Some Current Work at Bell Telephone Laboratories

*By **Karl K. Darrow***

FARADAY spoke in this hall, and many other eminent men of his century and of this one. Even for a Briton it must be thrilling to stand where they have stood, and for this American it is positively awe-inspiring. One wishes that their words had been preserved on records—and then one realizes that one would hardly care to meet their competition in this place. One indulges in the pastime, useless but harmless, of wondering what Faraday would say could he return to this stage. Looking around the city, I think he would be amazed to see the transformations wrought through his discoveries in the lighting, the transport and the industry of this great capital, in the heart of which the Royal Institution stands now as it stood then. Looking over the scene in physics, he would be astonished by the number of the research institutions and by the size of many of them; he would be amazed by the total amount of work, and surprised by the large fraction of it that is team-work. If he saw our budgets he might consider some of us, the nuclear physicists in particular, extravagant beyond reason. We could reply to him that he exhausted the surface-layers of the mine, and it is not our fault if the remaining ore is very deep down. In listening to a speech like this one he would be pleased to hear such words as "current" and "magnet" over and over again, but he would be confounded by some of the words that are mixed with them. From time to time he would be led into a realm entirely new to him. It is into such a realm that I will first lead you. This is not with the object of impressing Faraday, but I will admit to getting a little whimsical pleasure out of beginning in a field of which you hardly expected to hear in a talk with a title like mine.

The realm in question is that of the extremely cold; and the new work that I shall be describing is chiefly that of B. T. Matthias. I shall be saying many well-known things in the course of this lecture, to introduce one topic after another. It is well known that close to the absolute zero, many a metal opposes no resistance at all to the flow of electric current. Below a "threshold" temperature, such a metal is a perfect conductor. These are said to be superconductors, or to have entered the superconductive state. But this is an inadequate name. There is another feature of this state which is of equal strangeness. Beyond a very thin surface-layer, a proper superconductor simply will not tolerate any magnetic field within itself. In this hall where Faraday spoke, I may certainly dare to speak of "lines of force", though there have been times when people scorned this usage. If one puts a proper superconductor into a magnetic field, the lines of force bulge out and envelop it, like the lines of flow of water enveloping a stone in the bed of the stream. One can indeed make the magnetic field so strong that the lines of force will burst into the substance, but as soon as they do, the superconductive state is ended.

Thus the state of which I am speaking has two extraordinary attributes, inseparable from each other. There is no electrical resistance and there is no internal magnetic field. Clearly the state deserves a name suggesting both these attributes; but there isn't any in use, probably because any such name would be too long; and without attempting innovation I will call it the superconductive state.

The reason for speaking of the second quality is that it underlies an experimental method that we have been using (we were not the first to use it). Imagine that your piece of metal is sitting inside a solenoid, and around the solenoid is wrapped a secondary coil connected across a galvanometer. You apply the magnetic field by sending a current i through the solenoid: then you stop the current suddenly, and measure the kick K of the galvanometer, which is a measure of the magnetic flux through the cross section of the solenoid. You do this for various values of i, and you find that K is proportional to i.

At this point everyone thinks that I have forgotten to say whether the sample is in the superconductive state, or is not. But so far, it doesn't matter. Either way, the curve of K against i is a straight line. But suppose that the sample is in the superconductive state for low values of magnetic field, and then at some special higher value, the magnetic lines of force burst into it and put an end to the state. Now the curve will consist of two straight lines or of two sweeping curves that meet at an angle, and the point of the angle will be where the substance just ceases to be a superconductor. Thus a curve with a kink in it proves that the substance is a superconductor to the left of the kink, and a curve without a kink in it implies that the substance is not a superconductor at all. Here (Figure 1) you see

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a flock of curves of both kinds, all referring to the same substance—cobalt disilicide, $CoSi_2$—but to different temperatures. Below 1.45°, $CoSi_2$ is a superconductor so long as the magnetic field is not too high. From 1.45° on upward the curve is a single straight line, and the substance no longer enters into this singular state of the strange pair of qualities.

Now we indulge in some speculations about this two-faced state.

The only elements that exhibit it are found in certain columns of the Periodic Table. This implies that it is dependent on the number of valence-electrons. Here I am using "valence-electrons" as a shorter synonym for "electrons outside of closed shells." There are indeed elements of which the atoms have no closed shells at all, but I do not have to rephrase my definition on their account, for they do not become superconductive. In the atoms of the elements that do, most of the electrons are locked up together into structures that we call "closed shells". Such electrons largely neutralize one another, not in the sense of destroying one another's charge but in the sense of cancelling one another's chemical and magnetic effects. There are elements in which all of the electrons are in closed shells. These are the noble gases; at low temperatures they solidify, but they do not become superconductive. This is a negative fact of considerable importance.

There are also elements in which there is one electron (per atom) outside of closed shells. These include the best ordinary conductors that there are, sodium and silver for instance, and one might expect them to be especially eager to enter the superconductive state. On the contrary they don't enter it at all, and here is another negative fact of considerable importance. Moreover it is a fact of distinct inconvenience. These are the metals that theorists suppose that they understand the best, and therefore to find superconductivity we have to go on to the elements that are theoretically the tough ones.

