I know how to do; for example, our efforts in oceanography and our new program in meteorology."

I have at times, after frustratingly frequent encounters with this kind of reaction, asked knowledgeable friends in Washington when we will learn that we don't absolutely *have* to appoint scientists to these jobs irrespective of their political sophistication. "Not in the foreseeable future," is the answer I get, "because the entire scientific community would be up in arms if we considered nonscientists for them. All these jobs have to go to scientists, even when we can't attract our first or second choices to them."

Conclusions

Two comments seem in order. (i) The failure of the traditional policy-making machinery to grapple with the new technically rich problems that have arisen over the last 20 years is adequate explanation for the development of this attitude on the part of the scientific community. By and large, it has until now been better to have scientists than nonscientists in these jobs. (ii) The country's progress in dealing effectively with the important problems of science policy will be measured by the degree to which the scientific community progressively abandons this attitude. Military policy making has on the whole been better done since the professional military man gave up his special claim to omniscience and began to cooperate rather than dominate. The analogy with science policy is clear. The specialist *may* be the best man to deal with the policy implications of his field, but he is not always or by nature the best.

Of course, professional policy makers must first become more adept than they have been in dealing with issues that touch science before the government can safely lessen its encroachment on the scientist's time. It is not clear that physicists and chemists have to be in the policy-making jobs, but it is clear that these jobs must be manned by people who know what physicists and chemists do when they do physics and chemistry. The modern public servant, in other words, has to be scientifically literate. He must be able to understand a scientist when he talks. He has to be able to sift good from bad scientific advice. He has to be able to make his superiors in the Executive branch and in the Congress understand what science is really about, understand that it is more than modern sorcery. He must also be able to explain government and its special problems to the scientist, so that the scientist can provide more relevant advice to the government. He must function as the communications link, missing up to now, between the professional scientist and the professional politician.

This is no mean task. It is one to which this country is only now beginning to awaken. It is one to which public officials, professional scientists, scholars in general, and educators perhaps above all must henceforth devote themselves explicitly and systematically, in order to understand the problem and to help breed the new, technically sophisticated public servant who can deal with it. It is only when that is done that the scientist can reasonably be asked to yield to the new professional in government. But it is doubtful that he will even need to be asked. He will probably do so willingly—perhaps even eagerly—once he is convinced that the policy-making job will not be bungled by scientific illiterates.

Spectroscopy of Solids in the Far-Infrared

Studies of superconductors, magnetic materials, and ferroelectrics in this spectral region are rewarding.

M. Tinkham

By "the far-infrared" I mean here that awkward region of the electromagnetic spectrum between the microwave and the conventional infrared region. Until recently, this region had remained largely unexplored since the pioneering work of Rubens and his collaborators shortly after the turn of the century. To be specific, I use the term *far-infrared* to refer to the wavelength region of 0.1 to 1 millimeter, or 100 to 1000 microns. This means that $\bar{\nu}$ in spectroscopic wave-number units is between 10 and 100 cm^{-1}, or that the actual frequency, ν, lies in the range 3×10^{11} and 3×10^{12}. Put in more physical terms, photons in this region of the spectrum have quantum energies $h\nu$ corresponding to thermal energies kT for temperatures T of 15° to 150°K. (Here h and k denote the constants of Planck and Boltzmann, which are respective constants of proportionality connecting energy to frequency and temperature.) This energetic equivalence suggests one reason why the spectroscopy of solids at these wavelengths is interesting; namely, any phenomenon of ordering on the atomic level within a solid which has a characteristic temperature T_c lying in the convenient range 15° to 150°K may be expected to have characteristic energy-level separations which may be studied spectroscopically in the far-infrared.

An example of this is the transition of a metal to the resistanceless superconducting state, characterized by an ordered electronic state. We now know that a material which becomes superconducting at a critical temperature T_c has a characteristic energy gap of width $E_g \approx 3.5\ kT_c$ in its excitation spectrum at low temperatures. Since most known superconductors have T_c in the range 1° to 18°K, these gaps fall either in the far-infrared or the millimeter microwave region of the spectrum. Another

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example is the transition of paramagnetic crystals to an ordered state, which can be ferromagnetic (all the magnetic moments parallel), antiferromagnetic (the moments cancelling in antiparallel pairs), or some more complicated state. Denoting the transition temperature to the ordered state by the Néel temperature T_N, one sees that, if order begins to replace the thermal disorder at this temperature, the orientational energy μH_E of each atomic magnetic moment μ must be of the order of the thermal energy kT_N. This orientational energy is ascribed to an "exchange field" H_E of quantum mechanical origin acting on the atomic moment. Given this picture, it should be possible to observe the energy required to turn over a single magnetic moment in the exchange field by finding a resonant absorption of infrared energy when the quantum energy of radiation $h\nu$ is equal to the magnetic orientation energy $\mu H \sim kT_N$. In both these cases the spectroscopic study would be expected to provide much more detailed information than could be found from studying the temperature dependence of macroscopic properties, such as electrical resistance or magnetic moment, because the macroscopic properties necessarily represent averages over astronomical numbers of particles, with consequent loss of detail.

Given that studies in this spectral region would be interesting for the information they would give about interactions in solids, one might ask why relatively little work along this line had been done until the past decade. The reason is simply that this is a notoriously difficult region in which to work because there are no strong sources of radiation and no particularly sensitive detectors. This frequency region lies just above that in which microwave oscillators are practical. The limitation here arises because of the need to construct physical structures whose dimensions are small enough to be of the order of the desired wavelength, yet which are robust and able to carry away heat due to electron-beam impact. Although through ingenious designs there continues to be a decrease in the minimum wavelength which may be generated in this way, the present practical limit is near 1 millimeter, and even this is most easily obtained by harmonic generation, starting with longer wavelengths.

