The *g* Factor of the Electron

It is the index of the ratio of the electron's magnetic moment to its spin angular momentum. An interesting number in its own right, its precise measurement has had far-reaching implications

by H. R. Crane

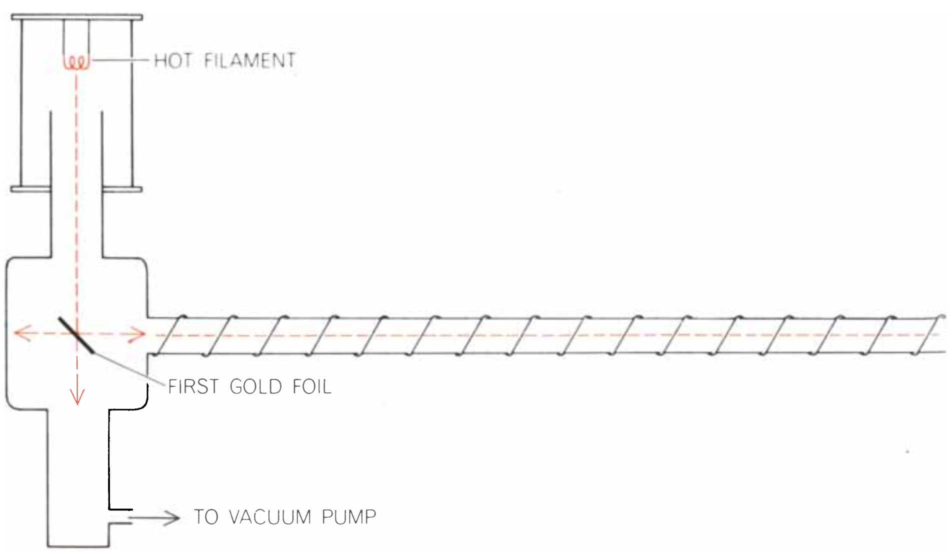
When my colleagues and I at the University of Michigan started our experiments on the *g* factor of the electron in 1950, we had no idea we would still be at it 17 years later. But now the sixth in a succession of Ph.D. students is beginning his work. It has been a leisurely, drawn-out affair. We seem to have been allowed to occupy a little corner of physics pretty much by ourselves—a privilege generally reserved to those who work on projects that are regarded as too hard, too tedious or of too little importance to be worthwhile game for competition. When we think that the results of more than 50 man-years of our labor and half a million dollars could probably be written in the margin of a postage stamp, it is not surprising that most people have been glad to see that kind of work done by someone else. The accidents that got us started, the shifts we had to make in our attack at several points along the road and the way everything worked out not as we had planned but much better than we had planned makes an interesting case history.

I shall include in this account as many of the uncertainties and human errors that beset us as I can recall. I could instead make it sound as if we knew exactly what we wanted to do at all times, but I shall save my talents along these lines for the writing of applications for funds or articles for physics journals. It seems to me that science is more interesting the way it is actually done, and that is the side of our adventures I want to show here.

The *g* factor is a number that might be applied to any spinning object with a magnetic moment parallel to its axis of rotation. (In everyday language the magnetic moment of, say, a bar magnet or a compass needle is simply its strength. The direction of the magnetic moment is along the line connecting the two poles.) The earth almost conforms to this description, and it would conform exactly if its north and south magnetic poles were not slightly out of line with respect to its north and south geographic poles.

If a spinning object with these properties is placed in an external magnetic field (a field other than the one due to the object's own magnetic moment), it will "precess" like a spinning top or a gyroscope, that is, its axis of rotation will slowly move around in a cone. The frequency of the precession will depend on the product of two factors: the strength of the external magnetic field and the ratio of the object's magnetic moment to its angular momentum of rotation. (The angular momentum of an object is its "amount" of rotation. For a wheel it would depend on the speed of rotation, the mass of the wheel and the way the mass is distributed in the wheel.)

Although the external magnetic field is at the disposal of the experimenter and can be made to have any desired strength, the ratio I have just mentioned (magnetic moment to angular momentum) is a property of the spinning object itself. This ratio has a unique value for the electron and is quite the same for every electron in the universe. Other kinds of particles (for example the proton) have their own unique ratios. Since only the ratios for the various particles, and not the separate values of the angular momentum and magnetic moment,



ORIGINAL APPARATUS built by the author and his colleagues at the University of Michigan was designed to study the polarization, or degree of parallel alignment, of the spin axes of the electrons in a high-energy electron beam by means of the double-scattering technique (*see illustration on page 74*)**. To avoid the possibility that X rays and electrical disturbance produced by the electron source would interfere with the counting of the electrons,**

are needed for interpreting many phenomena, the measurement of the ratios to a high accuracy has been the object of intensive research. The *g* factor of a particle is the index of that ratio.

So far I have indicated why the *g* factors of particles are interesting numbers, but I have given no hint as to why the *g* factor of the electron in particular has been the yeast in more than one significant revolution in physics. For that part of the story I must go back more than 50 years and begin with Niels Bohr's original model of the hydrogen atom.

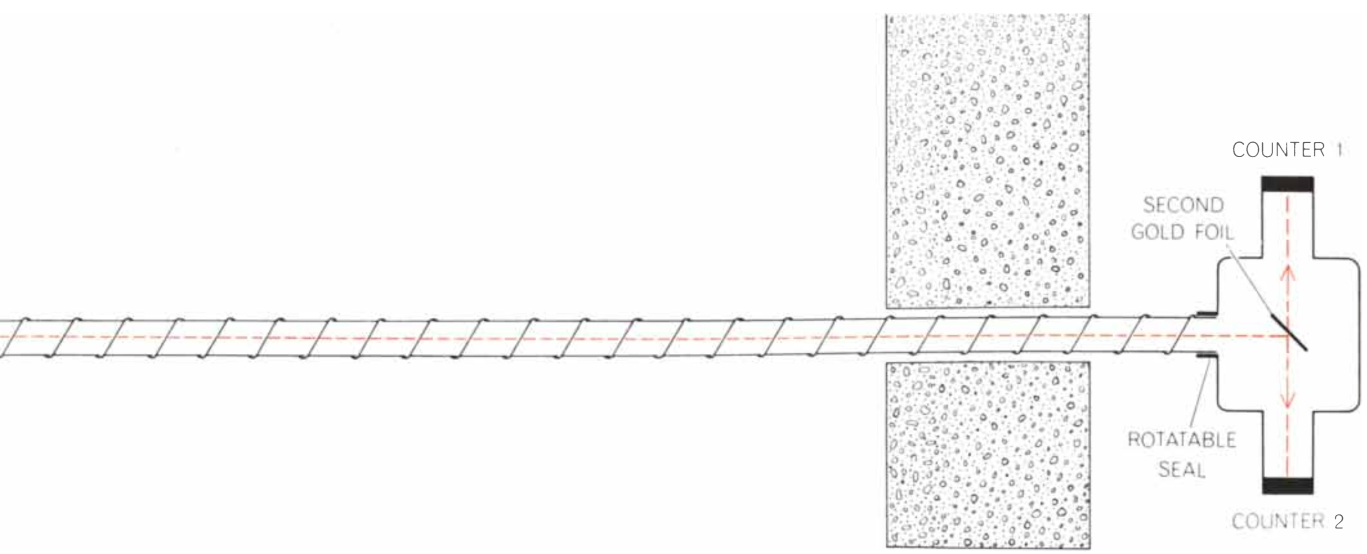
Following the spectacular success of Bohr's model in accounting for the lines in the hydrogen spectrum, it became apparent that the spectra of atoms of higher atomic number had complexities that would require for their explanation more descriptive factors (called quantum numbers) than were contained in the original model. This was strikingly shown by the "anomalous Zeeman effect" in the alkali atoms (such as the atoms of lithium and sodium). The Dutch physicist Pieter Zeeman had shown that when atoms were subjected to a magnetic field while radiating light, the normal lines were split into multiple lines that lay close together but remained sharp and distinct. If the magnetic field had merely shifted the wavelengths of the lines a little one way or the other, that would not have been surprising. After all, the electron circulating in its orbit around the atomic nucleus is equivalent to a current flowing around a loop of wire. Such a loop of current gives rise to a magnetic moment—a north and south pole if you like. Accordingly it would have been reasonable to have expected an external magnetic field to have a modifying effect on the electron orbits. What could not be understood at all on the basis of the Bohr model was that in the presence of a magnetic field single lines were split into two or more distinct lines.