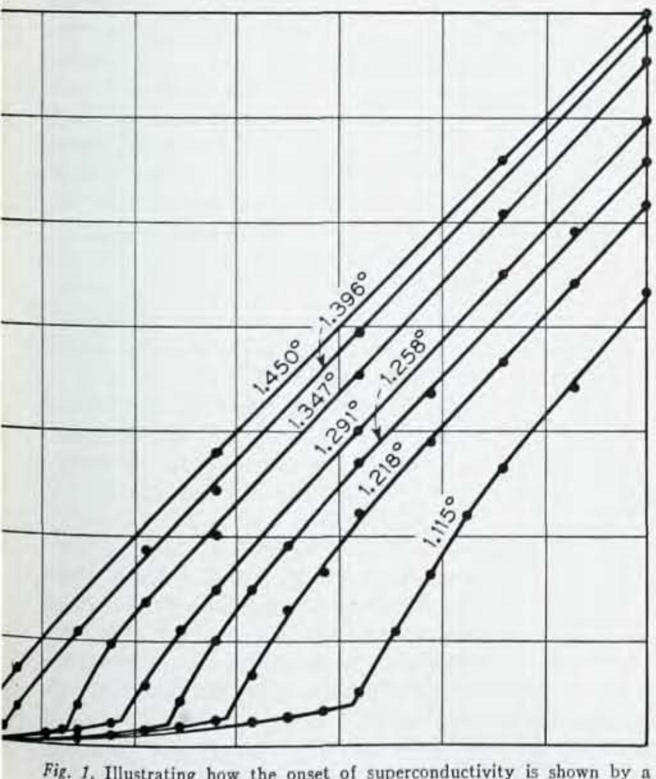

Fig. 1. Illustrating how the onset of superconductivity is shown by a non-zero angle between two straight-line segments of a curve. (After B. T. Matthias.)

The next step brings us at last to a positive fact. If we review the elements that have two valence-electrons, we find that some of them do enter the superconductive state. These are zinc, cadmium, and mercury. But there are also others that do not, and therefore there must be other factors at work—no surprising conclusion, indeed! One may reasonably suppose that among these factors are the mass M of the atom, and the atomic volume V which is a measure of the spacing of the atoms; and one may write down a tentative formula:

$$T_c = M^x V^y f(n)$$

Here n stands for the number of valence-electrons; x and y stand for exponents that one may hope to determine by experiment, if the formula is right at all; and T_c on the left stands for the threshold-temperature at which the substance enters into the superconductive state, which is as good a measure as any of the liability of the substance to become superconductive. The crystal lattice also is not without influence, but this we will set aside.

One would want to test this formula on an enormous number of superconductors, and in particular on a flock of superconductors with nearly the same values of M and V, and either the same or different values of n. But this goal cannot even be approached if we confine ourselves to superconducting *elements*. Elements are not very numerous, superconducting elements are few, and if two or more of them have the same value of n their values of M and V will be very different. One must broaden one's scope to include the superconducting *alloys*. Already there has been plenty of reason for doing this: I mention the long-known fact that there are binary alloys which become superconducting, even though neither of their components does so when pure.

Matthias has begun, and is extending, quite a survey of binary and even of ternary alloys which had never before been tested for superconductivity. I mention a couple of by-products of this survey which have set new records. One is cobalt disilicide, which has already furnished the basis for Figure 1. Here is a compound or mixture of two metals: neither becomes superconductive when pure: one of the two is ferromagnetic when pure, and this establishes a sort of double roadblock against superconductivity: yet the compound has it! Another is Nb_3Sn. This has the highest threshold-temperature of any substance known (I speak, of course, subject to instantaneous correction); it is at least 18°, may be as high as 19° when the proportions are just right and the purity extreme. This also is an alloy that Matthias created. Before I spoke with him I had the naive idea that the metallurgists had already made every binary and indeed every ternary alloy that can possibly exist. This was a gross exaggeration; I was overestimating the metallurgists, or more likely underestimating their task. I don't quite know whether to call the superconductivity of Nb_3Sn a discovery or an invention, but the point is that here is a case of a tentative theory leading to the making of a substance hitherto unknown which confirmed the theory. But now I return to the tentative formula, remarking that when one tries it on an alloy, M must stand for the average mass of the atoms, V for the molecular volume and n for the average number of valence-electrons per atom.

Matthias' present opinion about $f(n)$ is that it is portrayed by the very striking curve of hills and valleys in Figure 2. For $n = 0$ and $n = 1$ there is no su-

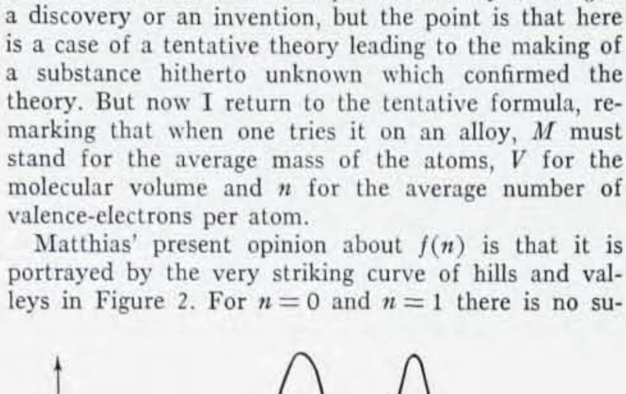

Fig. 2. Dependence of critical temperature (for onset of superconductivity) on number of valence electrons.