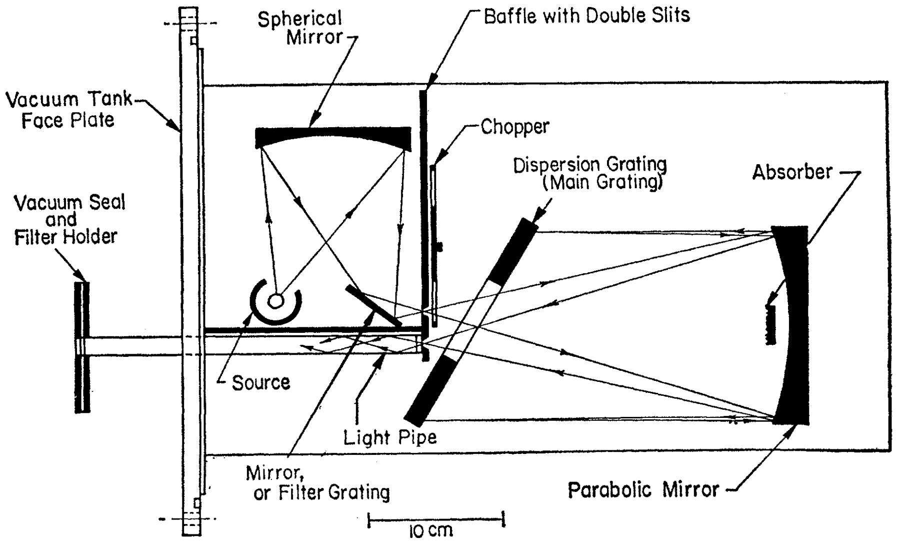


Fig. 1. Schematic diagram of the monochromator used for studies in the far-infrared. The diagonal mirror is usually replaced by a *Reststrahl* plate or a grating used in zero order to improve radiation purity.

Since construction of coherent sources is at present impractical, one must fall back on the incoherent (noise) output of hot objects or, more particularly, of a gas discharge. At these low frequencies (low compared to the thermal energy of a hot source, though high by microwave standards), the radiation available per cycle per second from a hot black body is proportional to the product of the temperature T and the square of the frequency ν. However, since the total power emitted from a black body increases as T^4, a 10,000-fold increase in total power supplied is required to produce a tenfold increase in power at long wavelengths. In practice one is limited to temperatures of about 1500°K for solid objects which approximate black bodies, and to effective temperatures of about 10,000°K for the hot electrons in a gas discharge. Given such limits on T, the ν^2 factor causes the available energy to be less by a factor of the order of 10^3 to 10^5 than the energy available in the near-infrared at wavelength of 3 microns. This difference cannot be made up in detector sensitivity, since the best available detectors for the far-infrared are bolometers, which have nearly the same sensitivity for all frequencies. Thus, the experimental problem in far-infrared spectroscopy is a low, energy-limited, signal-to-noise ratio, and there are very basic difficulties hindering any radical improvement. In recent years some limited improvements have been made, which, combined with the increasing interest in obtaining understanding, at the microscopic level, of the properties of solids, has led to an upsurge of research work in this field. We shall now consider briefly the experimental techniques which have been developed for this work, and then pass on to consideration of some of the applications and results in the study of solids.

Experimental Techniques

As indicated earlier, the best source of energy in the far-infrared is, surprisingly enough, a mercury arc lamp intended as an ultraviolet source. Although by far the greater part of the energy output from such a lamp lies in the visible and ultraviolet parts of the spectrum, still the small output in the far-infrared is greater than that from any hot solid source. The desired energy in a 10-percent bandwidth (a bandwidth which is 10 percent of the midband frequency) is of the order of 10^{-9} watt, which must be separated from several hundred watts of unusable background radiation at other wavelengths. This task of separation is performed by a monochromator (*1*), typically of the sort shown in Fig. 1. The system is enclosed in a vacuum tank to eliminate the extremely intense absorption of far-infrared radiation by water vapor in the air. Alternately, extremely well-dried air or nitrogen may be used to fill the monochromator volume. As may be seen in Fig. 1, the radiation from the mercury arc source first is reflected from a spherical mirror. This mirror is covered with soot from a smoky flame to absorb the visible radiation and other, short-wavelength radiation. The next reflection is from a diagonal mirror, which may also be sooted, or, more usually, from a filter grating used in zero order. Such a grating has no dispersion; it acts like a plane mirror for wavelengths much longer than the ruling interval of the grating, and it scatters short-wavelength radiation out of the beam in higher orders. Thus, by adjusting the courseness of this grating, one can adjust its high-frequency cutoff. After passing through a slit in the baffle, the radiation is next chopped at (typically) 9 cycles per second by a rotary chopper wheel. The purpose of the chopping is to allow alternating-current amplification and lock-in detection of the signal, to distinguish the desired radiation from the background thermal radiation emitted by any object seen by the detector. The chopped radiation is collimated into a parallel beam by the parabolic mirror, which may also be sooted. The collimated beam then diffracts from the main grating, used in first order, the diffracted beam being gathered by the parabolic mirror and focused on the exit slit. As indicated, there is a hole in the middle of the main grating to allow these beams to pass through. After passing through the exit slit, the radiation is conveyed out of the monochromator by a light pipe. This is simply a brass tube ½ inch (1.27 cm) in diameter; the radiation makes repeated glancing reflections on the inside wall and thus is passed down the tube. Since the reflection coefficient of metals in the far-infrared is very nearly unity, there is little loss of energy even over distances of a meter or so. Compared to a system of lenses or mirrors, this light-pipe scheme is much more effective in bringing the radiation in and out of experimental setups at liquid-helium temperatures. Although extremely simple, this feature is very important in making possible many of the desired experiments on solids.

