sume that the measurement of this parameter for numerous nonsuperconducting elements would assist the theorists in their efforts to predict superconductors.

The author would like to acknowledge helpful discussions with Dr. C. E. Chase, Jr., Dr. M. S. Dresselhaus, Professor E. Maxwell, Dr. R. Meservey, and Dr. M. Strongin.

---

*This work was supported in part by the U. S. Army Signal Corps (Contract DA36-039-sc-87376), the Air Force Office of Scientific Research, and the Office of Naval Research.

†Now at the Department of Physics and the Institute for the Study of Metals, University of Chicago, Chicago, Illinois.

[1] L. N. Cooper, Phys. Rev. Letters 6, 698 (1961). This model is the simplest within the framework of the rigorous, microscopic theory. Refinements such as those considered here would have to take into account the Fermi momentum, mean free path, etc., as Cooper pointed out.

[2] H. Meissner, Phys. Rev. 117, 672 (1960).

[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

[4] P. Smith, S. Shapiro, J. Miles, and J. Nicol, Phys. Rev. Letters 6, 686 (1961).

[5] J. K. Hulm and R. D. Blaugher, Phys. Rev. 123, 1569 (1961), have found it convenient in their study of alloys to introduce the concept of negative transition temperature to describe normal metals. This concept is equivalent to saying that the superconducting state has a higher free energy than the normal state.

[6] The author is indebted to Dr. E. Maxwell for suggesting this possibility.

[7] V. L. Ginzburg and L. D. Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) 20, 1064 (1950). In this paper $\psi(x)/\psi_0$ is depressed from unity because of the influence of the other metal, whereas in the Ginzburg-Landau theory this depression is caused by a magnetic field.

[8] M. Tinkham, IBM J. Research Develop. 6, 49 (1962).

[9] It is implicitly assumed here that the two-film system is in either the superconducting or the normal state. This assumption restricts the considerations to films that are less than their respective coherence lengths. For larger thicknesses an "intermediate state" will occur which will have a lower free energy than either the superconducting or normal state.

[10] C. J. Gorter and H. B. G. Casimir, Physica 1, 306 (1934).

[11] B. T. Matthias, IBM J. Research Develop. 6, 250 (1962).

TEMPERATURE DEPENDENCE OF A TRANSVERSE OPTIC MODE IN STRONTIUM TITANATE

R. A. Cowley*
Neutron Physics Branch, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

(Received July 9, 1962)
A.E.C.L. Ref. # A-2828-D

Cochran[1] has discussed the phenomenon of ferroelectricity in terms of the lattice dynamics of the crystal; the anomalously large dielectric constant is associated with a low-frequency transverse optic mode of long wavelength. Above the transition the static dielectric constant increases with decreasing temperature, and the frequency of this transverse optic mode decreases, until at the transition the crystal becomes unstable against this mode of vibration. The lowest frequency transverse optic branch, propagating in the [100] direction of strontium titanate, has been studied by the inelastic scattering of slow neutrons. The results are shown in Fig. 1. The dispersion curve is observed to be most temperature dependent at long wavelengths but almost independent of temperature at the zone boundary. The temperature dependence of the long wavelength mode (Fig. 2) is in good agreement with the temperature dependence of the dielectric constant interpreted through Cochran's theory.

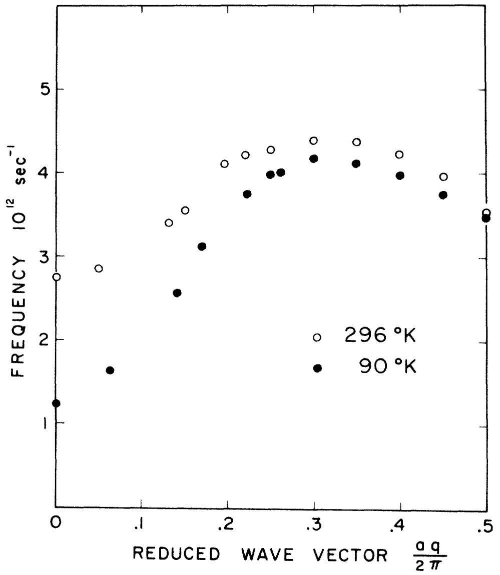

FIG. 1. The dispersion curve of the lowest frequency transverse optic branch along [100] at 90°K and 296°K.