perconductivity: this is what I mentioned already: it is formally described by saying that T_c is zero. Now notice that T_c again is zero, superconductivity is absent, for $n = 6$. This is exemplified by the elements Mo and W, and the alloy $NiSi_2$. Continue now to $n = 7$. What a change! We go from the deepest valley to the highest known peak. The cases here are the element technetium (I write out its name because its symbol Tc is confusingly like T_c) and the equimolecular alloy MoRu. Notice in particular that Mo and Ru are atoms for which n is 6 and 8 respectively: when the mixing of the two in equal proportions brings the average value of n to the favorable value 7, superconductivity occurs. Come back now to $n = 5$. Again we have a peak: the cases are the element Nb, the alloy NbN, and a mixture comprising carbon as well as niobium and nitrogen. The admixture brings n a little below 5, but does not take T_c down from the peak: this is perhaps an effect of the expansion of the lattice when the carbon is introduced. As for the dependence of T_c on the variables M and V, Matthias now conjectures that the exponent x of the tentative equation is somewhere between $+5$ and $+10$, the exponent y somewhere between -0.5 and -0.8.

MOST of the rest of this lecture will pertain to magnets. Faraday was very familiar with customary magnets, but not with the ones that I am going to speak about, even though these are responsible for those that were known to him. I refer to the magnets that are single electrons. Perhaps I should change the order of the words, and say that these are the magnets that single electrons are.

You are asked, in fact, to think of an electron as an invisibly small bar-magnet. Faraday, I conjecture, would have liked this idea (presuming him to have anticipated the electron) and would have found nothing strange about it. However he would certainly have been surprised by my next statement, which is, that the electronic magnet can set itself in one or the other of only two directions, with respect to a magnetic field. This is an example of what is called a "quantum attribute". It is correlated with the fact that an electron has an angular momentum of a certain value. I need not give this value numerically: it is sufficient to say that the electron has "spin ½".

Here (Figure 3) are a big arrow H to represent the

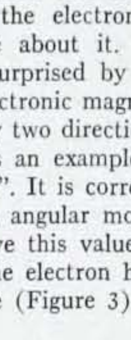

Fig. 3. Illustrating the permitted orientations of an electron-magnet in a magnetic field.

magnetic field, and two smaller arrows A and B to represent the electron in its two permitted orientations. It takes a definite amount of work to turn the electron from orientation A into orientation B. This amount is proportional to the magnetic field strength and is written as $2\mu H$. Suppose now that we take a substance—I might say "a substance containing electrons", but there is no other kind of substance—and apply to it an alternating magnetic field of constant frequency ν, and at right angles to this alternating field another field H which we can keep constant or vary, as we choose. When H has the value given by the quantum equation

$$h\nu = 2\mu H$$

the electrons which are in the orientation A may be turned into the orientation B, and energy will be absorbed from the alternating field.

The beautiful peak shown in Figure 4 is an illustration of this. The peak was obtained from the electrons in the compound called porphyrexide (you see it diagrammed in the figure) by my colleagues A. N. Holden, W. A. Yager, and F. R. Merritt. This is an example of "magnetic resonance". Since magnetic resonance is also displayed by nuclei, we need a special term for it when it is displayed by electrons. Various terms have been used, such as paramagnetic resonance and electronic resonance: I am going to adopt the newer name "electron-spin resonance", which stresses the fact that the angular momentum or spin of the electron is responsible for the two orientations A and B and therefore for the resonance. Now I must give the stipulation for the presence of electron-spin resonance.