The gratings of the monochromator are ruled either on aluminum or on solder deposited on a brass backing. There are typically from 10 to 100 rulings per inch (4 to 40 rulings per centimeter). Since the rulings are macroscopic, they are made with adequate precision with ordinary machine tools in the departmental machine shop here at the University of California. For maximum efficiency, we use echelette gratings. These gratings have a sawtooth groove profile, with the broad facets inclined at a well-defined angle to the plane of the grating. When used at the angle (called the blaze angle) such that the beam diffracted in first order is specularly reflected from these facets, all the energy at this wavelength is diffracted into this desired beam. In the vacuum monochromator shown in Fig. 1, the gratings are 6 inches (15 cm) square; in a larger monochromator operating in the atmosphere, we use 12-inch gratings.

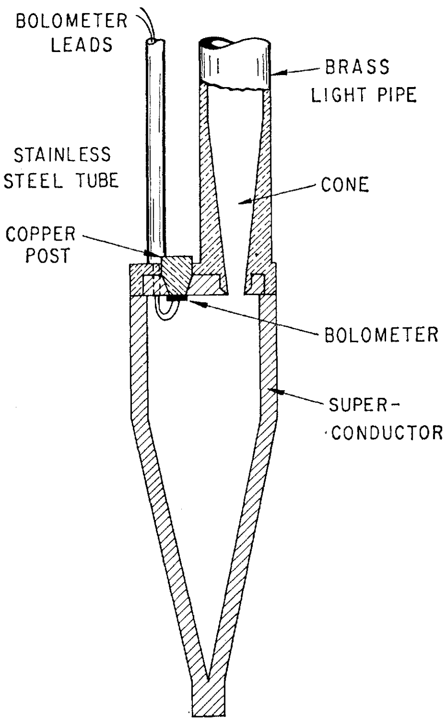


Fig. 2. Plan of nonresonant cavity made from the superconductor being studied. The conical shape of the cavity maximized absorption in the cavity; the cone in the light pipe decreased the size of the coupling hole.

The elimination of unwanted radiation by the soot layers, the zero-order filter grating, and the first-order dispersion grating is still not adequate at the long-wavelength end of the far-infrared range, because higher-order responses from the dispersion grating give rise to false energy at harmonic frequencies in the output. This effect is controlled by the use of transmission filters of crystalline quartz and rock salt of various thicknesses, which are inserted in the path of the beam at the point where the light pipe terminates in a vacuum seal. By using suitable combinations of all these filter techniques, it is possible to obtain radiation which is 90- to 99-percent free of false energy at all wavelengths between 100 and 1000 microns.

The output of the monochromator is conveyed through light pipes to the sample under study. The detailed arrangement of the sample depends on whether a transmission or a reflection measurement is being made; some examples are discussed later. If necessary, the radiation is conveyed from the sample to the detector by an additional light pipe. Until about 1957, the most sensitive available detector was the Golay pneumatic cell (*2*). This device utilizes the heating effect of the radiation on a thin absorbing membrane, the heat being sensed by ingenious optical amplification from the expansion of a small volume of gas in contact with the membrane. The limit of sensitivity of this device is given by the manufacturer as 6×10^{-11} watt. More recently, Boyle and Rodgers (*3*) have shown that a bolometer made of a piece of ordinary carbon resistor and operated at temperatures around 1.5°K (in the liquid helium range) is more sensitive by at least an order of magnitude. Still more recently, Low (*4*) has obtained somewhat higher sensitivity by using suitably doped germanium bolometers, also operated at liquid helium temperatures. Another very sensitive cryogenic bolometer is the superconducting bolometer (*5*) developed at Queen Mary College, London, by a group doing research in the far-infrared. Fundamentally, all these cryogenic bolometers have high sensitivity because the specific heats of all solids approach zero as the absolute temperature approaches zero. Thus, a small amount of absorbed radiant energy can produce a large rise in temperature. In combination with the extremely high temperature coefficients of electrical resistance of these three types of material, this low specific heat leads to very high sensitivity. The absence of a background of room-temperature radiation is also necessary for obtaining high sensitivity. Since most basic studies of solids are carried on at liquid helium temperatures anyway, there is an additional advantage in having the detector operating near the sample in the same helium cryostat: the radiation does not have to be brought back out to room temperature for detection. Thus, an effective tenfold to 100-fold gain in sensitivity results from the use of cryogenic detectors, as compared to the Golay cell. This corresponds to a 100-fold to 10,000-fold decrease in the time required to obtain data at a given signal-to-noise ratio, random noise being assumed. This substantial increase in detector sensitivity accounts to a considerable degree for the recent renewal of interest in the far-infrared spectroscopy of solids.