Strontium titanate was chosen because it exhibits a large static dielectric constant, whose tem-

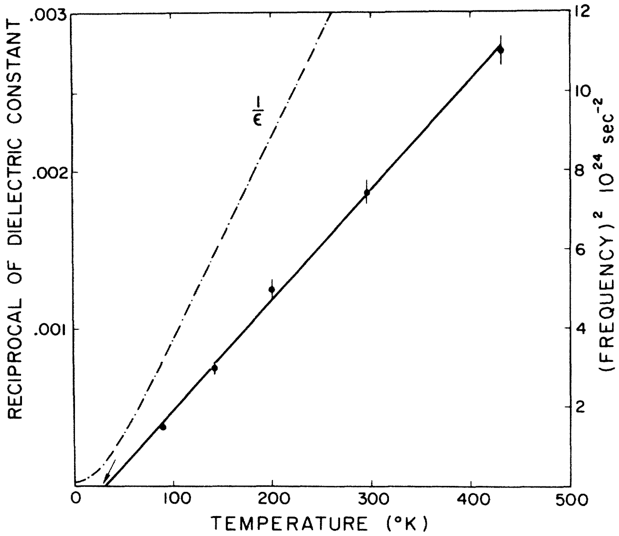

FIG. 2. The figure shows a plot of the square of the frequency of the $\vec{q}=0$ transverse optic mode against temperature. The solid line is a linear regression line through the points and gives a Curie temperature of 32 ± 5°K. The other line represents the reciprocal of the dielectric constant from the measurements of Mitsui and Westphal.[5]

perature dependence follows the familiar Curie-law temperature dependence above 70°K. An excellent single crystal for the experiments was provided by the Titanium Division of the National Lead Company.

The experiments were performed on the triple-axis crystal spectrometer[2] at the N.R.U. reactor in two different ways. The energy distributions were obtained while keeping the wave-vector transfer, $\vec{Q}=\vec{k}_0-\vec{k}'$, fixed. The centers of the neutron groups then give the frequency of the lattice vibrations of reduced wave vector $\vec{q}$, where $\vec{Q}=2\pi\vec{\tau}-\vec{q}$, through the energy conservation equation $h\nu=E_0-E'$. In these equations E_0, E' are the energies and $\vec{k}_0, \vec{k}'$ the wave vectors of the incoming and outgoing neutrons, respectively, while $\vec{\tau}$ is a reciprocal lattice vector.

Alternatively the energy transfer was fixed and the momentum transfer $\vec{Q}$ changed in such a way[2] that the reduced wave vector $\vec{q}$ was always along the desired direction, in this case along [1, 0, 0]. The centers of the neutron groups then give the reduced wave vectors of the lattice vibrations. This latter method was particularly useful for determining the parts of the dispersion curves where the frequency changes most rapidly with wave vector.

Figure 3 illustrates some of the neutron groups which were obtained using the constant $\vec{Q}$ method for the lattice vibrations with $\vec{q}=0$. The increase in intensity at frequencies of 0.7 and below is due to the low-frequency acoustic modes and to the Bragg peak associated with the (2, 0, 0) reciprocal lattice point. The asymmetry of the 90°K group probably arises from the finite resolution of the instrument in $\vec{Q}$ space sampling the region away from $\vec{q}=0$, where the frequency of the branch increases quite rapidly. The apparent change in width of the neutron groups is probably due to the change in the instrumental resolution with frequency, and the change in the shape of the dispersion curve with temperature.

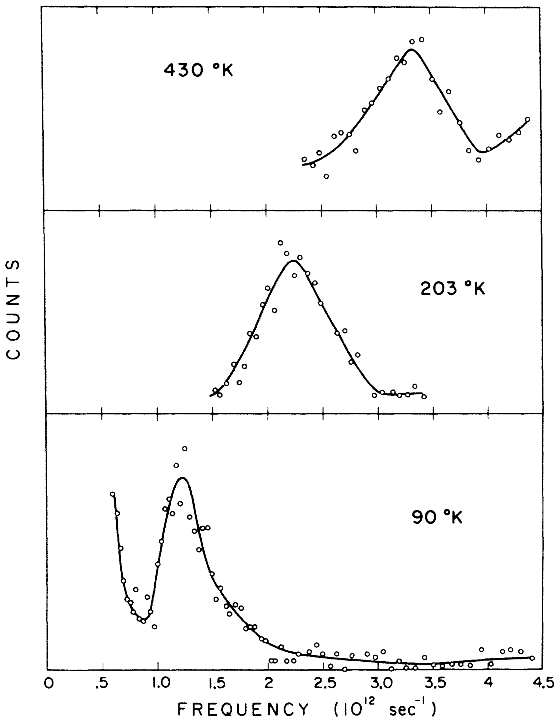

FIG. 3. The neutron groups obtained using the constant $\vec{Q}$ method, $a\vec{Q}/2\pi=(2,0,0)$, with fixed outgoing energy for the $\vec{q}=0$ mode of the transverse optic branch at three different temperatures.