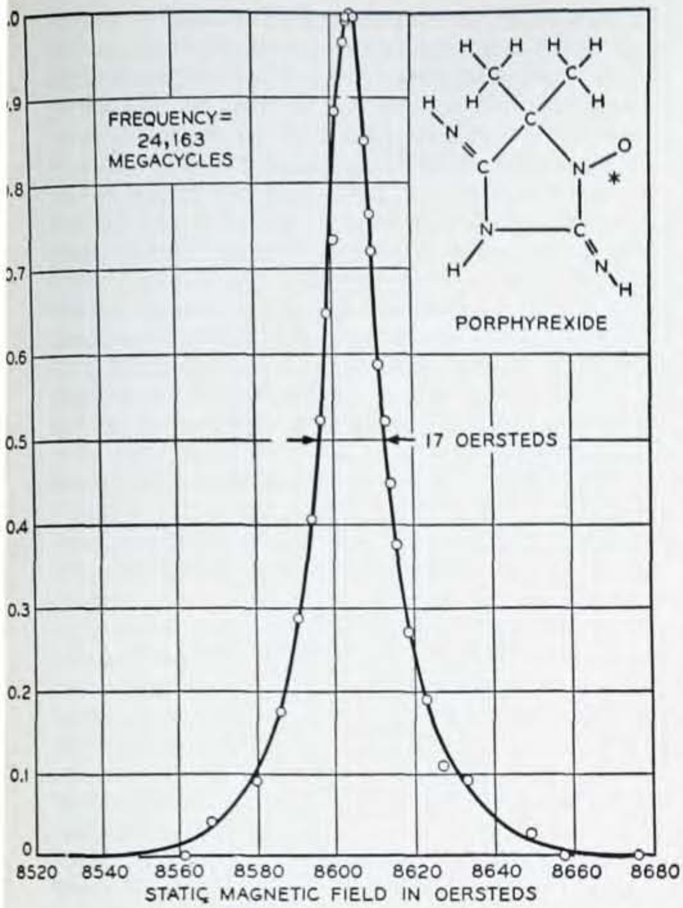

Fig. 4. Peak of electron-spin resonance in an organic free radical (porphyrexide). (After A. N. Holden, W. A. Yager, and F. R. Merritt.)

There are electrons in all substances, and yet electron-spin resonance is confined to substances of certain special classes. This is because of the law of Nature which is called the exclusion-principle of Pauli. For the present purpose I will express it roughly by saying that electrons have a mighty tendency to pair with one another, forming couples which are magnetically inert. One must therefore look for a substance with unpaired electrons. The simplest example of these is a gas of which the atom (or the molecule) has an odd number of electrons, so that one at least must be unpaired. Important work has been done on these with the molecular-beam method, but not by us.

Of the nongaseous substances that show electron-spin resonance, I name five categories. One consists of the strongly paramagnetic salts; as to these I can teach you nothing, they are a specialty of Britain. Another consists of ordinary conducting metals, of which the resonance of the conduction-electrons has lately been discovered in California. Another consists of the ferromagnetic metals and alloys; I shall speak of them later. Another consists of semiconductors with certain impurities; of these also I shall be speaking presently. The remaining one consists of "organic free radicals".

The adjective "organic" implies that these substances are made up exclusively of some or all of the four elements carbon, nitrogen, oxygen, hydrogen. The noun "radical" means that the molecule has an unpaired electron. Such a molecule is likely to be eager to hook itself onto another molecule, so that its unpaired electron can pair with another. If you can catch such a radical when it is not hooked onto another, or make one whose eagerness is not too great, you have a substance predisposed to electron-spin resonance. Such a one is called a "free radical", and porphyrexide is an example. You will have noticed that the porphyrexide peak is very narrow—a half-width of 17 gauss, the mean value being 8600. This shows that several broadening agencies, common in other substances, are almost if not quite absent in this one—notably, damping or dissipation of energy. Another free radical with a still narrower line is diphenylpicrylhydrazyl. This has a formula even more complicated than its name, but I do not have to write it down, for those who are chemists can construct the formula when they read the name and those who are not chemists probably will not care. The breadth of the peak of diphenylpicrylhydrazyl is only about two gauss. The position of this line has been measured with great precision at Bell Telephone Laboratories, and the line itself is often used in calibration of apparatus: I am happy to be able to say that samples of this compound have been sent to Britain to serve this purpose.

Now we go over to another class of substances with unpaired electrons. I take as an example silicon mixed with a small quantity of phosphorus, but first I speak of pure silicon. The atom of silicon has an even number of electrons; every one of them is paired, either with another electron of its own atom or with an electron of a neighboring atom; there is no electron-spin resonance, and except at high temperatures there is no conductivity. Now in imagination replace an occasional silicon atom by a phosphorus atom. The phosphorus atom has an odd number of electrons, and one is unpaired. The lattice of the solid now contains as many unpaired electrons as there are phosphorus atoms. At ordinary temperatures these odd electrons go rambling around in the solid. The substance is what is called an "*n*-type semiconductor", and these are the free or conduction electrons. The electron-spin resonance has been observed for these conduction electrons, but I cannot claim the discovery for Bell Telephone Laboratories. But now let the substance be cooled down to 4.2° absolute, the temperature of liquid helium. It ceases to conduct, because now these electrons are adhering to the phosphorus atoms—not adhering very tightly, but still they are adhering. The electron-spin resonance is still there, but now it has developed a strange feature. There are two resonance-peaks instead of one. What does this mean?

To see what it means, look at the sketch which is Figure 5. Here reappear the arrows H for the strong magnetic field, A and B depicting the allowed orientations of the electron. Two more arrows, 1 and 2, depict the allowed orientations of the phosphorus *nucleus*. Like the electron, the phosphorus nucleus has two permitted orientations, and for the same reason—it has

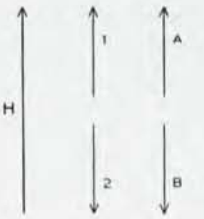

Fig. 5. Illustrating the permitted orientations of an electron-magnet and a nuclear magnet (phosphorus nucleus) in a magnetic field.

angular momentum, and this angular momentum is of the particular value which we call "spin ½". Now I introduce the symbols A_1, A_2, B_1 and B_2. A_1 stands for the energy of the system when the electron is pointing like A and the nucleus is pointing like 1, and you can now guess the meanings of the other three symbols. A_1 is different from A_2 because of the forces with which the electron and the nucleus act upon one another. So also is B_1 different from B_2. So also are the energy-differences $(A_1 - B_1)$ and $(A_2 - B_2)$ different from one another; and the two peaks correspond to these. These peaks correspond to transitions in which the electron turns and the nucleus does not turn. The nucleus "stays put" in orientation 2 or orientation 1, as the case may be, while the electron is turning from A to B.

