of a rather slow tortoise would have wave-length an inch long.

These relations are so far only formal. We do not expect to be able to see the crests of the waves or anything of the kind, but are only maintaining that certain experiments, at present quite impracticable, would reveal diffraction effects which would imply these wave-lengths. But let us take the relationship more literally and see what it implies. An electron-particle moving at a rate of one centimeter a second is an electron-wave of length seven centimeters. Now a wave of seven centimeters does not by any means signify a wave with only two crests seven centimeters apart; it means an infinite train of harmonic waves stretching to infinity in both directions, with all the crests regularly arranged at intervals of seven centimeters. Where, then, is the electron particle? The answer is that it may be absolutely anywhere! This was the key to the elucidation of the whole quantum theory; it was entirely unforeseen and it is the central fact of the new conception of matter. Let us examine the question in more detail. Perhaps we have taken a rather too pedantic view when we say that the mere calculation of a wave-length implies that there was an *infinite* train of harmonic waves, for after all a train of waves with twenty or thirty crests travels for a time in much the same way and could show diffraction. Such a group or *wave-packet,* as it is often called in the present connection, travels along with the group velocity, but spreads a little as it goes. Where is the electron-particle now? The medium carrying the electron wave is undisturbed, except where the packet is, and so we can say that the electron particle is at all events somewhere in the packet, but we do not know whereabouts in it. The packet moves with the group velocity, and the electron must keep in the packet, so it must move at something of the same rate too. But now there enters the important point that a wave-packet always spreads, and so at a later time is longer than at the start, and therefore there is a wider region available for the particle-electron. This can be expressed in another way; we may say that the speed of the particle is not exactly the same as the group velocity of the waves but may be a little more or less. For example, if the particle is at the hind end at the beginning and at the front end of the wave later, when it has spread, then it will have gone faster than the group velocity. On account of the spreading of the wave-packet there is an uncertainty of the speed of the particle. The point of the new outlook is that though we think of a particle as associated with the wave, it is *impossible* to know where in the wave it is, and *impossible* to say exactly how fast it is moving. Our first tendency is to resist this conclusion and to say that we can imagine ways of finding where the electron really is and how fast it is moving. We shall consider this point soon, and show how such an experiment is always defeated, but it will be best to accept it for the moment, simply taking the rule that the particle-electron is somewhere in the wave-packet, and consider what degree of uncertainty of position and motion this implies.

The uncertainty of position of the electron depends on the size of the wave-packet, so that for a long packet, containing a great many crests, the position of the particle is very uncertain. Such a wave group on the other hand does not spread very rapidly, and so we can say that the velocity is rather precisely given. Next consider the opposite case of a very short wave-packet. In such a case the spreading is very rapid, so that the velocity is very uncertain. The general result thus is that the greater precision we demand for either position or velocity, the less the precision that can be assigned for the other. The rule is more definite than this, and can be given a rough numerical value. The product of the uncertainties of position and momentum of any particle can not be brought below a value equal to the quantum. This is true for all particles, electrons, protons, photons, atoms, and so on. It is the uncertainty principle.

The relation between wave-length and momentum is only one way in which the wave and particle aspects are connected. There is another which in many ways is quite as important, and which must be described. We may recall that the character of a harmonic wave depends on both wave-length and wave-velocity, and that from these two a third can be devised, the frequency, which is the number of oscillations per second described by the medium at a fixed point. The frequency is really the most fundamental of the three, for if the medium has variable properties the wave-length and wave-velocity will vary in different places, but the frequency will be the same everywhere. The frequency of an electron belongs of course to its wave-aspect, and the corresponding quantity in the particle aspect is the energy. The energy can be derived by multiplying the frequency by the quantum. There is also an uncertainty principle for the energy, just as there is for the momentum. This asserts that if we want to measure energy accurately we must take a long time in order to do so. If, on the other hand, we want to know the energy at a certain moment, we must obviously only use a short interval of time round that moment to do the measurement, and the value we obtain will be inaccurate. It is easy to see why this should be so by taking account of the wave aspect. An accurate knowledge of the energy implies an accurate knowledge of the frequency, and this knowledge can only be attained by letting the oscillation run through a great many cycles, that is to say by taking a long time.