The Energy Gap in Superconductors

It has long been known that, for temperatures T well below the superconducting transition temperature T_c, a superconductor has absolutely no resistance at direct current, and is essentially a lossless conductor even for frequencies up into the centimeter microwave range. Yet it was also known that there was no measurable difference in electromagnetic absorption properties between the superconducting and the normal states of a metal if the measurements were made in the moderate-infrared or the visible regions, wavelengths of less than 14 microns having been tried. This behavior suggested that there might be a well-defined minimum frequency or, equivalently, a minimum photon energy $h\nu$, which could be absorbed by a superconductor at $T = 0$. This would correspond to an energy gap in the spectrum of excitations of the superconducting metal which would contrast strongly with the continuum of possible excited states of a normal metal. The existence of such a gap could explain certain thermodynamic properties as well, and general semi-quantitative arguments led to the expectation that the width of the gap E_g should be of the order of kT_c. These conjectures were made precise in 1957 by the advent of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity (*6*). This theory predicted that $E_g = 3.5\ kT_c$, and it also predicted the shape of the absorption edge for frequencies above the gap, where the absorption should rapidly approach that in the normal state.

In 1956, shortly before the appearance of the BCS theory, Glover and I, at Berkeley, had carried through the first experiments in which this energy gap was measured directly by spectroscopic means (*7*). The technique we used was to measure the transmission of far-infrared radiation through very thin superconducting films of lead and tin. To get sufficient transmission for making measurements, we had to use films of an effective thickness of only 20 angstroms. Since such films would oxidize very quickly on exposure to air, they were evaporated *in situ* on quartz plates inside the cryostat which would later provide the temperatures of about 1.5°K at which the experiments were carried out. At each frequency, the transmitted power in the superconducting state T_s was normalized with respect to the power transmitted in the normal state of the film, T_n. (The normal state was obtained by passing a current that exceeded the critical value which could be carried in the superconducting state.) It was found that for photon energies $h\nu \gtrsim 20\ kT_c$, this transmission ratio T_s/T_n was very nearly unity, as had been expected from earlier infrared data. However, as the photon energy was decreased toward the gap value, the transmission rose substantially *above* that in the normal state. This was initially surprising, since at low frequencies, where the material is a perfect conductor, the transmission must go to zero, all the energy being reflected. However, on further study it became clear that this was just the behavior that must be expected, and it is in fact predicted with satisfying precision by the BCS theory. At still lower frequencies, starting at about the gap frequency, the transmission did indeed fall toward zero as zero frequency was approached. From detailed analysis of the experimental data we reached the conclusion that the gap was of the order of 3 to 4 kT_c in tin and lead. This result, and the shape of the absorption edge, fitted in extremely well with the results of the BCS theory and formed one of the crucial supports for that theory.

These early experiments were refined and extended by Ginsberg and me (*8*). The main advance in technique lay in the use of carbon bolometer detectors at low temperatures, in place of the Golay cell used earlier. Use of the carbon bolometer made it possible to obtain more accurate data, and the measurements were extended to indium and mercury, in addition to lead and tin.

At this same time (1957–59), Richards and I made measurements of the gap by means of reflection measurements on bulk superconductors (*9*). Since the reflectivity even of normal metals in the far-infrared is typically 99 percent, the increases in reflectivity in the transition to the superconducting state can only be of the order of 1 percent. To build this up to a measurable effect, we used multiple reflections in a nonresonant cavity, as shown in Fig. 2. The incident radiation from the light pipe is reflected many times from the cavity walls before either being absorbed in the wall, being absorbed in the carbon bolometer, or escaping back out the entrance hole. The experiment consists of measuring the fractional *change* in power reaching the bolometer, $(P_s - P_n)/P_n$, when the superconductivity is destroyed by application of a magnetic field above the critical value. This change is nearly proportional to the change in absorption or "surface resistance" associated with the superconducting transition.

Now, the absorption by a normal metal increases roughly as the square root of the frequency. So long as the superconductor is lossless, then the *difference* in absorption will increase in a similar manner. When the frequency of the energy gap is reached, however, the superconductor will start to absorb energy also, and the difference begins to fall. This behavior is shown in the experimental data of Fig. 3. After the initial rise there is a sharp break in the curve, and the difference signal drops rapidly to zero. The break determines the energy-gap frequency in a very direct way. In this way, energy-gap values were found for the seven metals shown, all falling in the range 3.4 to 4.6 kT_c except for tantalum and niobium, for both of which surface contamination is likely. In the cases of lead and mercury there is a curious precursor structure on the curves at frequencies below the energy-gap frequency. The interpretation of this

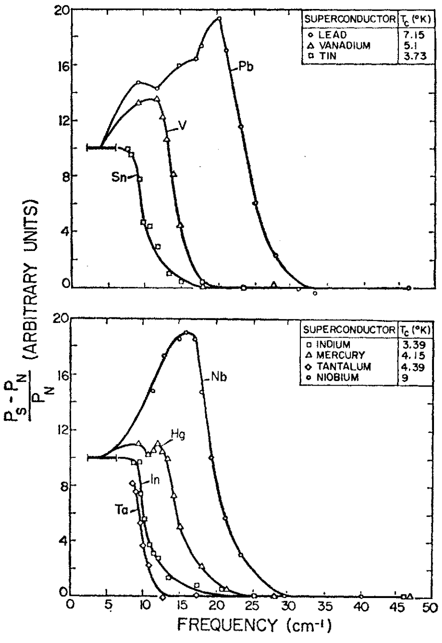
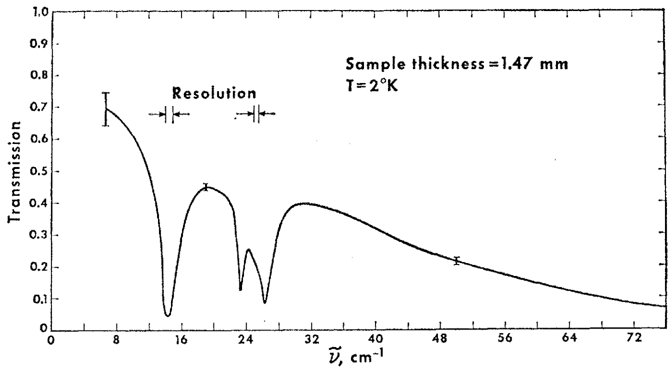


Fig. 3. Low-temperature absorption curves for seven superconductors plotted as a function of frequency in wave numbers. These curves have been normalized for purposes of display, so that the ordinate of the lowest frequency point is the same for each. This point was obtained by using the coarsest dispersion grating in zero order. The estimated spread of frequencies is indicated by the horizontal bar. All other points have bandwidths of the order of 10 percent of the nominal frequency for the point.