We go a step further. The following relations exist:

$$A_1 = A_2 - a;\ B_1 = B_2 + a$$

Here a stands for a constant, of which the absolute value is immaterial to this argument; what matters is that it is the same in both equations. Note first that

$$(A_2 - B_2) - (A_1 - B_1) = 2a$$

This is the spacing between the two peaks of which I have been speaking. Note next that

$$(A_1 - B_2) - (A_1 - B_1) = a$$

The quantity $(A_1 - B_2)$ corresponds to a transition in which *both* the electron and the nucleus turn. The equation tells us that if such a transition occurs, its peak will be found midway between the other two. Such a peak has in fact been found. It is not so tall as the others, and is therefore called a "satellite". I must however interpolate that another theory has been suggested for this peak, and the question is not yet settled.

Now think of silicon mixed with a small quantity, not of phosphorus but of arsenic. The arsenic atom is like the phosphorus atom in having an odd number of electrons, and the mixture is an n-type semiconductor. On performing the experiment at liquid-helium temperatures one finds, not one peak of electron-spin resonance and not two, but *four*. This means that the arsenic nucleus has *four* permitted orientations, a fact already known from experiments of quite another kind. Each of the four peaks corresponds to a transition in which the nucleus stays put and the electron turns. In between them, midway in the gaps, are three shorter satellite peaks, presumed to be amenable to the same theory as will eventually be chosen for the satellite observed with phosphorus.

Now think of silicon mixed with antimony. Repeating the experiment, one now finds *fourteen* peaks, eight of one height and six of another. This remarkably opulent structure is as lucid as the simpler ones. Antimony has two isotopes; the nucleus of one has eight permitted orientations, the nucleus of the other has six. These facts were known beforehand, and so was the ratio of the abundances of the two isotopes; this ratio we compare with the ratio of eight times the height of the lines of the group of eight to six times the height of the lines of the group of six, and we find that the two ratios are equal as they should be. The midway satellites ought to be there too, but the pattern is crowded together and it is not surprising that they have not been distinguished. The names which are associated with these experiments are R. C. Fletcher, W. A. Yager, G. L. Pearson, A. N. Holden, W. T. Read, and F. R. Merritt.

Notice at this point that if the number of permitted orientations had not already been known for phosphorus and arsenic and antimony nuclei, it would have been discovered by these experimenters. This gives me a welcome occasion to mention the work of B. Bleaney of Oxford, who before us did similar work on many of the strongly paramagnetic salts, and did indeed become the discoverer of the number of permitted orientations for many nuclei for which this number had not been known before. Let me mention that in describing the results of such observations people usually give not the number of orientations N but the value of the nuclear spin I, which is connected with N by the equation $N = 2I + 1$.

Again I go somewhat outside of the confines imposed by the title of this lecture, in order to mention "cyclotron resonance". To find this resonance one must expose a conducting substance—as I should better say, a substance with free electrons—to the same combination of steady and alternating magnetic fields as one uses when seeking the electron-spin resonance. The cyclotron-resonance occurs when the relation between frequency ν and field strength H is such that the free electrons are impelled to describe ever-widening spirals, as they do in the cyclotrons of the nuclear-physics laboratories. This resonance is shown by an absorption of energy, just as is the other. Many people in many different places, among them my colleague, W. Shockley, thought of it as a possibility before it was discovered by Charles Kittel. I regret that I cannot now describe Kittel as my colleague; he was once, but unfortunately for us he went to the University of California, and that is where this discovery was made. One of its consequences is that it has made the term "electronic resonance" ambiguous. This is why I have been careful to speak of the other type as "electron-spin resonance". Now we turn to the category of the ferromagnetic substances.

Electron-spin resonance in ferromagnetic substances has special features and a special name; the name is "ferromagnetic resonance".

Ferromagnetic resonance is a discovery of Britain. The man to whom we owe it is J. H. E. Griffiths. He observed it in iron, cobalt, and nickel, which I suppose are to this day the most famous of ferromagnetic substances. However I shall be speaking not of them, but of the examples of the new and fascinating class of the ferrites. I must not call it "new" without making one romantic exception. If the legends of the Greeks are true, the first of ferromagnetic bodies ever to be observed was probably a ferrite: for the little bits of magnetic stone found in the fields of the land of Magnesia are presumed to have been bits of magnetite. Apart from this quaint historical item, the ferrites are new by comparison with the iron-cobalt-nickel trio and the alloys of these. Their technical importance arises from the fact that their electrical resistance is high, and this minimizes the effect of eddy-currents. I do not have to tell you what a drawback eddy-currents are in many applications; the point here is that if they are missing, the problems of the theorist are simplified for him.