We have seen how the uncertainty principle arises quite naturally from the behavior of wave-packets. But we must now assure ourselves that no experiment can be devised which would directly determine both position and speed with a higher accuracy than the principle permits. In the first place a simple calculation shows that bodies of ordinary size, on account of their great weight, have so little uncertainty of velocity that the ordinary disturbances of the world will far exceed it. The effect only becomes perceptible for particles as light as atoms, and the most favorable case of all is the lightest particle, the electron. Let us therefore imagine that we have a skeptical experimenter, who refuses to believe in the wave theory, and sets to work to show that he can fix the position and speed of an electron at the same time with as high accuracy as he pleases. To make his experiment easier he will take the electron to be at rest, but it should be mentioned that this has nothing to do with the uncertainty principle; for that principle the difference between an electron at rest and moving at a centimeter a second is just the same as the difference between one moving at a thousand centimeters a second or a thousand and one. Our experimenter claims to have got an electron precisely fixed and at rest. We will cross-examine him about his work and see what he has found.

Q. How did you know the electron was there?

A. I saw it.

Q. An electron is a pretty small thing and not easy to see. How did you manage?

A. I had a microscope.

Q. Even a microscope can only see things of the size of a wave-length of light. You can't be much of a precisian if you say you knew exactly where it was from that. I thought you said you would guarantee to know *exactly* where it was.

A. Yes, but you see I had taken a course in optics at the University, and so I was not caught out as easily as that. I invented a special X-ray microscope. It has a wave-length of a thousand millionth of an inch. Of course there are the cosmic rays with still shorter wave-length, but nobody seems to know where they come from, so they would not be very handy. Any how I think I have done fairly well.

Q. Well, I haven't yet heard of an X-ray microscope on the market, but I suppose there will be one soon. Perhaps it would be pedantic to want you to do better. What did you see?

A. It was rather tiresome to get it going, but when I had done so an annoying thing happened. I knew the electron was there or thereabouts, because I had put it there; and it was at rest because otherwise it would have gone off while I was getting the microscope ready. Well, I was adjusting the microscope, and the electron was coming into focus beautifully, when it seemed to give a jump and run away. So that experiment was spoilt and I had to start again.

Q. Did you have better luck next time?

A. No. It was most curious; exactly the same thing happened every time. I think there must be something wrong with the microscope stage. I am going to have a shot to improve it. But as the microscope was certainly right in principle for seeing things to a thousand millionth of an inch, and as the electron stayed there all the time I was focussing it seems to me that I must be right. It is only a matter of overcoming the troublesome details that turn up in all experiments.

Q. It is not a matter of troublesome detail and there is nothing wrong with your microscope stage. Your trouble is not with the electron being there and staying there, it is with the seeing of it. You can't see the electron without light to see it by, and the light disturbs the electron and drives it away. It does not matter how many different experiments you design, you will always get caught out in one way or another. There is no escape from the uncertainty principle.

The old particle theory breaks down not because it is inconceivable to imagine a particle at rest at a definite place, but because every method that can be contrived to *observe* that it is there always introduces a disturbing element. The ordinary experiments with gross matter are made with instruments so designed that they do not perceptibly disturb the object measured. It would be a poor way of measuring the length of a stick to hit it with a steam hammer, and if we want to see what a microbe looks like we do not place it in the focus of a powerful burning glass. The measuring instrument is always chosen lighter or weaker than the object measured; but this can not be done when the object is the lightest thing that there is, an electron. In designing the experiment which is going to observe the electron we have to examine all its details so as to be sure that the method of observation is not going itself to introduce some disturbance. We do not of course expect anything as crude as the burning of the microbe, but we must estimate what effect there may be. We shall find that the effect exactly explains poor A's troubles, but in order to do so must make a digression.

