possible location of the hole demarcation level for the occurrence of superlinearity, infrared quenching, etc. It would still seem likely that the 0.89-ev transition must be attributed to a transition from a level near the top of the filled band to the defect levels; in this case the level from which the 0.89-ev transition is made would be located about 0.2–0.3 ev above the filled band. Figure 16(b) indicates the infrared quenching transitions involved in this model.

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Frequency Dependence of Magnetic Resonance in α-Fe₂O₃

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Magnetic resonance absorption in single crystals of natural α-Fe₂O₃ was examined in the wavelength range from 5.4 mm to 6.2 cm. Resonance fields H_r observed in the basal plane do not give a quadratic relation with the normal resonance field H_0 as predicted by the usual Kittel formula, but rather the following linear relationship: $h\nu/g\beta = H_0 = H_r + H_A$, where H_A is $4.2_5 K$ oe and g is 2.5_4.

1. INTRODUCTION

MAGNETIC resonance in single crystals of α-Fe₂O₃ has been observed at 1.25-cm wavelength by Anderson et al.[1] We refer to their paper as (A) in the following. They assumed the usual Kittel formula[2]:

$$H_0 = [H_r(H_A + H_r)]^{\frac{1}{2}}, \qquad (1)$$

where H_0 is the normal resonance field, H_r the observed resonance field in the basal plane, and H_A the anisotropy field in the direction of the ternary axis. Then, under the assumption $g=2$, they obtained the anisotropy field $H_A \simeq 30\,000$ oe. These resonance absorptions may be caused by the parasitic ferromagnetism of this crystal.

We have examined single crystals of natural α-Fe₂O₃ (α-hematite) by the usual method of magnetic resonance absorption at seven different wavelengths (from 5.4 mm to 6.23 cm). The resonances were observed at various orientations of static magnetic field and at room temperature except where the temperature is shown.
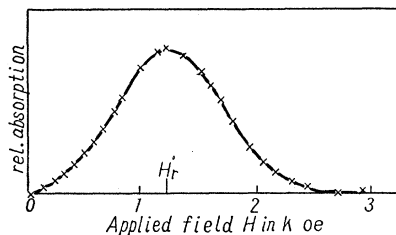
2. EXPERIMENTAL

The samples used were obtained from Sagashima, in the western part of Japan. The crystals have metallic luster and are disk-shaped with a diameter of about 10 mm and a thickness of 0.5–1 mm. They have (magnetically) hexagonal symmetry. The symmetry axis is perpendicular to the disk plane, so we call this the "basal plane." They easily cleave in this plane. Since the absorption is very strong and the nonmagnetic loss is fairly large, thin specimens of about 5-mm² area were used. At shorter wavelengths, specimens of only about 0.5-mm² area were used.

The method of measurement is almost the same as described elsewhere,[3,4] but in the present case it differs from the past descriptions in two respects. One is that the field modulation method was used to obtain line widths, though the direct galvanometer method was also used at some wavelengths. The other is that we omitted the procedure of tuning the sample cavity to cancel out the dispersion effect accompanied by reso-
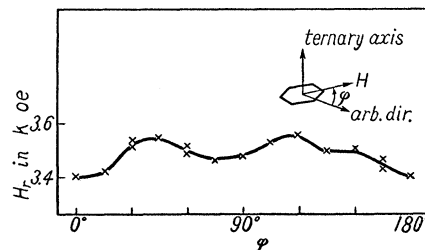

Fig. 1. Resonance absorption in α-Fe₂O₃ at λ = 15.3 mm and at room temperature. The static magnetic field is applied in the basal plane, i.e., perpendicular to the ternary axis.

Fig. 2. Variation of resonance field H_r in the basal plane. (λ = 11 mm.)

[1] Anderson, Merritt, Remeika, and Yager, Phys. Rev. 93, 717 (1954).
[2] C. Kittel, Phys. Rev. 73, 155 (1948).
[3] H. Kumagai et al., J. Phys. Soc. Japan 9, 369 (1954).
[4] H. Abe et al., J. Phys. Soc. Japan 9, 814 (1954).

nance. So the "width" in this article may be larger than the true width of the absorption line.