Let me remind you what a ferrite is. I write a formula, neither the most general nor the most restricted.

$$(NiO)_x(FeO)_{1-x}Fe_2O_3$$

If here I put $x = 0$ I have the formula for magnetite, the ancient ferrite that I lately mentioned. This is a relatively conductive ferrite. If I put $x = 1$ the formula becomes that for nickel ferrite, a relatively resistant one. If I put $x = 0.75$ the formula describes an intermediate ferrite, the one about which most of the following remarks will be made: I will call it the 75–25 ferrite. The crystals of this ferrite were grown by G. H. Clark of the Linde Air Products Company.

Now from the work of W. A. Yager and J. K. Galt I reproduce in Figure 6 the electron-spin resonance peak for the nickel ferrite. As you see, it is much blunter than the sharp peak which I lately showed you for porphyrexide, and the peak for the 75–25 ferrite is still broader. This implies some sort of damping, or dissipation of energy. I must avoid giving the impression that a broad peak *always* implies dissipation of energy; here in truth it does, but there are cases in which it merely implies an unresolved fine-structure.

There is more than one parameter of a resonance-peak that may be used as a measure of the dissipation of energy. The easiest to see and to measure is the breadth, or more strictly the half-width, of the peak. The continuous curves in Figure 7 represent the dependence of the half-width on temperature for the 75–25 ferrite. First I allude to the part which is of smaller theoretical importance. This is the rising part of the curve on the right. It is dominated by the eddy-currents, which though small are not negligible. You see arcs of other curves above it: these were obtained with larger spheres of the ferrite; the larger the sphere the more important the eddy-currents, and as you see, the larger the sphere the higher up lies the curve. But now go over toward the left, in the sense of decreasing temperature. The resistance of the ferrite rises, for in this respect ferrites resemble semiconductors and not metals; the eddy-currents become insignificant, and this part of the curve is not confused by them.

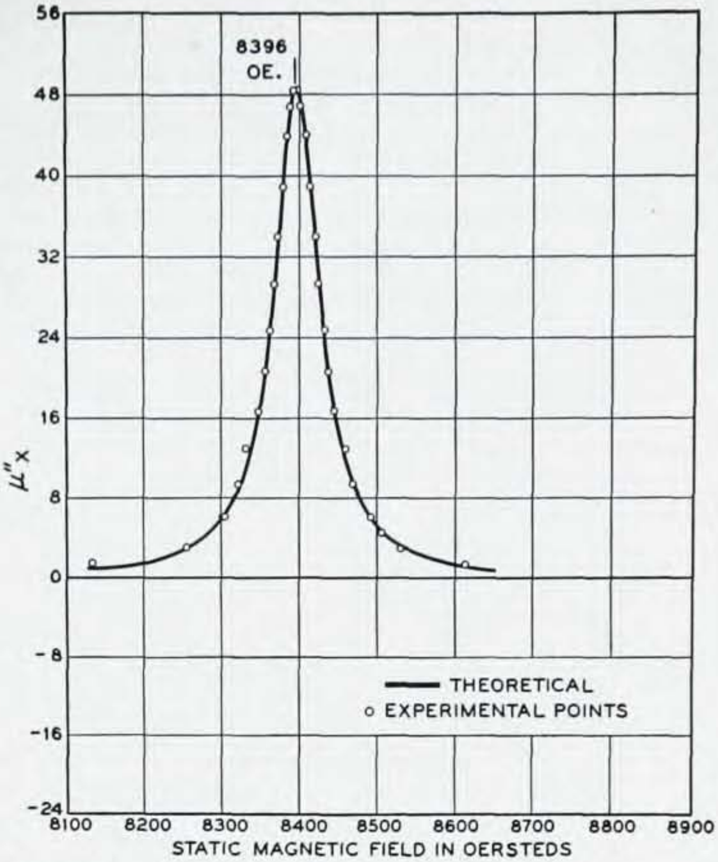

Fig. 6. Peak of electron-spin resonance in a ferromagnetic substance (nickel ferrite). (After W. A. Yager and J. K. Galt.)

The peak which you see implies a mechanism of damping which is frequency-dependent, and which has an optimum frequency. It has been conjectured that the mechanism works as follows. Let me go back to the formula, in order to point out that the symbol Fe does not mean quite the same thing in the two places where it occurs. In one place it means divalent iron and in the other it means trivalent iron. The process suggested is an interchange of divalent and trivalent atoms. This is not so formidable a process as it sounds, because it suffices that an electron should jump from a divalent to a trivalent iron atom, and the interchange is done. If this idea is correct the peak would not appear if divalent iron were missing. The lower curve corresponds to the intermediate ferrite with 95% divalent nickel and only 5% divalent iron. The divalent iron is nearly gone, and you see that the peak is nearly gone also. The idea of electron-interchange between divalent and trivalent iron ions was propounded by H. P. J. Wijn of Holland to explain observations of another kind on ferrites of another makeup.