It was known as early as the eighteenth century that all forms of wave exert a pressure on any obstacle that is reflecting them. This can easily be seen with a stretched string. Instead of tying the string to a support at the right-hand end, suppose that it passes through a hole in a frame and is made fast somewhere beyond. The string just fits the hole, and the frame is held firm. When a wave of vibration travels along from the left towards the frame it can not pass the hole but is reflected back, forming "standing waves" with the hole as one of the nodes. Now consider the forces acting on the frame. The string has a bend at the hole (except at the moments when the phase of the wave makes it straight), and the frame has to bear the pressure of this bending. The direction of the force evidently bisects the angle between the string on the two sides of the hole, and so is nearly sideways, but not quite so, for the bisector must always fall to the right a little way behind the plane of the frame. The principal component of the force which is in the plane of the frame is alternately in opposite directions and so averages out; but the longitudinal component is to the right whether the vibrating part of the string is up or down, and so there is a residual force to the right on averaging. If we do not wish the frame to move, it will be necessary to hold it with a small force pushing towards the left, the direction from which the waves are coming. This means that the waves exert a pressure on the frame. More detailed consideration shows this pressure to be proportional not to the amplitude, but to the intensity of the waves.

It is found to be a universal rule that waves of every kind exert a pressure on an obstacle reflecting them. This must therefore be true of light, and the effect was predicted and many of its consequences were worked out long before the phenomenon was observed. The effect is very small indeed for any available source of light—the total force exerted by the sun shining vertically on a square mile of the earth is equal to a weight of about 3 lbs. The first attempt to detect the effect had a rather surprising result. Crookes made a little wind-mill with vanes blackened on one side and polished on the other. The polished sides reflect light, while the black absorb it. In consequence the force on the black side is half as great, for though it is receiving the wave it is not returning it. When exposed to a bright light, the radiometer should therefore go round with the black sides leading. It does go round, but the other way! This was ultimately traced to an effect of the irregular heating of the residual gas in the vessel; though very small it still far outweighs the minute direct effect of the light. It is only in comparatively recent times that this difficulty was overcome, first by Lebedev in Russia, and the actual pressure of light directly observed.

The pressure observed in this way is the gross pressure observed on the whole of a body in bulk. This must be regarded as the result of all the separate pressures on the atoms and electrons. The simplest inference that could be made was that each electron just took its proportional share of the whole. But with the development of the quantum theory it became possible to admit that this might not be so. If, for example, a few of the atoms got a violent kick and the rest none at all, the cohesive forces of the material would enable the few to drag the many with them, and the result in bulk would be just the same as though all the atoms had experienced a feeble force. This was the guiding idea in the very important discovery by A. H. Compton in 1922. From general considerations of the quantum theory as it then was, Compton put forward the idea that when light falls on an electron the process should be regarded as though it were a collision between two particles. Remember that this was before any one dreamed of the wave aspect for matter, and though the particle aspect of light was well known, no one before had ever dared to take it in anything like as literal a form. With the details of the Compton effect we shall be concerned in a later lecture. Here it suffices to describe the outline. When an electron scatters light it is thereby caused to recoil and the speed of the recoil depends only on the wave-length of the light and not at all on its brilliance. For visible light the recoil is feeble, but for x-rays it becomes very easily perceptible, and in fact Compton verified his theory in all its details by using x-rays. The only distinction between the effect of a bright light and of a faint one is that bright light will scatter an electron sooner than the faint, but the speed at which the electron goes will be the same in either case, provided the wave-length of the light is the same.

We may now return to our experiment with the microscope, and we know where the trouble lies. A microscope system consists of two parts, the condenser and the microscope proper. The condenser focusses light on the object, the object scatters it, and the microscope then refocusses into the eye. If we are to see an object, that object must have scattered light, and must itself recoil in consequence. So the mere fact that we see the electron guarantees that it is set in motion; even if it was at rest before we saw it, it can not be so afterwards. The mere carrying out of the experiment spoils the result aimed at. Notice that if we are content with knowing the position rather inaccurately we need not use light of a very short wave-length, and shall not then get much recoil; but if we want the position accurately, we must have a short wave-length and then the recoil will be large. So we see that the uncertainty principle is maintained; high precision in position or velocity can only be attained by the sacrifice of precision in the other.