3. RESULTS AND DISCUSSIONS

When the static magnetic field is in any direction in the basal plane, a single peak is observed as shown in Fig. 1. When the static field is rotated in this plane, the resonance field varies slightly as in Fig. 2. We cannot clearly find the regular dependence with φ,

$$H_r = \text{const} + A \sin 6\varphi, \qquad (2)$$

as described in (A). Even if there existed this relation, A seems to be smaller than 70 oe in the case of both $\lambda = 11$ mm and 5.4 mm.

The observed line widths are slightly larger than those of (A), as shown in Table I. Since, however, in our present experiments we are not principally interested in the line width, some precautions are omitted which must be taken for the measurement of line width. So the difference in the observed widths in Table I has little physical meaning.

The observed resonance field H'_{res} in the plane containing the ternary axis is similar to that in (A). It satisfies approximately, at $\lambda = 6.5$ mm and 11 mm,

TABLE I. Observed line widths of resonance absorption in α-Fe$_2$O$_3$.

λ in mm	Observed width in oe	Reference
5.4	930	
11	1000	
12.5	600	(A)

a relation

$$H'_{\text{res}} = H_r / \sin\theta, \qquad (3)$$

as shown in Fig. 3, where θ is the angle between the ternary axis and the direction of the static field, and H_r is the resonance field in the basal plane. Equation (3) shows that the magnetization responsible for this resonance absorption is confined within the basal plane, which fact might be ascribed to an axial anisotropy field. This is compatible with Néel's hypothesis[5] given in explanation of the magnetostatic behavior of this crystal.[6]

At 3-cm wavelength, the resonance occurs at about zero field both when the static field is parallel to and when it is perpendicular to the ternary axis, and the absorption intensity is half its maximum (that at zero field) at 1100 oe and 340 oe respectively. The absorption coefficient in this case has a hysteresis relative to the applied static field. Even at $\lambda = 6.2_3$ cm, we can see a weak tail of absorption at zero field. The maximum absorption at this frequency is only about 0.5% of the incident power which is much weaker than that at shorter wavelengths.

[5] L. Néel, Revs. Modern Phys. **25**, 59 (1953).
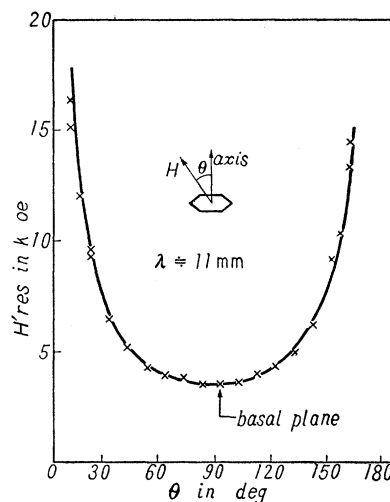[6] L. Néel and R. Pauthenet, Compt. rend. **234**, 2172 (1952).

FIG. 3. Variation of resonance field H'_{res}, when the static field is rotated in a plane containing the ternary axis.

To obtain the resonance field H_r in the basal plane, we choose the minimum of the resonance field as obtained in experiments such as those shown in Fig. 2, because errors in setting the specimen must bring about higher resonance fields as shown in Fig. 3.

Data on the resonance field thus obtained are listed in Table II. They are also plotted in Fig. 4 as a function of measuring frequency ν, in which the plotted circles are much larger than the range of observed values. In measurements at 3 and 6 cm wavelengths, the static magnetization of the sample may not be saturated, as the static magnetic field is low. At other shorter wavelengths, the static magnetization of the sample may be considered to be at saturation. When we omit the results at longer wavelengths where the static magnetization is not saturated, we obtain the following linear relation between the resonance field H_r and the normal one H_0,

$$H_0 = H_r + H_A, \qquad (4)$$

where

$$H_0 = h\nu / g\beta. \qquad (5)$$

Our experimental data are best fitted to the above relation (4) when we take the values $g = 2.5_4$ and $H_A = 4.2_5$ kilo-oersteds.

Since a strong anisotropy field really exists in the

TABLE II. Frequency dependence of resonance field H_r in the basal plane of α-Fe$_2$O$_3$ natural crystal.