Another measure of the damping which a resonance-peak betrays is called the "relaxation-time". The formula which links relaxation-time with line-breadth is a very complicated one, and I shall not present it here. The important thing is that the relaxation-time varies as $\exp(-A/kT)$. Here A is a constant which the experi-

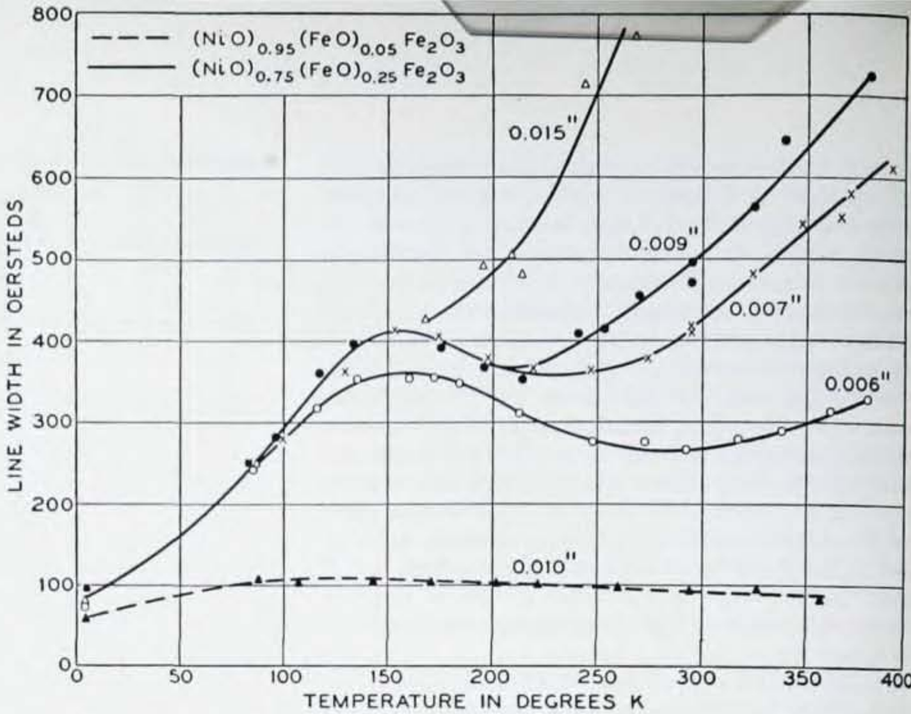

Fig. 7. Electron-spin resonance in two "mixed" ferrites: dependence of half-width of resonance-peak on temperature. (After W. A. Yager and J. K. Galt.)

ments determine. We shall meet again with it before long.

Now we will consider another way of turning over the electronic magnets, and this is the oldest and the most familiar of all. It consists in exposing the ferromagnet to a steady magnetic field, which need not even be a strong one: in favorable cases, a field of even less than one gauss will suffice. Now I remind you of "domains". Pierre Weiss speculated half a century ago that a ferromagnetic substance will and must divide itself, spontaneously and with no assistance from without, into regions in each of which the spins of the electronic magnets are pointing in the same direction. These are the domains—a sort of three-dimensional mosaic, though I hesitate to use the word "mosaic" here, because it has other specific meanings in solid-state physics. In half a century they have evolved from speculations into visible and almost tangible objects, and so have the walls between them. So evolving, the domains and the domain-walls have followed the course of that much more celebrated object, the atom.

The walls between the domains can be made visible where they come up to the surface of the ferromagnet. The art consists in covering the surface with a colloidal suspension of a ferromagnetic powder, which disposes itself into instructive patterns. It is by no means a new art; but at its beginnings it was applied to mechanically-polished surfaces of metal, and the strains which such polishing causes make the patterns hard to read. It has been applied at Bell Telephone Laboratories (and elsewhere) to surfaces of iron polished chemically but not mechanically, and also the iron itself was treated in various ways to make the domains grow to quite respectable dimensions.

Here (Figure 8) is a sketch of something that looks like a picture-frame of somewhat eccentric shape. It stands for a single crystal with a hole in the middle, and four limbs inclined to one another at angles chosen in accordance with the crystal structure. Such a crystal

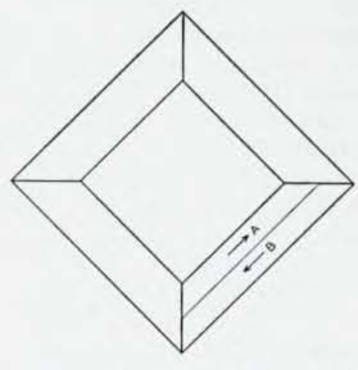

Fig. 8. Illustrating a crystal with a limited number of domains and a mobile domain-wall.

may consist of four domains only, one to each limb of the frame, separated by the four diagonal domain-walls that I have sketched as thick lines. These walls are stationary. But also each of the four limbs may be parted into two domains by a longitudinal wall, here indicated by a thin line. This wall is mobile. The arrows are inserted to show how the electronic magnets are oriented on each side of the mobile wall. I speak of the orientations as the A orientation and the B orientation, and of the sides as the A side and the B side.

The first to make such frames was H. J. Williams of Bell Telephone Laboratories; his were of silicon-iron alloy. But we are now concerned with ferrites, and what I have to show you is a picture of the surface of a sample of the 75–25 ferrite, taken by J. K. Galt. Here, by the way, the angles at the corners of the frame are approximately 70° at one pair of corners and 110° at the other pair, and the whole breadth of the frame may be as much as half a centimeter.