We have seen how one method of defrauding the uncertainty principle is defeated, but may there not be others that are more successful? Of course, the only way of proving that none can succeed is by the use of the general principles of the quantum theory, but it is profitable to consider a few further examples and show in detail how the attempts fail. We have seen that a microscope is no use, and so we try to make use of a method that does not require one. If, for example, we have a shutter with a very small hole in it, and have a source of electrons on one side, then if we find one on the other, we know it must have come from the hole, and so we can locate its position in that way. We must work out the experimental arrangements a little more carefully. The experiment might be done in this way. We have a pair of parallel plates ABC and FGH. Electrons start at rest from ABC and fall under the influence of a force

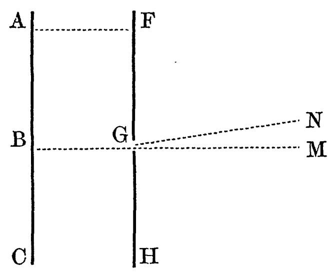

FIG. 1

towards FGH. They will move exactly in directions parallel to AF. The idea behind the experiment is a little more complicated than before because it is necessary to consider the different directions separately. When an electron has emerged from the hole at G, it thereby tells us what its position is as far as concerns the direction GF, but says nothing about its position in the direction GM. So our interest is in the velocity in the direction GF and we do not care what the component in the direction GM may be. Now to the left of G we know the electron's motion to be along BG, that is to say its component in the direction GF is zero. We seem to have conquered the uncertainty principle since we know the speed to be zero and the position is given as accurately as we please by taking the hole at G small enough. But we only know that the electron was on the line BG and not on the line AF because it emerges at G, and in emerging it will be diffracted, say along the line GN, and so will acquire a component of velocity transversely, and one which is uncertain in amount. Once again the mere fact of finding the position has introduced an unwanted velocity. Notice too that if the hole is rather large there is not much diffraction and so very little uncertainty in the velocity, but to counterbalance this advantage there is no very precise knowledge of the position; while, on the other hand, with a very small hole we can fix the position accurately, but pay for it by strong diffraction and so great uncertainty in the speed of the electron after it has emerged.

We will not yet confess defeat. It is true that the electron has been diffracted, but can we not measure through what angle it has turned? If we can do so we can conquer the uncertainty principle, not by avoiding the effect of the observing instrument, but just as successfully by measuring it. We might proceed for example as follows. The electron has altered its course in passing through G. A force of some kind must be necessary to produce this deflection, and this will react on the shutter and tend to push it in the opposite direction. If then we measure this reaction we can assert what path the electron has taken, and this is what we want to know. The simplest way of observing the reaction is to make the shutter free and very light, so that as the electron passes it will be set in motion. We adopt this method. But if the shutter is free, how do we know where the slit is at the moment the electron is passing? We have settled the question of the momentum satisfactorily, but in doing so have lost the position. We must try again, and devise a plan by which to know the position. We therefore send a beam of light through the hole and by watching this beam we can see where the hole is. Surely we now know both position and momentum at the same time. But no, we have forgotten something, for the light itself will behave in the same way as it did in the microscope; it will be diffracted at the hole and will itself start giving impulses to the shutter. There is no way of knowing whether the impulse we observe belongs to the electron or to the light, so that we have regained the measurement of the position, but have paid the price by once more losing the momentum.

It is not by any means easy always to detect the fallacy in experiments like this, but there always is something wrong. Each time we find the defect in our process, we must install some extra piece of apparatus to put it right, and the addition, in the course of overcoming the old difficulty, always introduces a new one. There is no escape from the uncertainty principle.