It was this puzzle that led two young Dutch physicists, Samuel A. Goudsmit and George E. Uhlenbeck, to postulate in 1925 that the electron itself had an angular momentum and a magnetic moment. In a recent speech before the American Physical Society, Goudsmit recalled that it was he who had arrived at the conclusion that an additional quantum number, necessary to give the added complexity in the spectra, probably was to be associated with the electron, whereas it was Uhlenbeck who had seen that the new property would have to be of the nature of an intrinsic angular momentum. Thus was born the concept of electron spin.

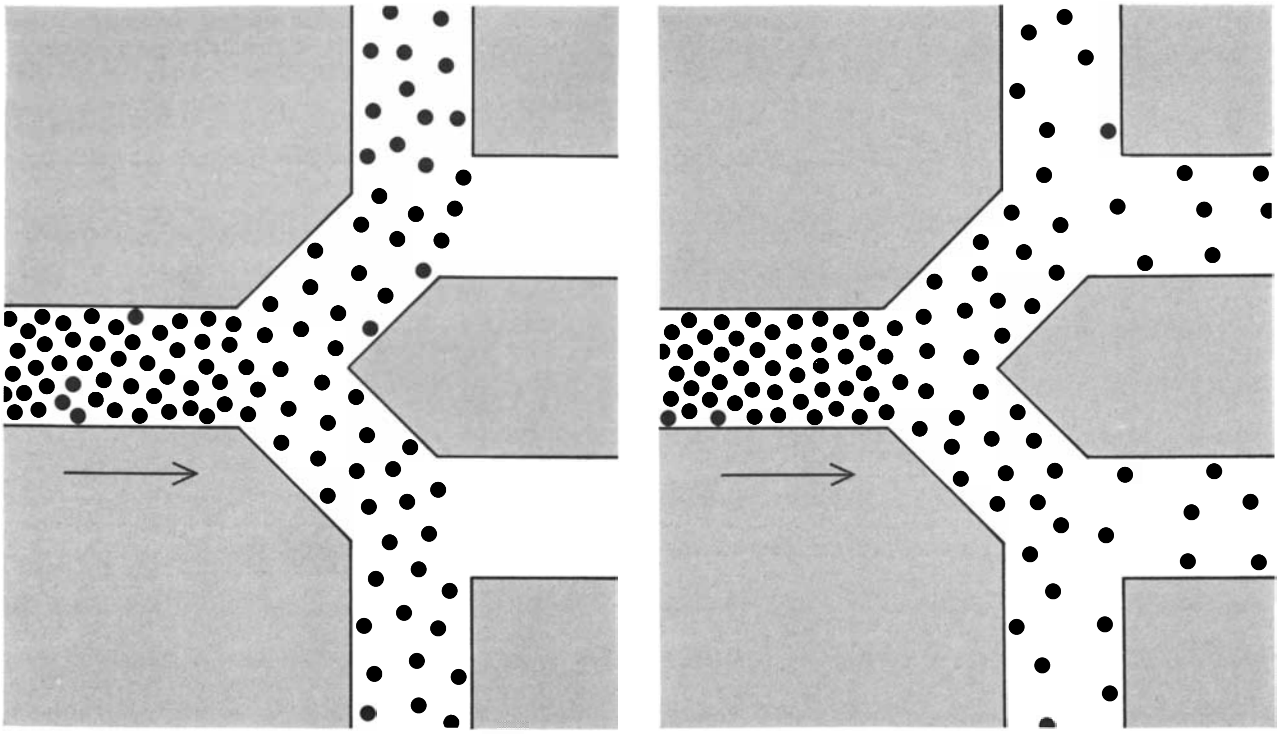
That the electron should have in addition an intrinsic magnetic moment was part and parcel of the idea that it was spinning. Any charged, rotating body would, by the simple concept of a circulating current, be expected to have a magnetic moment. It was a daring hypothesis, by no means immediately accepted. The spin gave the additional quantum number required to explain the splitting of the lines in the spectra. In fitting the values of the electron's angular momentum and magnetic moment to conform to the experiments on the anomalous Zeeman effect, Goudsmit and Uhlenbeck found a strikingly simple relation. The electron's intrinsic angular momentum had to be exactly half the angular momentum of the orbital motion of an electron in its lowest Bohr orbit in the hydrogen atom, or $\hbar/2$, where $\hbar$ is short for Planck's constant (h) divided by 2π. The intrinsic magnetic moment had to be equal to that produced by the orbital circulation of an electron in its lowest orbit in the hydrogen atom. The latter quantity, called the Bohr magneton, is $e\hbar/2mc$, where e and m are the charge and mass of the electron and c is the velocity of light [*see illustration on page 79*].

Thus at the time of the discovery of electron spin the *g* factor of the electron could be expressed as the number of "natural units" of magnetic moment ($e\hbar/2mc$) divided by the number of "natural units" of angular momentum ($\hbar$). When defined in this way, the *g* factor for the orbital motion of the electron in its lowest energy state in hydrogen is 1, whereas the *g* factor of the free electron is 2. (The *g* factor as a term designating a ratio of magnetic moment to angular momentum in these special units had been introduced a few years earlier for the case of the atom by the German physicist Alfred Landé.)

There being no reasons to the contrary, the relations given above were



the site of the second scattering was located in the next room at a distance of about 30 feet. When the first tests were made, however, too few electrons arrived at the second scatterer, because the beam tended to fan out in the 30-foot pipe. A layer of current-carrying wire was therefore added to the outside of the pipe in order to establish a magnetic field in the pipe parallel to its axis; this focuses the electrons and also causes their axes of spin to precess slowly. When the use of a magnetic field was first considered, it became apparent that by measuring the amount by which the spin axes precessed it might be possible to determine the electron's *g* factor.



DOUBLE-SCATTERING TECHNIQUE is at the root of the *g*-factor experiments. In order to polarize a beam of electrons whose axes of spin point randomly in all directions, all one needs is a sorting mechanism, so that one can keep the ones that are pointing in a particular direction and discard the rest. To get an observable effect, however, one must do the sorting twice. At the first sorter equal numbers will be deflected to the right and to the left. Actually the direction in which a particular electron is deflected depends in part on whether its north pole is pointing up or down. This effect is not yet observable, however, since the equal division of the beam could be due to pure chance. It takes a repetition of the scattering process to bring out the result of the sorting in an observable way. A 100 percent inequality after the second sorting is shown at left for clarity; in actuality the inequality of the beams is at best only about 6 percent. If the two sortings were due only to chance, the beams after the second sorting would still be equal (*right*).

taken to be exact, and they stood unquestioned for about 20 years. In physics there are good reasons for assuming that simple relations are exact until it is proved otherwise. There are many of them that do hold, and this is one of the reasons why some people find beauty in the subject. In the case of the *g* factor of the electron, a strong reinforcement for the belief in the exactness of the value 2 came in the late 1920's from the new formulation of quantum mechanics by P. A. M. Dirac. In his formulation Dirac did not "put in" a *g* factor of 2 as a requirement of a model of the electron. He applied the basic laws of physics (including relativity) according to a simple set of conditions, and the *g* factor of exactly 2 "came out." After World War II, however, this situation began to change.