The photograph appearing on the cover of this journal shows part of the surface of a frame, not bare, but covered with a colloidal ferromagnetic substance that has been dropped upon the surface with an eye-dropper and squeezed down by a glass plate. The white line indicated by the arrow is the intersection of a mobile domain-wall with the plane of the surface. You may well ask how I can tell that this is a domain-wall and the other white lines are not. My answer would be the same as if I were showing a cosmic-ray photograph and pointing out the track of a meson. I can't tell with my own eyes which is the track of a meson and which is the line of a domain-wall, and no more can anyone else who has not been trained: we have to rely on what the experts say.

Now arises the question: what happens when a field is applied in such a direction that it tends to turn the electronic magnets out of the A orientation and into the B orientation? One might guess that all of the magnets on the A side of the wall would suddenly turn and the wall itself suddenly vanish. One might guess that they would turn one after another at haphazard points, and the wall itself fade out. Both guesses would be wrong. What happens is that the domain-wall marches across the crystal, at a constant velocity u at right angles to its plane. It acts as though it were tangible: its equations of motion are those of a solid plate being dragged through a viscous fluid.

This speed u, in this case as in others that were earlier explored, is proportional not quite to the field-strength H but to $(H - H_c)$: here H_c stands for a constant which turns out to be none other than the coercive force of the ferrite. Let us form the ratio $(H - H_c)/u$. If the domain-wall were an actual solid plate (a porous plate might be a better analogue) being dragged through an actual viscous fluid, this ratio would be a measure of the viscosity of the fluid or the damping of the motion. Here too it may be called a "damping-coefficient". It goes down very fast as the temperature goes up. Its reciprocal varies as $\exp(-A/kT)$. We met with this law in a previous case: there, it pertained to the relaxation-time deduced from the electron-spin resonance. In that previous case and in the present one, the values of A are, within the limits of experimental error, the same.

NOW I take you discontinuously over to the final topic of this lecture, to a device which seems to have a great future before it, a future of the utmost practical interest. It is called the "Bell Solar Battery".

The Bell solar battery depends upon a p-n junction. This I will describe as a piece of semiconducting matter which is inhabited by free electrons in one part, by free holes in another part. The material is silicon, and the two parts differ because in one there are occasional arsenic atoms which contribute the free electrons, and in the other there are occasional boron atoms which contribute the free holes. The p-n junction is strictly the boundary between these two parts, though in the last sentence but one I used the term more loosely. Of the holes I will say that they are things that act like free positive electrons, but for theoretical reasons ought not to be called positive electrons. The theoretical reasons are embedded in quantum mechanics, and I shall not attempt to expound them here. Suffice it to say that in pure silicon there is a collectivity of bound electrons which do not conduct, but when N of the silicon atoms are replaced by boron atoms the collectivity is diminished in number by N (since the boron atom has one electron fewer in its outer shell than does the silicon atom), and the remainder of the collectivity then conspires to act as if it were a flock of N mobile positive electrons. This is a doctrine which is amply substantiated by experiment. Owing to the fact that there are free electrons on one side of the boundary and free holes on the other, a "built-in" potential difference arises between the two parts. This is essential to the working of the device, and there is one more essential fact. When a photon or corpuscle of light is absorbed in the silicon, a bound electron of the collectivity is set free, and the remainder of the collectivity now behaves as though one more hole or positive electron had been added to the flock. We speak of the creation of a "hole-electron pair".

Let the terminals of the p-n junction be connected through a wire. If the junction is in the dark, nothing perceptible happens. If however the junction is bathed in light, hole-electron pairs spring into being. The built-in potential-difference works upon them, driving holes one way and electrons the other way. A current flows in the circuit.

If the silicon p-n junction is exposed to full sunlight in our latitude and a load consisting of an ordinary wire resistance is connected across its terminals, the heat developed in the resistance amounts to 60 watts per square meter of the exposed surface of the silicon. This is six percent of the solar radiant energy falling upon the junction. Six percent is very good.* The best prior achievement that my colleagues have been able to find on record is one percent, obtained with a thermoelectric device. Conversion of the solar energy into heat is convenient for measurement, but of course it is not the purpose of the device. The energy can be diverted into mechanical work: it can run a motor—and it has. The open-circuit voltage in full sunlight amounts to 0.5 volt. The names here to be mentioned are D. M. Chapin, C. S. Fuller and G. L. Pearson.

Can we hope for much better? I would not say that the practical limit has been reached; but there is one obstacle that is truly insuperable, and this is the character of our sun. No photon can create a hole-electron pair unless its energy exceeds some critical value, of the order of 1.1 electron-volt in silicon. Though this figure corresponds to a wave length well out in the infrared spectrum, still the sun emits a great number of photons of inferior energy, and these cannot be utilized in the solar battery. There are also very numerous photons of energy superior to the critical value, and these can create hole-electron pairs, and there will be energy left over which will become kinetic energy of the electrons and the holes. This left-over energy cannot be converted into mechanical work, and so must be considered as lost. What we need is a sun that shall emit all of its energy in photons of exactly the critical value. There is no way of getting such a sun as a replacement for ours; but we should not like it if we had it.

* Between the delivery of the lecture and the printing of these pages, the six percent was improved to eleven percent.