The uncertainty principle is essentially only concerned with the future; we can install instruments which will tell us as much about the past as we like. Suppose, for example, that we have two shutters, each provided with a very small hole, and a source of electrons to the left of both. The holes are usually blocked up, but for a very short space of time I first open the one in the left shutter, and at a definite time later I do the same for the one on the right. I look for electrons to the right of both shutters. If I see one, I can be quite certain that it went along the line between the holes and took a definite time in doing so; that is to say, I can know its position and speed precisely. What the principle asserts is that this knowledge is no use in predicting what is going to happen later, for it gives no knowledge of how the electron will be diffracted on emerging from the second hole.

This must revolutionize our ideas about one of the most fundamental principles which have always been accepted in science, the principle of causality. We are accustomed to take it for granted that a *full* knowledge of the present would enable us confidently to predict the future. When we are defeated in our attempts at prophecy, we attribute it to ignorance, with the tacit assumption that with more knowledge of the present we could have done better. It never occurred to any one that the present is definitely unknowable; but we have just seen that the mere effort to know it can not help introducing new errors in the determination. It has been suggested that the new outlook will remove the well-known philosophical conflict between the doctrines of free will and determinism, and it has been welcomed by many for that reason. I would personally offer a most strenuous opposition to any such idea. The question is a philosophic one outside the region of thought of physics and I can not see that physical theory provides any new loophole. We can not say exactly what will happen to a single electron, but we can confidently estimate the probabilities. If an experiment is carried out with a thousand electrons, what was a probability for one becomes nearly a certainty; that is to say, we shall expect to have to repeat our experiment a great many times before we get a result departing far from the average. Physical theory confidently predicts that the millions of millions of electrons concerned in matter-in-bulk will behave even more regularly, and that to find a case of noticeable departure from the average we should have to wait for a period of time quite fantastically longer than the estimated age of the universe. How then does the uncertainty principle help to free us from the bonds of determinism?

SERIAL LITERATURE USED BY AMERICAN GEOLOGISTS

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IN 1927, Gross and Gross[1] applied the method of statistical investigation in its simplest form to the problem of evaluation of the periodical literature of a science. They tabulated the references, to other periodicals, in a volume of the *Journal of the American Chemical Society,* and drew certain conclusions concerning the needs of college chemistry libraries. They expressed the hope that workers in other fields might make similar surveys. The interest among librarians and chemists was sufficient to show that the results were worth the labor expended. More recently, other studies have appeared, dealing with mathematics[2] and electrical engineering.[3]

A primary difficulty was encountered in sciences other than chemistry. The *Journal of the American Chemical Society* seems to be unique among scientific periodicals, in that a single volume contains more than 5,000 pages, about 700 articles, and about 5,000 citations to serial literature. It is also sufficiently well balanced in regard to the various branches of chemistry to assure a representative sample of the needs of the American chemist. In other sciences several source journals must be selected.[4]

The present investigation deals with the serial literature of geology, including mineralogy. Six American journals for 1929 were chosen, and the references tabulated. In Table I are listed these *source journals,* together with the total number of pages of the actual articles studied, the total number of citations in each journal, the number of references to books and to personal communications, and the net total, which represents the citations to serial literature. It is these last mentioned references which will be considered in further detail. The totals are probably slightly high, due to unintentional counting in single articles of repetitions of the same citation.

The net total of 3,574 references from six journals of geology (Table I) corresponds to a total of 2,165 from nine journals of mathematics, as reported by Allen,[5] and about 5,000 such references from a single volume of the *Journal of the American Chemical Society.* The contrast between chemistry and the other sciences is evident.

The count of references to books and to personal communications was made because it shows the relative importance of the various sources of information.

If one considers several source journals to be of equal importance, it is evident that there are at least three distinct methods of evaluation: first, an equal

[1] P. L. K. Gross and E. M. Gross, "College Libraries and Chemical Education," SCIENCE, 66: 385, 1927.

[2] Edward S. Allen, "Periodicals for Mathematicians," SCIENCE, 70: 592, 1929.

[3] J. K. McNeely and C. D. Crosno, "Periodicals for Electrical Engineers," SCIENCE, 72: 81, 1930.

[4] An investigation of the serial literature of physics, in progress here, suggests that the *Physical Review* is now so large and varied that it may prove adequate as a single source journal for the science.

[5] *Loc. cit.*