In the first few years after the war some striking experimental and theoretical developments occurred that led to what is now called the new quantum electrodynamics. A central part of this work involved taking into account the interaction of the electron with the empty space around it, or with what physicists call the "vacuum." If it seems strange to say that empty space could have an effect on the electron, it is because one tends to think of empty space in the ordinary sense of its being devoid of gross objects such as gas molecules. In the context of the subatomic world, however, empty space is by no means devoid of properties. There can be the creation and annihilation of electron pairs and other kinds of particle pairs, local fluctuations of electric and magnetic fields, and of course the propagation of radiant energy. When in the new quantum electrodynamics the effect of empty space on the electron was properly accounted for, the result was an increase in the *g* factor to slightly more than 2. In itself the change in the *g* factor does not sound very startling. But the whole development was a profound one, as attested by the fact that five of the people most closely involved were awarded Nobel prizes: Willis Lamb and Polykarp Kusch in 1955 (for experimental work), and Julian Schwinger, Richard Feynman and Sin-Itiro Tomonaga in 1965 (for theoretical work).

It would be impossible, without devoting the entire article to it, to trace this development in any detail. There are, however, some comments I should like to make. The term "new quantum electrodynamics" does not imply that the existing theory was junked in favor of the new theory. The new theory was rather an extension of the existing theory, which had stopped short of including the interaction of the particles with the vacuum. Theorists had been trying to include it, but the formulas came out containing infinite terms, which could not be got rid of by the accepted theoretical methods, and so the matter had hung in the limbo of speculation. But when experimental results suddenly began appearing that did not agree with the existing theory and that gave actual numbers against which attempted solutions could be tested, progress became quite rapid. A way that had been proposed earlier for circumventing the infinities proved itself by giving answers that were consistent with the experiments. The methods were still not unquestioned; for example, as Dirac later remarked in *Scientific American* (May, 1963), he could not help looking on the

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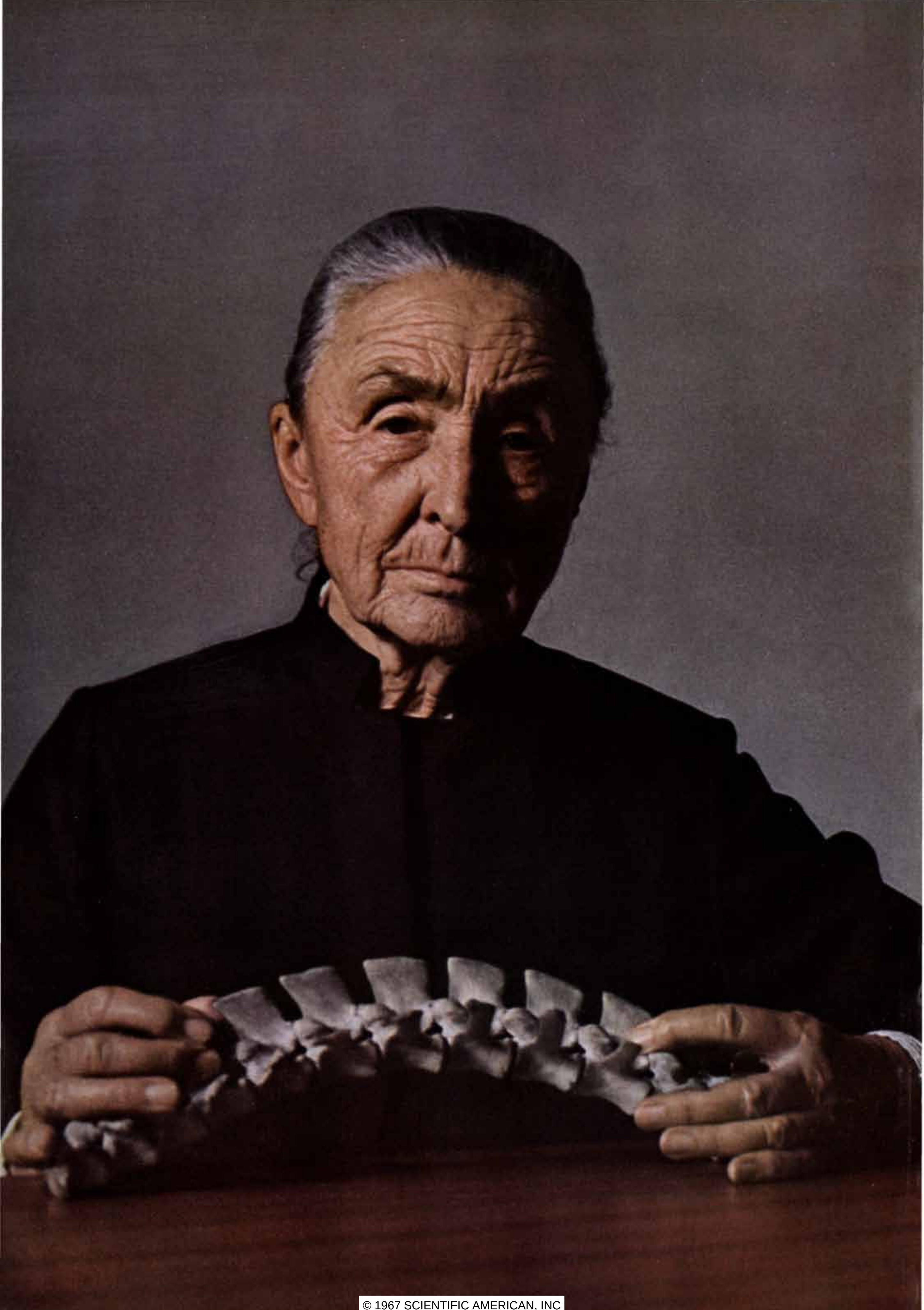


Halsman on Halsman on Polaroid Land Film

Polaroid Corporation asked Philippe Halsman to photograph any subject he wished, black and white or color, and tell about his experience.

"I first photographed Georgia O'Keeffe 18 years ago for Life magazine.

We were doing a story on the American Southwest and of course she had become a symbol of the region. So I photographed her as a symbol, against a brown adobe wall with the bleached skull of a steer in the background.

But this time, I wanted to photograph Georgia O'Keeffe. Not as symbol, not as painter, but as a person of great wisdom and beauty.

To do that, to show people as they are, I believe one has to reduce form to its simplest. Almost to the point of abstraction.

That's easier said than done, of course. It took a two-hour session to get the simplicity I wanted. Even using Polaroid Land film.

But Polaroid film did much more than save time. It also helped me make a very difficult decision: black and white or color.

You see, when you first look at Georgia O'Keeffe, you want to photograph her in black and white. Color often gets in the way with a powerful personality like hers.

On the other hand, if you have the right kind of color, subtle rather than blatant, you can do strong subjects. The Dutch painters of the Rembrandt era did it all the time.

To me, Polaroid film has that kind of color. As you can see.