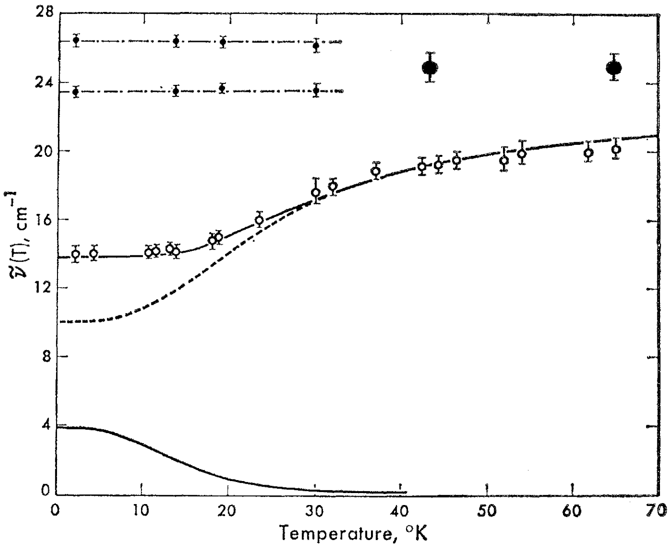


Fig. 4 (left). Transmission through a pressed powder sample of ytterbium iron garnet, 1.47 millimeters thick, at a temperature of 2°K. The sharp dips reveal magnetic resonances; the smooth decrease toward higher frequencies is caused by increasing lattice absorption. Fig. 5 (right). Temperature dependence of the magnetic resonance frequencies in ytterbium iron garnet. The two highest frequencies are essentially temperature-independent. Above 30°K only the center of gravity of the doublet could be measured. The dashed curve gives the calculated temperature dependence of the exchange frequency in the isotropic approximation. The upper solid curve demonstrates the good agreement between theory and experiment when the anisotropy energy is introduced. The low-frequency curve (lower solid curve) is the predicted frequency of the mode in which both iron and ytterbium ions precess as a unit about the easy axis.

structure is still uncertain, but it may represent some sort of collective excitation which has an energy less than that for single-particle excitation across the energy gap.

Since these measurements of energy-gap frequencies in the far-infrared were made, it has been shown that the technique of electron tunneling (*10*) leads to a simple and direct measurement of the energy gap in materials which form suitable films. Where such measurements are available, the results are generally in satisfactory agreement with the spectroscopic ones.

Far-Infrared Magnetic Resonance

As indicated at the beginning of this article, the energies of orientation of the magnetic moments of ions in magnetic crystals are of the order of kT_N, where T_N is the Néel or ordering temperature for the material. Although these energies often correspond to far-infrared photon energies, it is not always possible to observe them spectroscopically. In fact there is a selection rule which excludes the observation of such transitions in simple ferromagnets and antiferromagnets in which there is no anisotropy. This selection rule is based on the fact that the high-frequency magnetic field of the radiation acts equally on all magnetic moments and turns them all a little bit rather than turning one all the way over with respect to the others. This leads one to think of collective excitations of the magnetic spins, in which all spins participate in simply correlated motions.

The first such case to be considered which is relevant to the far-infrared was that of *antiferromagnetic resonance*, first treated in 1951 by Kittel and Nagamiya (*11*). As the name implies, this is a resonant mode of excitation of an antiferromagnetic crystal, which is a magnetically ordered crystal with equal numbers of up and down spins. These two sublattices of spins are constrained to be antiparallel by the exchange field

$$\mathbf{H}_E = -\lambda \mathbf{M} \qquad (1)$$

which each sublattice exerts on the other. As indicated by Eq. 1, these "fields" are antiparallel to and proportional to the sublattice magnetization producing them. When excited in this resonant mode, the sublattices of up and down spins precess en masse about each other in a motion symmetrical about the "easy axis" of the crystal. This easy axis is the direction in the crystal along which the aligned spins prefer to point so as to have the lowest energy. The anisotropy energy producing the preference may arise from the ordinary magnetic-dipole interaction between the spins, from the crystalline electric field via spin-orbit coupling, or from various other sources, such as anisotropic exchange. In any case, it is often convenient to replace it by an effective anisotropy field $\mathbf{H}_A$, acting on the spins. The dynamics of this resonant mode are then worked out simply according to the view that each spin precesses because of the torque produced by the sum of the anisotropy field and the exchange field produced by the other sublattice. The resulting resonant frequency is

$$\omega_{AF} = \gamma[H_A(H_A + 2H_E)]^{\frac{1}{2}} \qquad (2)$$

where γ is the gyromagnetic ratio characteristic of the type of magnetic ion in question. In the usual case, in which $\mathbf{H}_E$ is much larger than $\mathbf{H}_A$, this frequency is approximately proportional to the geometric mean of these two effective fields. Note that if there were no anisotropy, the resonant frequency would be zero. Although I have not shown it here, the intensity also goes to zero as $\mathbf{H}_A$ goes to zero, so that the resonance would in this case be unobservable, as required by the general selection rule.