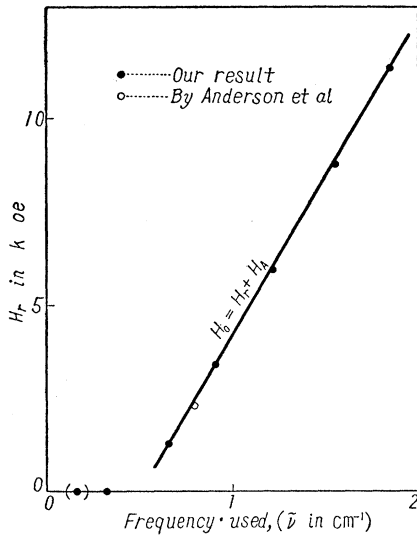| λ in cm^{-1}	H_r in oe
1.84	11 380±100
1.55	8800±100
1.21$_4$	5980±100
0.90$_6$	3400± 50
0.65$_3$	1300± 70
0.31$_8$	~0
0.16	⋯

FIG. 4. Frequency dependence of the resonance field H_r in the basal plane.

direction of the ternary axis, which can be deduced from the results shown by Eq. (3) at this temperature, Kittel's considerations on ferromagnetic resonance offer a quadratic relation, Eq. (1), between the observed resonance field H_r and the normal one H_0. In his results, a linear relation can be obtained only when the static field is applied in the axial direction of the anisotropy field in uniaxial crystals.

We have plotted, in Fig. 5, the value
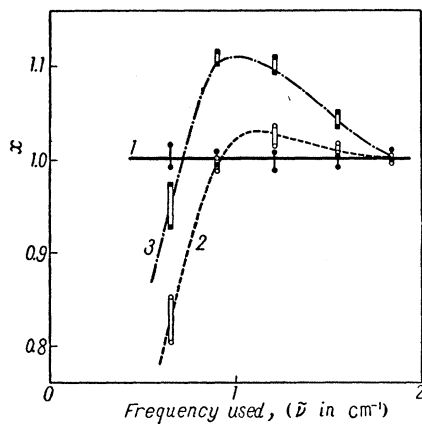
$$x = [H_r(H_A + H_r)]^{\frac{1}{2}}/H_0$$

FIG. 5. Quantity x normalized at the highest frequency, where x is defined as follows. Case (1): $x = (H_r + H_A)/H_0$ with $H_A = 4.2_5$ kilo-oersteds. Case (2): $x = [H_r(H_A + H_r)]^{\frac{1}{2}}/H_0$ with $H_A = 30$ kilo-oersteds. Case (3): $x = (H_r)^{\frac{1}{2}}/H_0$. The quantity x should be independent of $\bar{\nu}$.

in Eq. (1) as a function of ν; x should be a constant for a suitable value of H_A when Eq. (1) is valid. We cannot realize a constant value of x with any value of H_A. On the other hand, $x = (H_r + H_A)/H_0$ maintains a constant value for $H_A = 4.2_5$ kilo-oersteds. This shows that only the linear relation of Eq. (4) holds within experimental error.

The result in (A) can be fitted to our linear relation (4) as shown in Fig. 4.

When the sample is cooled the absorption intensity observed at $\lambda = 6.5$ mm does not change from room temperature to $-10°C$ and does not shift or broaden appreciably; but the absorption intensity observed at $\lambda = 3$ cm slowly decreases and goes down to zero at about $-50°C$ as shown in Fig. 6.

Our transition temperature is lower than that of the static susceptibility χ observed by Morin,[7] that of neutron diffraction observed by Corliss et al.,[8] and that of resonance absorption in a synthetic crystal observed by Anderson et al.[1] This difference may be due to an
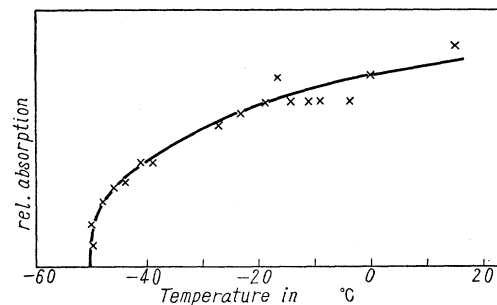

FIG. 6. Temperature dependence of absorption height with H in the basal plane at $\lambda \doteq 3$ cm.

impurity (e.g., TiO_2), but it cannot be considered to affect the essential features of the resonance, expressed by Eq. (4).

It is desirable to repeat the above experiments with synthetic crystals or natural ones from other sources, but, so far, they are not available to us.

4. ACKNOWLEDGMENTS

[7] R. J. Morin, Phys. Rev. 78, 819 (1950).
[8] Corliss, Hastings, and Goldman, Phys. Rev. 93, 893 (1954).