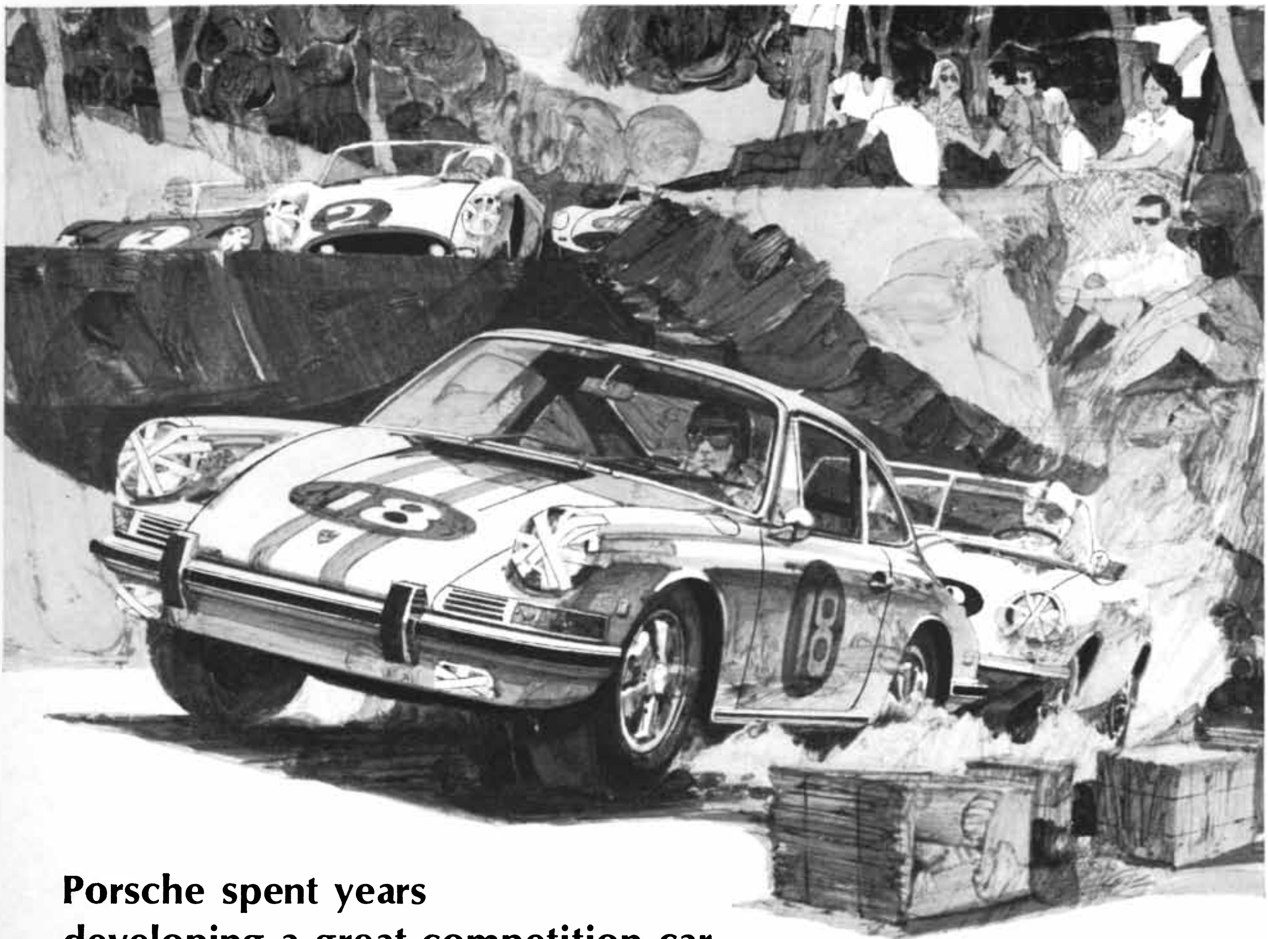
And, of course, it didn't take long to know that Georgia O'Keeffe and Polacolor film were made for each other.

Best of all, I could see the finished photograph. Otherwise the session might have continued well beyond two hours.

You see, there are some things one can't be sure of until after the film is processed. Like tiny changes in expression or mood.

But with Polaroid film, I was sure in a minute.

Which leads me to the conclusion that Polaroid film may be the salvation of photographers who don't know when to stop."



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solution of the problem of the infinities as a "fluke." I suppose he meant that a method that evidently worked in a particular application should still be held questionable as to its generality.

This, then, is where things stood in 1950, when we embarked on our g-factor measurements. There had been a shake-up. The new theory gave a g factor of the electron about .1 percent larger than 2, and there were experimental results that were in agreement, within modest limits of accuracy. Because the new theory was based on unconventional methods, its acceptance rested on a pragmatic basis. A measurement of the g factor to a much greater precision would be more than just a routine verification; it would be one of the critical tests of the new theory. If at that point we had taken up our experiments in answer to this clarion call, the story would read as a story is supposed to read. That is not the way we got into it at all. We backed into it. Here is what really happened.

	ORBITAL ELECTRON	FREE ELECTRON
ANGULAR MOMENTUM	$\hbar$	$1/2\,\hbar$
MAGNETIC MOMENT	$\frac{e\hbar}{2mc}$	$\frac{e\hbar}{2mc}$
$\frac{\text{MAGNETIC MOMENT}}{\text{ANGULAR MOMENTUM}}$	$\frac{e}{2mc}$	$\frac{e}{mc}$
g FACTOR	1	2

***g* FACTOR OF THE ELECTRON was defined at the time of the discovery of electron spin (1925) as the number of "natural units" of magnetic moment ($e\hbar/2mc$) divided by the number of "natural units" of angular momentum ($\hbar$). When defined in this way, the *g* factor for the orbital motion of the electron in its lowest energy state in hydrogen is 1, whereas the *g* factor of the free electron is 2. These relations were taken to be exact for about 20 years.**

We had begun in 1946 a project of designing and building one of the largest electron accelerators of that time, which we called the "racetrack" synchrotron. The project presented a series of problems that had to be worked out as we went along. Meanwhile graduate students were working on the project who did not have forever to wait for the synchrotron to operate in order to do their thesis problems and get their Ph.D.'s. One of these students was William H. Louisell, who has since joined the faculty of the University of Southern California. Robert W. Pidd (now at Gulf General Atomic Inc.), one of several professors associated with the synchrotron project, was chairman of Louisell's doctoral committee, and I was a member. We decided to try to define a thesis problem that would use not the entire synchrotron but just the parts that were finished at that time. One part that was finished was the "electron gun," a high-voltage vacuum tube that could produce an intense beam of electrons at energies of up to 600,000 electron volts. Its purpose was to inject the electrons into the synchrotron, where they were to be further accelerated up to 300 million electron volts. Before becoming involved in building the synchrotron, both Pidd and I had had an interest in polarization effects in electron beams, as studied through double-scattering experiments. We thought that the electron gun of the synchrotron would be an ideal tool for such experiments. Accordingly we put our interests and our available tools together and came up with a thesis problem for Louisell.

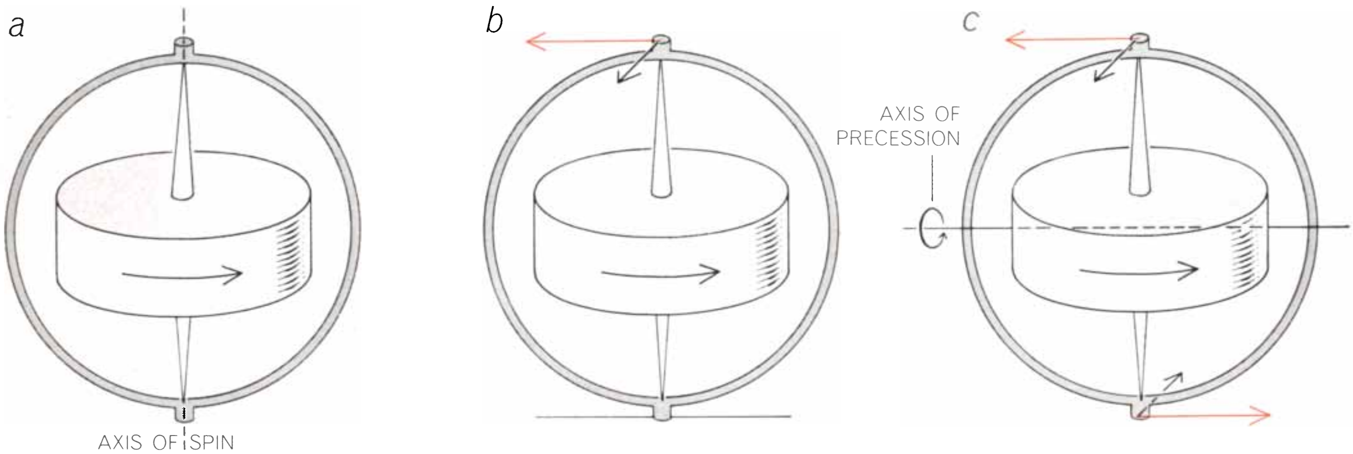
At this point I should like to elaborate a bit on double scattering, a technique that in addition to being basic to our own experiments has a broad application in physics. Electrons that are emitted from a hot filament have their axes of spin pointing randomly in all directions. If some of these electrons are accelerated and formed into a beam, the beam is said to be unpolarized. In order to polarize the beam it is not necessary to turn the electrons so that their north poles all point in the same direction; in fact, we know no way of doing that. If there are plenty of electrons to spare, all one needs is a sorting mechanism, so that one can keep the ones that are pointing in a particular direction and get rid of the rest. We do know how to make a sorter. Curiously enough, in order to have an observable effect it is necessary to do the sorting twice. Hence the term double scattering.