Such a resonance was first observed in the far-infrared in 1958 by Ohlmann and me (*12*), in FeF_2. At low temperatures ($T << T_N$) the resonance occurs at a frequency of 52.7 cm^{-1}, in quite good agreement with estimates based on approximate determinations of H_E and H_A from other types of data. By applying a magnetic field along the easy axis of the crystal we were able to split the resonance into two circularly polarized components. From the separation between them, we found that the *g*-value of the Fe^{++} ion in this lattice was 2.25, in agreement with inferences from samples of ZnF_2 containing small concentrations of Fe^{++} ions. As the temperature is raised, the resonant frequency approaches zero at the Néel temperature, as had been expected, and the resonant line becomes broad and indistinct.

Subsequent to this work, Sievers and I made similar studies of the antiferromagnets MnO and NiO (*13*). These differ from FeF_2 in having a hard axis and an easy *plane*. This type of anisotropy lifts the degeneracy of the two modes, leaving a single nondegenerate, linearly polarized mode in the far-infrared. In this case there is no first-order effect of a magnetic field on the resonance. The resonances in these materials, too, were studied as a function of temperature. The low-temperature limits of the resonance frequencies were found to be quite close to those estimated on the basis of dipolar anisotropy. The temperature dependences of the resonant frequencies were compared with those expected theoretically on the basis of the temperature-dependent sublattice magnetization, as determined by neutron scattering. The satisfactory agreement obtained shows that the theory of the temperature dependence of the relation of the anisotropy to the magnetization is sound; thus further theoretical effort may be confined to explaining the anomalous sublattice magnetization in these materials.

Another class of magnetic materials which Sievers and I have studied extensively are the rare earth iron garnets (*14*). These are ferrimagnetic crystals containing antiparallel but unequal magnetic moments arising from the iron ions and the rare earth ions, leading to a net magnetic moment. The exchange coupling among the iron ions is very strong, leading to ordering at about 550°K, so that the order is very complete at low temperatures. The coupling between the iron and the rare earth sublattice is weaker, corresponding typically to ordering at 30°K. It is this coupling which is accessible to far-infrared study.

Because the two sublattices are substantially distinct, the collective mode of oscillation differs in behavior from the antiferromagnetic resonance described earlier. In particular, the resonant frequency does not go to zero in the absence of anisotropy. As shown by Kaplan and Kittel (*15*) in 1953, this so-called exchange resonance frequency should be given by

$$\omega_E = \lambda(\gamma_2 M_1 - \gamma_1 M_2) \qquad (3)$$

where λ is the exchange-coupling parameter and γ_1 and M_1 are the gyromagnetic ratios and magnetizations of the two sublattices.

In addition to this mode, there should also be resonant modes in which the rare earth ions precess in the exchange field of the iron sublattice, which is essentially stationary. The quantum energy $h\nu$ corresponding to the precessional frequency ν of such a mode is equal to the energy required to reverse a single rare earth spin in the exchange field produced by the iron sublattice. Because there are two sets of rare earth ions inequivalently oriented with respect to the exchange field, there are two distinct resonances of this sort.

Yet another observable resonant mode is the one corresponding to precession of the entire spin system, iron plus rare earth, as a whole about the easy axis of the crystal. The resonant frequency of this mode is a direct measure of the strength of the anisotropy favoring the easy direction.

The most thoroughly studied of the garnets is ytterbium iron garnet. Fig. 4 shows the far-infrared transmission spectrum of a disc of ytterbium iron garnet at low temperatures. The prominent features are three sharp absorption lines superimposed on a background attenuation with increases smoothly to-