The frequency of the $\vec{q}=0$ mode was measured at five temperatures and the results are presented in Table I. The third column compares the measurements with the frequencies which have recently been deduced[3,4] from the far infrared reflectivity.

The dispersion curve along [1, 0, 0] for this transverse optic branch at 90°K and 296°K is shown in Fig. 1. The scatter of the experimental points shows that the constant $\vec{Q}$ measurements and constant energy transfer measurements are in good agreement.

Table I. The frequency of the lowest transverse optic mode at $\vec{q}=0$ for five different temperatures.

Temperature (°K)	Frequency (10^{12} sec^{-1}) Neutron	Far infrared
90	1.23 ± 0.03	1.2[a]
142	1.72 ± 0.04	
203	2.24 ± 0.05	
296	2.73 ± 0.05	3.0[a] 2.63[b]
430	3.32 ± 0.07	

[a] See reference 3.
[b] See reference 4.

The temperature dependence of the dielectric constant ϵ is given by:

$$\epsilon \propto 1/(T - T_c),$$

where T_c is the Curie temperature. If only the lowest transverse optic mode is strongly temperature dependent then its frequency is given by[1]

$$\nu \propto (T - T_c)^{1/2}.$$

Figure 2 shows the good agreement obtained between this relation and the experimental measurements. A linear regression line through the five points give a Curie temperature of 32 ± 5°K. The other line on the figure shows the temperature dependence of the reciprocal of the dielectric constant,[5] which above 70°K predicts a Curie temperature of 28°K. The Curie temperature has also been deduced from measurements of the microwave losses by Rupprecht and Bell,[6] who obtain a temperature of 37°K.

I am grateful to a number of colleagues, especially Dr. B. N. Brockhouse and Dr. W. Cochran, for their help and encouragement, to the Titanium Division of the National Lead Company for providing the crystals, and to the Department of Scientific and Industrial Research for the award of a maintenance grant.

---

*Visitor from the Crystallographic Laboratory, Cavendish Laboratory, Cambridge, England.

[1] M. Cochran, Advances in Physics, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1960), Vol. 9, p. 387.

[2] B. N. Brockhouse, Inelastic Scattering of Neutrons in Solids and Liquids (International Atomic Energy Agency, Vienna, 1961).

[3] A. S. Barker and M. Tinkham, Phys. Rev. 125, 1527 (1962).

[4] W. G. Spitzer, R. C. Miller, and D. A. Kleinman, Bull. Am. Phys. Soc. 7, 280 (1962).

[5] T. Mitsui and W. B. Westphal, Phys. Rev. 124, 1354 (1961).

[6] R. O. Bell and G. Rupprecht, Phys. Rev. 125, 1915 (1962).

MAGNETIC ROTATION OF VISIBLE LIGHT BY FERROMAGNETIC $CrBr_3$

J. F. Dillon, Jr., H. Kamimura,* and J. P. Remeika
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received July 10, 1962)

Radiation passing through a magnetic crystal will interact with the magnetization to some degree. Rotation of plane-polarized light, magnetic birefrigence, and circular dichroism are manifestations of this interaction. This paper includes a description of exceedingly large rotations observed in visible light transmitted by ferromagnetic $CrBr_3$ single crystals as well as an outline of the theory of these rotations.

This material was found to be ferromagnetic only recently.[1] Its Curie point is at about 37°K, and its magnetization at 0°K is 3.0 μ_B/Cr^{+++} ($4\pi M_0 = 3520$ gauss). The crystals are of hexagonal symmetry, and the anisotropy is such that the magnetization prefers to lie along the sixfold axis.[1,2] The nuclear magnetic resonance of the Cr^{53} nucleus in this compound has been studied[3] as has the electron spin resonance[2] in the ferromagnetic and paramagnetic states.

The technique for growing the crystals was similar to that described by Tsubokawa.[1] Chromium tribromide has a layer structure in which hexagonal nets of chromium ions are covalently bonded[4] between two layers of bromine ions. Its poor mechanical properties make the preparation of good samples difficult. We used thin sheets from 4 to 40 μ thick whose surfaces were parallel to the hexagonal plane.

The upper curve in Fig. 1 shows the course of the absorption[5] at 4.2°K from the near infrared to a band edge in the green. It is necessary to make these observations with the crystals in a saturated condition. If this is not done