I shall use a simple analogy to show why two sorters are necessary. Suppose we make 1,000 small cards, of which 500 say "Always take the right turn" and 500 say "Always take the left turn." We shuffle the cards and give one to each of 1,000 motorcycle riders, who have agreed to cooperate. Each reads his card and puts it in his pocket, and they all start down a road. After the first fork in the road, does an outside observer see any effect traceable to the cards? No. He sees only that 500 motorcycles have taken each road at the first fork, which could be due to pure chance. The observer must wait until the second fork to see the effect. The effect is then dramatic. Those traveling on the road that went to the right at the first fork will now all take the right-hand road at the second fork. Similarly, those on the other road will all turn to the left. In the language of electron scattering, the first fork is the polarizer and the second the analyzer. Not until after the motorcycles have passed the analyzer does the observer have visible evidence that sorting has been accomplished [*see illustration on page 74*].

An electron doesn't carry a card, but it may have its north pole up or it may have it down, and that makes it belong to one class or the other. If one shoots a beam of electrons through a thin piece of material, say a gold foil, many electrons will be deflected to the right and to the left. The two classes (north pole up and north pole down) will have been sorted as were the motorcycles at the first fork of the road, but the fact will not yet be observable. It will take a repetition of the scattering process, performed on either the right or the left beam, to bring out the result of the sorting in an observable way. When the electrons pass through the second gold foil and are scattered—this time unequally between right and left—under the best conditions the inequality is only about 6 percent. The sorting is by no means as perfect as it was in the example of the motorcyclists, but it is good enough to make an experiment possible.

The theory of the double scattering of electrons was put forward by N. F. Mott in 1929, and the process goes by his name. Surprisingly, about six years passed before anyone succeeded in producing the effect experimentally, and even in 1950, when Louisell undertook to study the effect, little had been found out about it in a quantitative way. That is why the double-scattering of electrons looked like a good thesis problem.

The synchrotron injector that was to be used for the electron source was in



MODEL OF A SPINNING ELECTRON, consisting of a piece of wine-bottle cork with a toothpick stuck through it and some negative electric charge on the cylindrical surface, turns out to have a *g* factor of 2. The amount of charge and the mass of the cork must be in the same ratio as the charge and mass of an electron. When the model is spinning (*a*), the ratio of its magnetic moment to angular momentum is e/mc, which is a *g* factor of 2, regardless of the speed of spinning, and regardless of the size or the length-to-diameter ratio of the cork. Such a model behaves as a gyroscope. If one gently pushes the top of the toothpick sideways (*b*), it will refuse to go that way but will go in a direction at right angles to the direction of the force. If the model is spinning in open space and opposite forces are applied to the ends of the toothpick from the left and the right (*c*), one end will come forward and the other end will go backward. It is this turning of the spin axis that is termed precession. Now, if the model is placed in a magnetic field (*d*), the

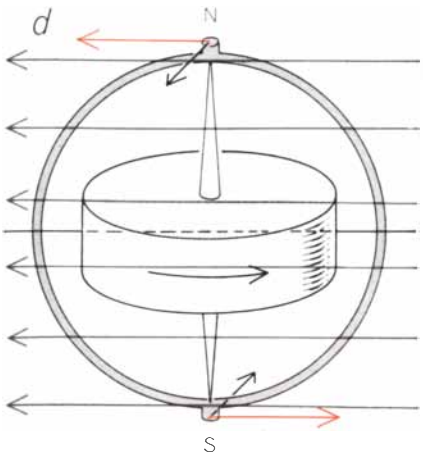
the main synchrotron room. When the injector was running, it produced a high level of X rays and electrical disturbance, and we knew this would interfere with the detecting and counting of the electrons after the second scattering process. We therefore elected to locate the site of the second scattering some distance away, in fact in the next room at a distance of about 30 feet. We provided an evacuated pipe for the electrons to travel through [*see illustration on pages 72 and 73*]. We were perhaps unduly attracted to this scheme because the wall separating the rooms was made of concrete three feet thick and it already had a porthole in the right place. The arrangement seemed ideal. When the vacuum pipe was in place and the first tests were made, however, we found that far too few electrons arrived at the second foil, simply because the electron beam tended to fan out in the 30 feet between the targets.

A standard method of focusing the electrons from one end of a pipe to the other is to establish a magnetic field in the pipe parallel to its axis. All that is required is a layer of wire on the outside of the pipe with current in it. I suggested this was a way of conserving our electrons, but immediately caught myself and asked: "What would the magnetic field do to the polarization?" (The electrons traveling down the pipe were presumably polarized as a result of the sorting by the first gold foil.) It did not take us long to decide that if the electrons behaved like spinning magnets, the effect of the magnetic field on them would be to cause their axes of spin to precess slowly, just as the axis of a toy top precesses while it is spinning on the pavement. The orientation of the axis of spin would be altered before the electrons arrived at the second foil. It was clear that if such a precession did occur, and if we could measure the change in the direction of the spin axis, we would have a way of determining the value of the magnetic moment—a much more interesting pursuit than the one we had originally started with. But would electrons really behave that way? Mechanical models are powerful tools for thinking (some of us—I for one—would be lost without them); however, one has to be exceedingly cautious in using them in the realm of the very small, where quantum effects become overriding, to make sure at every turn that one is not asking the model to perform in ways that are in conflict with quantum principles. It was at this point that our theorist colleagues began flashing yellow caution lights at us—with good reason.

A mechanical model of the spinning electron—even though suspect—has some intriguing properties, which I should like to describe here. A model of the spinning electron made in about the simplest possible way turns out to have the *g* factor given by the Dirac equation, namely 2. Take any solid right circular cylinder, such as a wine-bottle cork, and stick a toothpick through its ends [*see illustration above*]. Then put some negative electric charge on the cylinder's surface but none on the ends. The amount of charge and the mass of the cork must be in the same ratio as the charge and mass of an electron. Now, when the cork is spun on the toothpick as an axle, the charge, moving around in a circle, acts as a loop of current and gives the model a magnetic moment. In addition the rotating cork has angular momentum. The ratio of the magnetic moment to the angular momentum of this model is e/mc, which is a *g* factor of 2, regardless of the speed of spinning, and regardless of the size or the length-to-diameter ratio of the cork! (It might appear that a still simpler model would be a cork ball, but that would not have a *g* factor of 2.)

The model behaves as a gyroscope. If one sets it spinning vertically and gently pushes the top of the toothpick sideways, it will refuse to go that way but will go in a direction at right angles to the direction of the force. If the model is spinning in open space and opposite forces are applied to the ends of the toothpick from the left and the right, one end of the toothpick will come forward and the other end will go backward; the model will keep turning in this way, making several complete revolutions. It is this turning of the axis (in contrast to the rotation of the cork) that is termed precession. The tips of the toothpick never do move in the directions in which they are being pushed.

Now, if the spinning-magnet model is placed in a magnetic field, the north pole will be pulled one way along the field lines and the south pole the other way. The axis of spin will turn in the manner of the gyroscope, and the num-



north pole will be pulled one way along the field lines and the south pole the other way. The axis of spin will turn in the manner of the gyroscope, and the number of complete turns it will make per second will be proportional to the *g* factor and the strength of the applied field. In the original apparatus there were about five full turns in 30 feet.