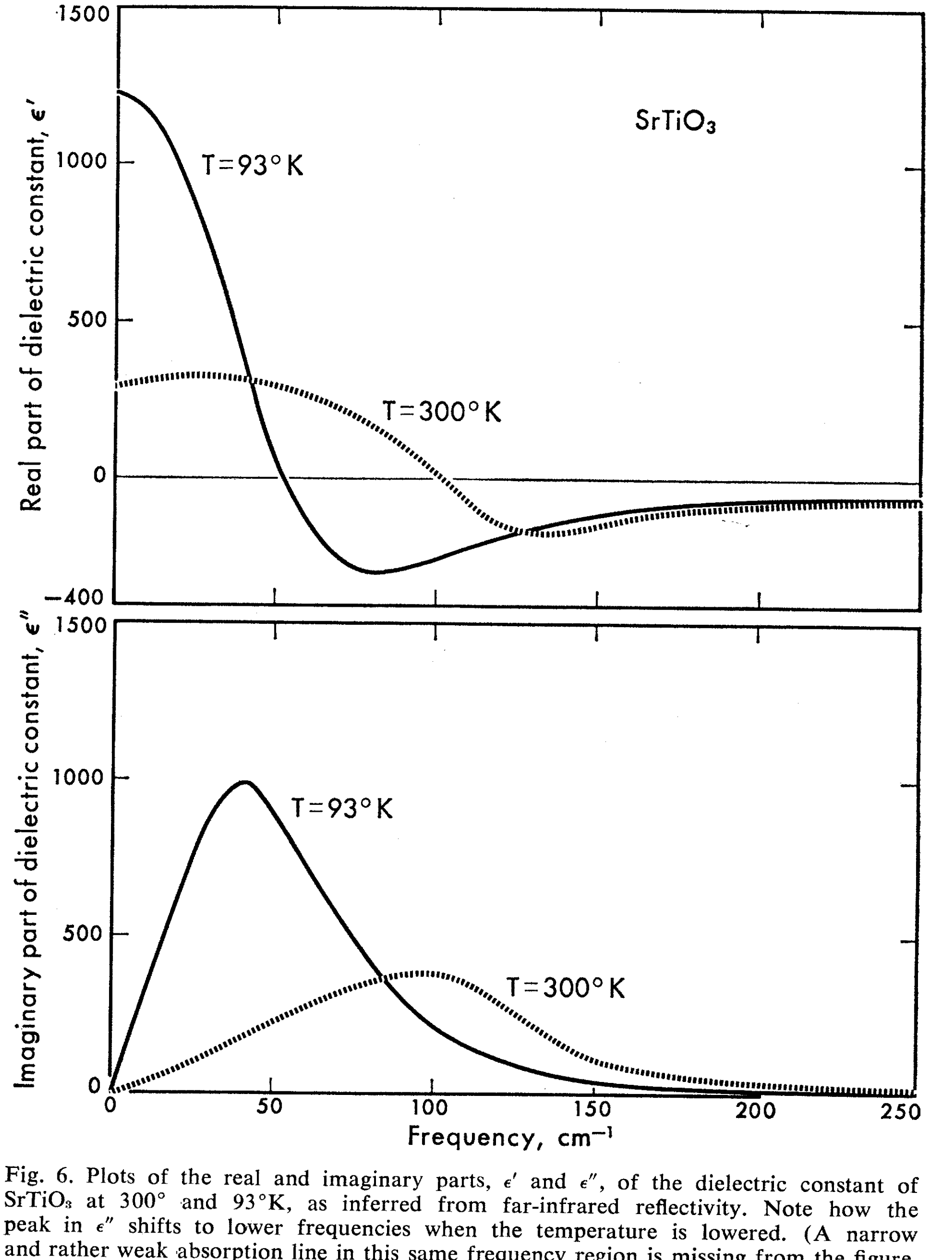


Fig. 6. Plots of the real and imaginary parts, ϵ' and ϵ'', of the dielectric constant of $SrTiO_3$ at 300° and 93°K, as inferred from far-infrared reflectivity. Note how the peak in ϵ'' shifts to lower frequencies when the temperature is lowered. (A narrow and rather weak absorption line in this same frequency region is missing from the figure, since it was missed in the data from which the figure was prepared. It has no effect on the ferroelectricity, which is dominated by the strong absorption peak shown here.)

ward higher frequencies as one approaches the frequencies of the strong absorption due to lattice vibrations. Whereas the background absorption is similar for all the garnets, the sharp lines are characteristic of ytterbium iron garnet. The assignment of the lines to specific modes is facilitated by inspection of the temperature dependence of the frequencies, as shown in Fig. 5. The two single-ion transitions are essentially temperature-independent (apart from a broadening and overlapping of the lines at higher temperatures), since the frequencies are proportional to the iron magnetization, which is nearly constant at these temperatures. On the other hand, the exchange resonance depends also on the rare-earth magnetization, which drops sharply with increasing temperature in this temperature range. The dashed curve of Fig. 5 gives the temperature dependence that would be predicted if there were no anisotropy, and the upper solid curve is corrected for the effects of anisotropy. It is evident that the fit with theory is quite good. The lower solid curve gives the predicted frequency of the general precession mode in the presence of anisotropy. Richards (*16*) has observed this mode (at a slightly lower frequency than that predicted) by means of an interferometer-type far-infrared spectrometer superior in performance to the simple grating instrument described in this article. Thus, in general there is a very satisfactory agreement between the theory and the experimental results, which has made it possible to extract precise and detailed information about the interactions which lead to the macroscopic properties of this material. Similar, but less complete, studies have been made on many other garnets (*14*).

Ferroelectric Crystals

A number of dielectric crystals, such as $BaTiO_3$ and KH_2Po_4, have large dielectric constants which include a temperature-dependent term of the form

$$\epsilon - \epsilon_\infty = \frac{C}{T-\theta} \qquad (4)$$

which diverges as $T \rightarrow \theta$. (In Eq. 4, ϵ_∞ is the temperature-independent dielectric constant appropriate for very high frequencies.) At a temperature near θ, these crystals acquire a macroscopic electric polarization, even in the absence of any external field, and the Curie-law behavior of Eq. 4 breaks down. Such crystals are called ferroelectric, by analogy to ferromagnetic materials which develop spontaneous *magnetic* polarization (*17*).

The theoretical understanding of such materials is far from complete, but it seems clear that an important feature is the near-cancellation of long-range electric forces arising from the polarization of the material and the short-range interatomic forces. The shift of this balance with temperature, if linear, leads to the characteristic form for ϵ, given in Eq. 4, with complete cancellation presumed to occur at $T = \theta$ if no structure change intervenes first.

Various authors (*18*) have suggested that such a temperature dependence of interatomic force constants should lead to a temperature dependence of certain vibrational modes of a crystal. In particular, a "soft mode" depending on the nearly cancelling force constant should have a frequency varying as $(T - \theta)^{\frac{1}{2}}$, and its contribution to the static polarizability leads to the Curie-law behavior of ϵ. Because of the weak restoring force for such a mode of vibration, the resonant frequency would be expected to lie in the far-infrared rather than in the ordinary infrared, where molecular virbration modes are normally found.