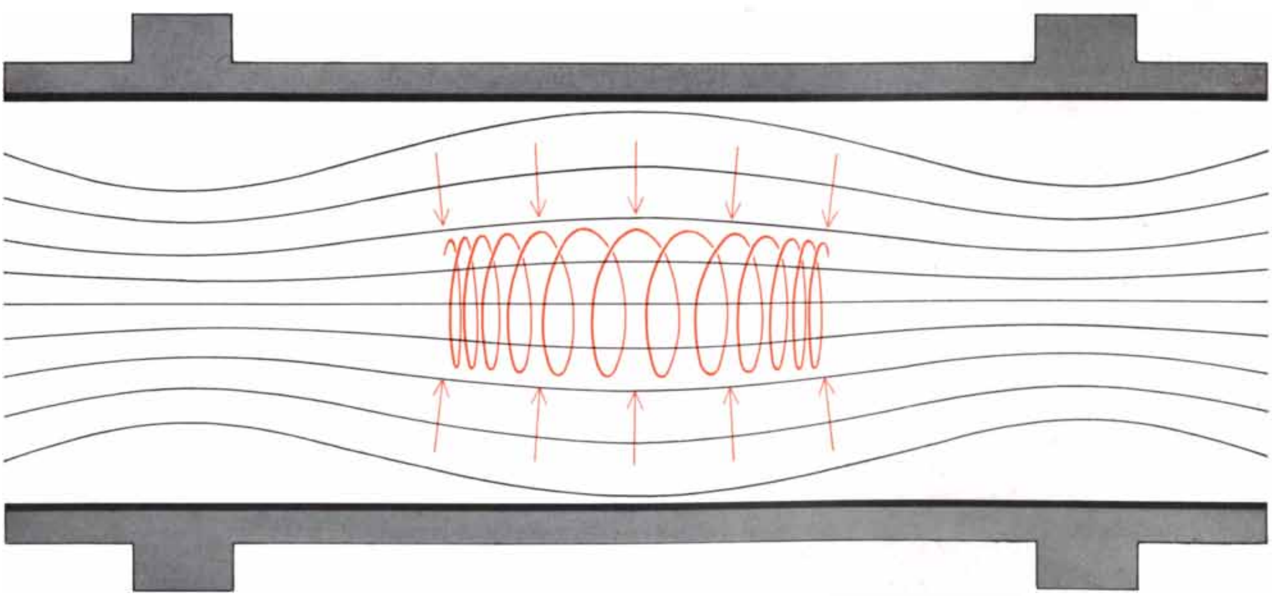
ber of complete turns it will make per second will be proportional to the *g* factor and to the strength of the applied magnetic field. In Louisell's apparatus there would be about five full turns of the spin axis while the electrons were going the 30 feet down the pipe. He would have only to measure the exact amount of turning in order to solve for the *g* factor—if the experiment would work at all! Many physicists held strong reservations about it.

The doubts that our experiment would work were prompted by some arguments that had been put forward by Bohr in a lecture in the 1920's. At the time only two experiments by which one might attempt to observe the magnetic moment of the free electron had been imagined. One was to detect the magnetic field of the electron directly, by means of a sensitive magnetometer; the other was to sort electrons as to the orientations of their magnetic moments by sending a beam of them through a nonuniform magnetic field. Bohr had demolished both schemes by subjecting them to the test of the Heisenberg uncertainty principle, which states that there is a natural limitation on the precision with which the position and the linear momentum of a particle can be known simultaneously. Both schemes, if they were to work, would require measuring these quantities to greater than the possible precision.

Bohr's calculations were back-of-the-envelope type: simple and unequivocal. The mistake was made not by Bohr in his proofs but in the sweeping generalization that was subsequently made of them by others. It was, in effect, that no experiment to measure the magnetic moment of the free electron directly could succeed, by reason of the uncertainty principle. This got into the textbooks and became, one might say, gospel. When, more than two decades later, we proposed an experiment to measure the precession of the free electron, an experiment that in fact did not require the simultaneous knowledge of the position and linear momentum of the particle beyond the limits prescribed by the uncertainty principle, it was this old belief that no experiment whatever could work that we encountered head on.

I can recount an incident that is amusing in retrospect to show the firmness of the conviction that experiments on the magnetic moment were not possible. At the meeting of the American Physical Society in Washington in April, 1953, Louisell presented his first successful measurement, and two theorists in our department, Kenneth Case and Harold Mendlowitz, presented proof that the concept of the experiment was in harmony with quantum mechanics. Yet the evidence was not persuasive to several physicists in the audience, who rose to cite the Bohr proofs to us. The person who voiced the strongest objection said later that when he was halfway home on the airplane he satisfied himself that there was no conflict between our experiment and what Bohr had shown!

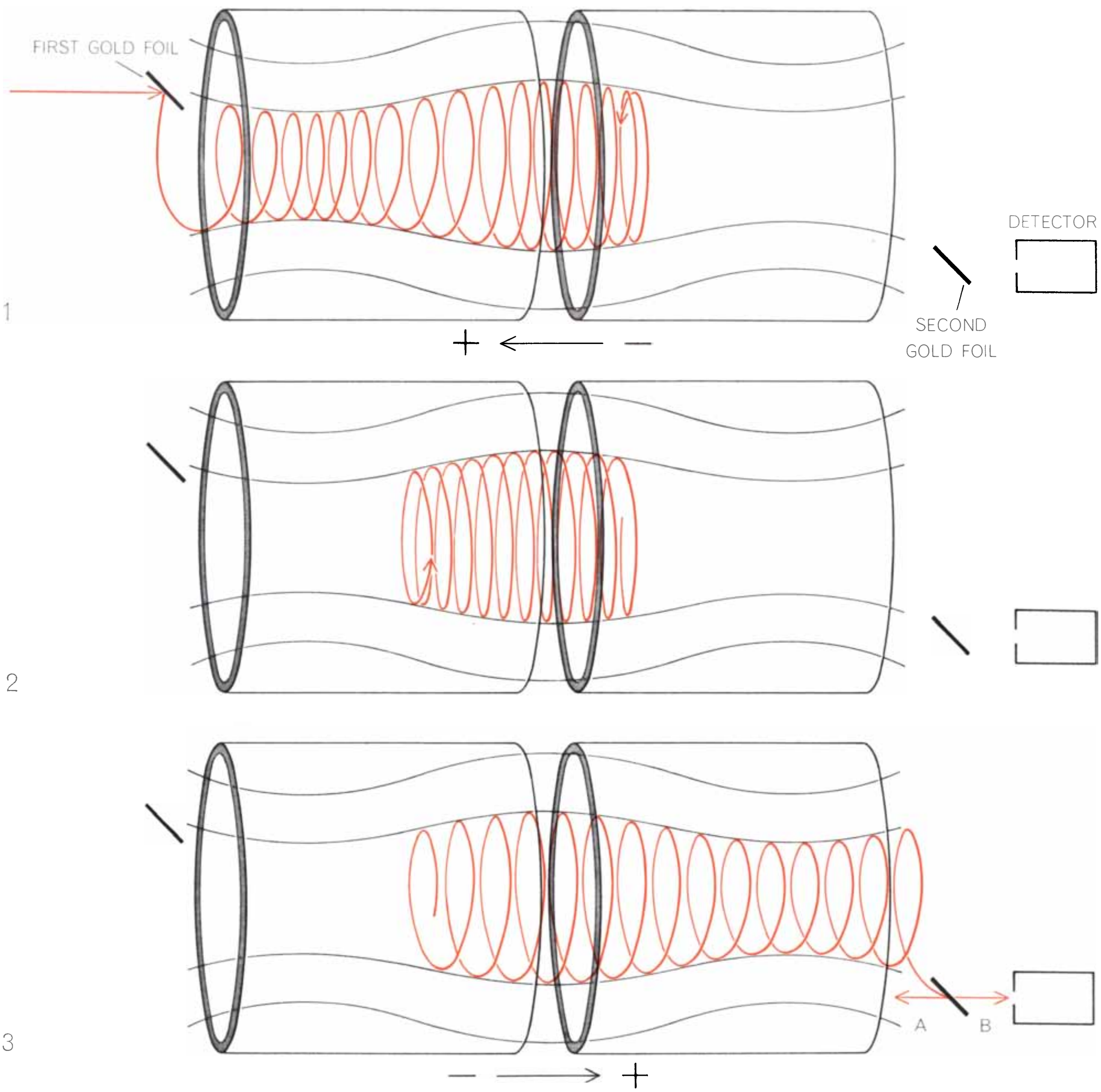
By the time Louisell had his experiment under way we realized that the number of revolutions of the precession that would occur in his 30-foot pipe would be far too few. There would be only five. If we were to get many more revolutions by extending the pipe, however, it would reach to the next town. I was able to devise a change in the arrangement that would overcome this