In an attempt to confirm this idea, Barker and I studied the reflection spectrum (*19*) of $SrTiO_3$, a material having a large Curie-law term in the dielectric constant ϵ, with $\theta \approx 0$. This material was chosen in preference to the classic ferroelectric $BaTiO_3$ because $SrTiO_3$ has a lower value of ϵ, giving a reflectivity further from unity, which allows changes in reflectivity large enough for observation with adequate signal-to-noise ratio. Since the reflectivity depends on both ϵ' and ϵ'' (the real and imaginary parts of ϵ, which describe the in-phase and out-of-phase polarizability, respectively), dispersion analysis is required to convert the reflectivity data to curves of ϵ' and ϵ''. The frequency of a resonant mode is best located by noting the position of a peak in ϵ'', which locates the maximum of dielectric loss. From the data of Fig. 6 it is clear that there is a strong low-frequency mode which shifts downward in frequency from 100 cm^{-1} to 40 cm^{-1} when the temperature is lowered from 300° to 93°K. This shift is in reasonably good agreement with the simple prediction of a $(T - \theta)^{\frac{1}{2}}$ dependence. Thus the relation of ferroelectricity to lattice vibration dynamics is confirmed in $SrTiO_3$.

Subsequent studies by Barker and others (*20*) on other dielectric materials have shown that, although the behavior found in $SrTiO_3$ is probably characteristic also of $BaTiO_3$ and TiO_2, it is not found in all ferroelectrics. In materials such as KH_2PO_4 and triglycine sulfate Barker finds that any low-frequency mode which exists is so highly damped as to render a description in terms of resonance inappropriate. Since these latter materials are believed to have a ferroelectric transition of the order-disorder sort, such a difference in dynamic behavior is not entirely unexpected.

Summary

The far-infrared spectral region (10–100 cm^{-1}) is a fruitful one for studies of solids. The experimental obstacle of weak sources has been partially overcome in recent years by the introduction of very sensitive bolometric radiation detectors cooled by liquid helium to temperatures near 1°K. Used with a mercury arc source and a simple grating monochromator, these detectors have made work in a number of areas of solid-state physics possible. Important examples of such work are, (i) demonstration of the energy gap in superconductors and measurement of gap widths in various metals; (ii) observation of magnetic resonances in ordered magnetic materials, from which precise information about exchange fields and anisotropy energies can be obtained; and (iii) demonstration of the existence of a temperature-dependent low-frequency vibrational mode associated with the Curie-law dielectric constant in certain types of ferroelectric crystals.

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Germfree Animals and Biological Research

The gnotobiote is an improved investigative tool for biology.

Morris Pollard

During the past 35 years a methodology has been developed whereby animals can be maintained and propagated free of a demonstrable microbial flora (*1*). They are referred to as germfree, axenic, or gnotobiotic animals, as distinguished from "conventional" animals.

Originally the laboratories involved in germfree research were few. They were located at l'Institut Pasteur, the University of Notre Dame, and the University of Lund. The first of these laboratories is no longer active, the third has been moved to Stockholm, and a number of new laboratories have been added to the list. The era of "gadgeteering" in developing essential equipment and procedures was so successful that definitive experiments with germfree animals are now being conducted in increasing numbers of laboratories the world over.

The Lobund Laboratory of the University of Notre Dame (*2*) has aided in the establishment of germfree laboratories in France, Holland, Japan, and England and in several areas of the United States. Frequent exchanges of information and of personnel among germfree laboratories have helped to clarify the range of application of germfree methodology as a unique tool for biological research. It is to the credit of such contemporary investigators as Reyniers, Glimstedt, Gustafsson, Trexler, Miyakawa, and their associates that germfree research has now attained "respectability" and acceptance in the circles that advise on the support of research programs. Even greater credit is due the institutions with which these workers are associated and the government agencies that supported programs which were at times vague in purpose or generally unpopular. Valuable support for activities of the Lobund Laboratory came from the Office of Naval Research, the National Institutes of Health, the Department of the Army, the Nutrition Foundation, the National Science Foundation, the Atomic Energy Commission, the Tobacco Research committee, county cancer societies, and the University of Notre Dame.

The early developments in germfree methodology received a good deal of publicity, much of it in semitechnical publications or in popular magazines and journals. Undoubtedly the need for support may have been a stimulating factor in the earlier splashes of publicity. As important as the early developments, however, is the more recent technical breakthrough whereby animals in large numbers can be maintained, propagated, and utilized for experimentation under germfree conditions.

The maintenance, production, and utilization of germfree animals requires rigid attention to procedures which only experienced technicians can carry out (*3*). Once mastered, the procedures become routine. Any investigator who is willing to devote time, effort, and money to this problem can eventually develop a team of competent technicians for this work. Standard procedures have been recorded, established laboratories are willing to train visiting neophytes, and training workshops are held annually at which new developments are disclosed.

The Lobund Laboratory has provided nuclei of breeding stock to technically qualified laboratories newly engaged in such work. Germfree animals have been flown from the University of Notre Dame to laboratories in Paris, Amsterdam, Nagoya, and London and to a number of laboratories in the United States. The animals were delivered germfree in portable isolators, and they constituted the breeding nucleus of germfree animals, or of pathogen-free derivatives of such animals. If the investigator has no inclination to master the methodology, or if he has only limited need for germfree animals, he can purchase germfree mice and rats in a completely stocked isolator through commercial channels. Animals provided in a stocked isolator should be used for only a limited time, since the chemical quality of the food deteriorates after a certain period.

It should be emphasized that germfree animals must be maintained under controlled (gnotobiotic) conditions throughout the experiment. If they are not, there is no procedural advantage in using them. I make this somewhat obvious statement in response to a suggestion from a prominent microbiologist that the expense of germfree research could be reduced through removal of the animals from the controlled environment at the beginning of an experiment. Orientation in using the techniques of this discipline is clearly needed.

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