MAGNETIC BOTTLE consists of an empty space in which there is a magnetic field that is a little stronger at each end than in the middle, so that the lines of force (*black*) pinch together to form necks. A particle trapped in such a bottle moves in a helical path (*color*) around the axis of symmetry of the field. When the particle approaches one of the necks, it is always turned back toward the center of the bottle, because the force acting on the particle, being at right angles to the field lines, has a component toward the center.

limitation, not for Louisell's experiment—he could hardly be asked to start over again—but for the next experiment and the next graduate student. The new scheme makes use of what is commonly called a magnetic bottle [*see illustration on preceding page*]. The correct analogy here would actually be a bottle with a neck at each end, since such a device consists of an empty space in which there is a magnetic field that is a little stronger at each end than in the middle, so that the lines of force pinch together to form two necks.

A particle trapped in such a bottle moves in nearly circular motion around the axis of symmetry of the field. The motion is not exactly circular; it is helical, with closely spaced turns. The particle progresses slowly back and forth trying to get out first one neck of the



MAGNETIC BOTTLE IS USED to obtain many more revolutions of the precession of the spin axis of the electron in the g-factor experiment without extending the length of the apparatus unreasonably. In step *1* electrons scattered from the first gold foil barely make it through the neck into the bottle. When they pass from the positively charged metal can (+) to the negatively charged one (—), they lose some of their axial velocity. Therefore they fail to make it out the right end of the bottle and are turned back. In step *2* the electrons have moved back to the left end of the bottle, but they have not regained their lost axial velocity, because the charges on the cans had been removed before the electrons started their return trip. They therefore do not have enough axial velocity to escape from the left end of the bottle. They are temporarily trapped in the bottle. In step *3* the charges are put back on the cans again, but with the opposite polarity. As a result the electrons now gain some axial velocity going from left to right. This enables them to escape through the right neck of the bottle and hit the second gold foil. Some are scattered in direction *A* and some in direction *B*. The relative numbers in these two directions reveal their polarization. Only the ones going in direction *B* are counted.

bottle and then the other. It is always turned back toward the center of the bottle, however, because the force, being at right angles to the field lines, has a component toward the center. In the new scheme the electron gun and first scatterer are placed so that the electrons that have been scattered at 90 degrees by the scatterer are traveling in just the right direction to begin the helical path.

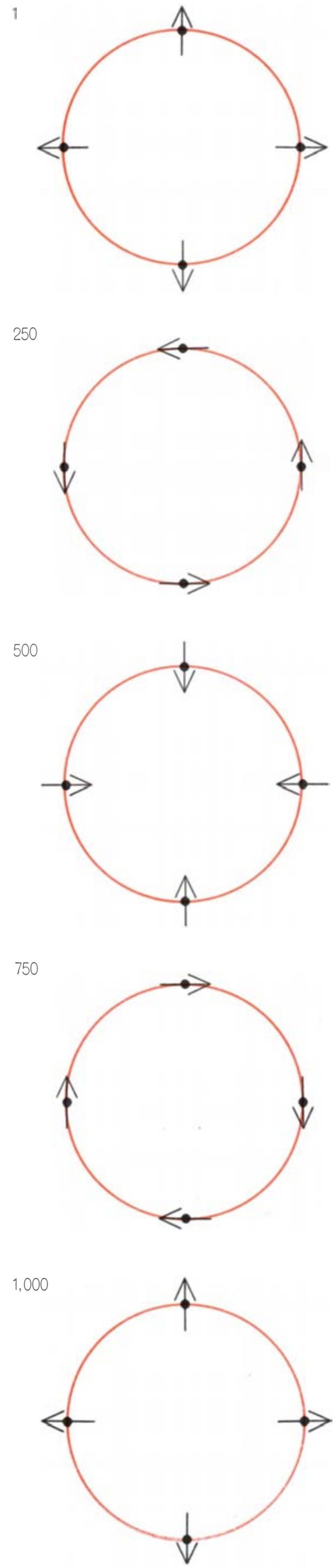
Catching some electrons in the trap, letting them out and getting them through the analyzer to the final counter is not simple. The complete sequence of events takes place within 100 microseconds (millionths of a second) or so [*see illustration on opposite page*]. First the electron gun turns on for .1 microsecond, letting a burst of electrons strike the first scatterer, which consists of a piece of gold foil. About 10 billion electrons hit the foil. Only about 100,000 are scattered by the gold nuclei in just the right direction to follow the helical path required for entrance into the bottle.

At this point we have the problem of catching these 100,000 electrons so that they will stay in the bottle. It is a problem because those that have enough axial velocity to be able to get through the neck into the bottle will for the same reason be able to pass through the neck again at one end or the other and escape. Some of the axial velocity has to be removed after they get in. Accordingly while the swarm of electrons is making its first pass through the center of the bottle, we put the brakes on by applying a retarding electric field in the direction of the axis of the bottle. With their axial velocity reduced the electrons do not escape at the right end; they turn around and come back toward the left end. But at about the time they turn around the electric field is removed, so that in moving from right to left they do not regain their lost axial velocity. They therefore cannot escape at the left end and are trapped. From that time on they move in a helical path with very closely spaced turns, progressing slowly back and forth between the ends of the bottle.

After imprisonment for a period of our choosing, we again apply the electric field, but this time in such a direction as to speed them up toward the right. They easily clear the right neck of the bottle and after a few more turns strike the gold foil of the second scatterer. At the second scatterer the number of electrons that get scattered in the desired direction is again a very small fraction of the number striking the foil. If all the 100,000 trapped electrons hit the second scatterer, only one or fewer than one, on the average, is scattered at the correct angle to strike the final counter. This may sound highly inefficient, and so it is, but the entire cycle I have just described is repeated about 1,000 times per second. The counting rate is therefore on the order of a few hundred per second. The whole process of course works automatically by electronic timing circuits. I might add that an electron trapped in this system for 100 microseconds precesses as many revolutions as it would in traveling through a straight pipe six miles long!

The new scheme gives us another advantage, separate and distinct from the increased number of revolutions. This advantage lies in the fact that the spin axis precesses through almost exactly a complete turn while the electron makes one lap around its helical path. If the g factor were exactly 2, the two motions would keep in step exactly. We therefore need only to measure the small amount by which the two rotation rates differ in order to find out how much the g factor differs from 2. In this way we get far more precision than we would if we were to measure the spin precession rate by itself, because the difference in the two rates is only about a thousandth of the rate of the precession.

To see how the two rotations combine, consider the situation for an electron at different times after it starts its captivity in the bottle [*see illustration at right*]. Owing to the sorting by the first scatterer the electrons that start the helical motion have their spin axes pointing radially away from the common axis of the helix and the bottle. Because the two rotations of each electron are so nearly equal, the spin-direction arrow during the first orbital revolution appears to turn as if it were painted on the rim of a wheel. A few hundred revolutions later, however, the rotation of the spin axis has gained perceptibly on the orbital rotation, and it no longer points in

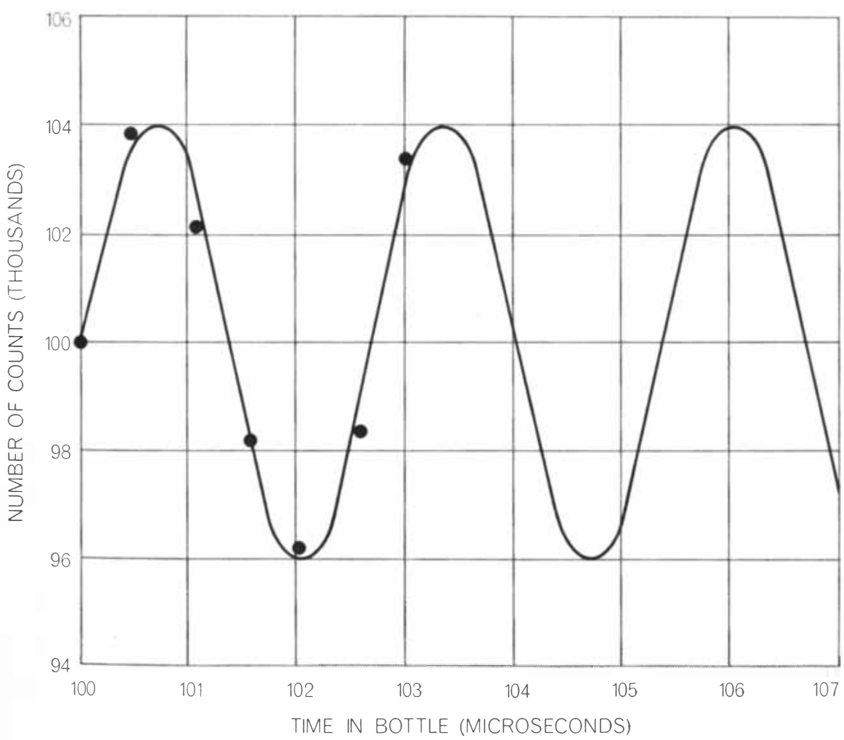


ANOTHER ADVANTAGE of the magnetic-bottle version of the *g*-factor experiment lies in the fact that the spin axis of the electron (*small arrows*) precesses through almost exactly a complete turn while the electron makes one lap around its helical path (*large circles*). If the *g* factor were exactly 2, the two motions would keep in step exactly. By measuring the small amount by which the two rotation rates differ, therefore, one can find out by how much the *g* factor is greater than 2. The spin axis returns to its original orientation after completing about 1,000 laps (*bottom*). The view is along the common axis of the helix and the bottle.

the radial direction. The spin direction continues to gain until after about 1,000 revolutions it has gained a full revolution on the orbital motion and is back in its original orientation. Obviously if the electron were let out of the trap after approximately 1,000, 2,000 or 3,000 revolutions, it would have the same spin orientation as it started with, and if it were let out after 500, 1,500 or 2,500 revolutions, it would have the opposite spin orientation.

The electrons, after they are let out of the trap, strike the second scatterer (also a gold foil). The chance of the electrons' being deflected along a given path depends on the spin orientation. Actually only the ones that go along one direction are counted. The count is alternately maximum and minimum when the number of revolutions has been 0, 500, 1,000, 1,500 and so on. (I have used round numbers here for illustration; the maxima and minima are not exactly multiples of 1,000, and determination of the exact number is the purpose of the whole experiment.) In actual practice we look for the maxima and minima in terms of the length of time the electron has spent in the bottle, rather than in terms of the number of orbital revolutions it has made. Either way would give the result we are after, but doing it in terms of the time is more convenient.

I have mentioned that the time of captivity in the trap can be set to any value we choose. Suppose we set the timing circuits so that each injected batch of electrons is held in the trap for 100 microseconds. The whole process therefore repeats 1,000 times per second. Say we run for 10 minutes (some 600,000 batches) and record the total number of counts of the detector (about 100,000). Next we move the trapping time up to 100.5 microseconds and make another 10-minute run; then we move up to 101 microseconds, and so on. The number of counts for each 10-minute measurement interval is now plotted against the length of time the batch of electrons was held in the trap [*see illustration below*]. To get from one maximum to the next we have to increase the time in the trap by about 2.6 microseconds, which means about 1,000 additional revolutions of the electron's helical motion. To get the time separation between the maxima in the curve with the greatest possible accuracy, which is the crux of the experiment, we take data over a time range that includes several hundred maxima and minima, and determine the average value.



SINE CURVE relates the number of counts recorded in the detector in a 10-minute interval to the length of time each batch of electrons was trapped in the bottle before being let out. The electrons make approximately 1,000 revolutions in their helical motion from one peak to the next. In practice, of course, the data points do not fall perfectly on the sine curve, because in a finite number of counts there is an element of chance. The crux of the experiment is to determine the average time separation between the peaks in the curve with the greatest possible accuracy, taking data over a time range that includes hundreds of peaks.

Such measurements do not yield the g factor of the electron directly. Instead they give a value for what is called the g-factor anomaly—which is equal to half the amount by which the actual g factor exceeds 2. This anomaly is inversely proportional to the time between the maxima in the curve that represents the experimental results. Since the anomaly is nearly 1,000 times smaller than the g factor, however, this means that our measurement has, you might say, a head start on accuracy by a factor of nearly 1,000. If we measure the anomaly to a part in 100,000, we will get the g factor to about a part in 100 million.

The first experiment along the lines I have just described was done by Arthur A. Schupp, the graduate student who followed Louisell. When he started, we moved from the subbasement to the top floor of the building (by that time the synchrotron needed its electron gun) and built new apparatus. This took a lot of development work, because it was the first attempt to use the new method involving the magnetic bottle. Schupp was unbelievably persistent, and when all the problems were solved he came out with an answer for the g factor that was accurate to a few parts in 10 million.

As in many experiments, by the time Schupp was through with his measurements (soon after receiving his Ph.D. he joined the General Dynamics Corporation) we knew of many improvements that could be made. So when the next graduate student, David T. Wilkinson, took over, he started by tearing down the parts of the equipment that most needed improving. He could find no stopping place before he had passed the point of no return. The entirely new apparatus he built was not different in principle, but it incorporated many features that enhanced the reliability and accuracy. Wilkinson's result went two decimal places beyond that of the previous result. He found g equal to $2.002319244 \pm .000000054$. This was, and still is, one of the most precise measurements in all physics. The theoretical calculation gave 2.002319230. So far, to this degree of accuracy, theory is substantiated. But neither we nor the theorists want to let it rest there. We are therefore exploring other means, and a new graduate student, John Wesley, is well along in developing a new experiment.

Before Wilkinson left the project to join the faculty of Princeton University, he and the next graduate student, Arthur Rich (now on the Michigan faculty), turned their attention to the possibility of measuring the g factor of the positron. The positron is the electron of antimatter, the oppositely charged twin of the electron. In our world the positron exists only briefly before combining with an electron in mutual annihilation, converting matter into radiant energy. Positrons for the g-factor experiment are obtained from a radioactive emitter. The main part of the experiment—trapping the particles in a magnetic bottle—follows the general scheme used for the electron. The polarization and analysis are done differently, however. The experiment is extremely difficult because of the small number of positrons available. Nevertheless, Rich has been able to obtain a value for the g factor of the positron that is accurate to a part in 100,000. It agrees with the value found for the electron. John Gilleland, another graduate student, is now preparing a measurement in which he hopes to improve on that accuracy.

One might ask why it is important to measure the g factor of the positron if we believe it is the exact twin of the electron. It is true that we do not expect to find a different result for the positron, probably to the greatest degree of accuracy we can ever reach, but we should not take it for granted. The questions of symmetries in nature, of which this is an example, have become very subtle and are not yet fully understood. There is abundant evidence that not only the electron but also every other kind of charged particle will be found to have an opposite twin. A great many twins have been produced and studied. One therefore can visualize an antimatter world, made entirely of these opposite particles [see "Antimatter and Cosmology," by Hannes Alfvén; Scientific American, April, 1967]. In this sense the electron is a citizen of our world and the positron is a foreigner. As I stated earlier, the anomaly in the g factor is related to the coupling of the electron with the world it is in. The extension of this thought raises an amusing question: Would we expect to find exactly the same g factor for the electron and the positron only if each were in its own world? To settle the issue would require that we do the electron experiment in a matter world and the positron experiment in an antimatter world. But where can we find an antimatter graduate student who will go to an antimatter world and make the measurement?

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