Ferromagnetism at Very High Frequencies

I-Magnetic Iron at 200 mc

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IT is possible to determine the complex permeability, $\mu_1 - i\mu_2$, of a magnetic metal by measuring the phase velocity and attenuation in a coaxial line whose center conductor is the metal under investigation. The fractional deviation of the phase velocity from the velocity of light in vacuum, β, which is of the order of 0.5 percent, as well as the attenuation, α, are essentially fixed by the permeability and conductivity of the metal. We have succeeded in *simultaneously* measuring β and α with sufficient precision to determine μ_1 and μ_2.[1]

Our experiments have been made at 200 mc in a half-wave coaxial resonator part of whose center conductor was the substance under examination.[2] The Q of the cavity and its resonant frequency[3] were measured as a function of a d.c. polarizing field, H_0, which was everywhere parallel to the high frequency magnetic field. In Fig. 1 we have plotted our experimental results for magnetic iron. The top curve is the ratio of Q at a polarizing field H_0 to $Q = Q_{\text{bias}}$ at a polarizing field of 6.25 oersteds which was continuously maintained throughout the measurements. The saturation limit, Q_∞/Q_{bias}, was found independently by measuring the cavity Q with a brass center conductor and making the proper correction for the difference in conductivity between brass and magnetic iron. The lower curve is the difference, δ, in resonant frequency for the cavity with a polarizing field H_0 and with a polarizing field of 6.25 oersteds. Here there is no independent way of fixing the saturation limit, δ_∞, which must be found by extrapolation. Hence, it is much less accurately determined ($\sim\pm 2$ percent) than the limit of the upper curve.

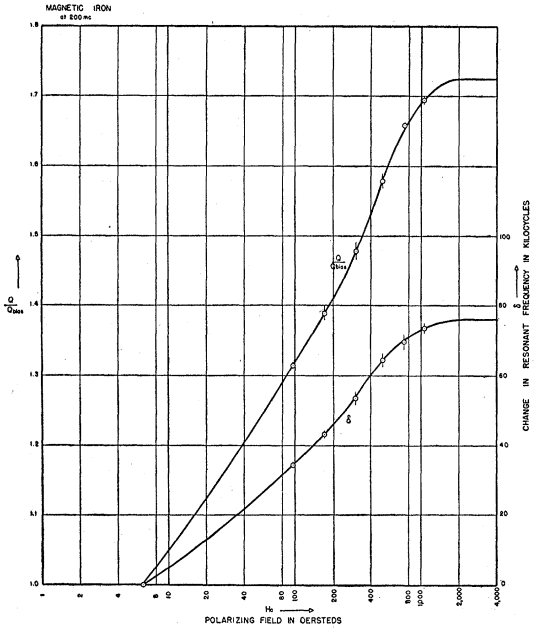

FIG. 1. Q ratio and change in resonant frequency as a function of the polarizing field H_0.

From the ratios Q/Q_{bias} and Q_∞/Q_{bias} and the geometry of the cavity, α can readily be calculated. Similarly, from δ and δ_∞, β can be calculated. With the known conductivity of iron, μ_1 and μ_2 can then be found. In Fig. 2 we have plotted μ_1 and μ_2 determined in this way from the curves of Fig. 1. The error in μ_1 is estimated as less than ± 5 percent. However, the values of μ_2 (which depend on $\alpha - \beta$) are considerably more uncertain. The error in μ_2 is estimated as less than ± 10 percent for small values of H_0 and as less than ± 50 percent at $H_0 = 500$ oersteds.

In Fig. 2 we have also plotted values of the incremental d.c. permeability[4] for a sample of magnetic iron cut from the same rod as the specimen used above. It will be noted that *the experimental values of μ_1 are in excellent agreement with the d.c. incremental permeabilities for $H_0 > 15$ oersteds.* Below 15 oersteds the d.c. permeability is larger than μ_1, the ratio reaching a value in excess of 3 at 2 oersteds. Values of μ_1 for $H_0 < 6.25$ oersteds, which are not shown in Fig. 2, depend very much on the cycle by which the state of magnetization is reached as well as on H_0 (hysteresis effects). However, our measurements show that μ_1 is always less than 60, so that μ_1 at $H_0 = 6.25$ oersteds is within 20 percent of its maximum value. The measurements also show that μ_2/μ_1 is always less than $\frac{1}{2}$.

These results can be interpreted by a modification in the standard description of magnetization: reversible and irreversible displacements of the boundary walls between domains below the "knee" of the magnetization curve and rotation of the domain spins toward the direction of the field above the knee. Our results show that $\mu_2/(\mu_1 - 1) \sim 0.15$ and that μ_1 is very nearly equal to the d.c. incremental permeability above the knee ($H_0 > 15$ oersteds). We conclude that *at* 200 mc *magnetization by rotation of the domain spins takes place with a relaxation time, τ, approximately equal to* 10^{-10} sec. ($\omega\tau \sim 0.15$). Our measurements indicate that τ does not change by more than 50 percent in the range $15 < H_0 < 500$ oersteds.

For small values of H_0 the incremental permeability is much larger than μ_1. Since $\mu_2/\mu_1 < 0.5$, the discrepancy

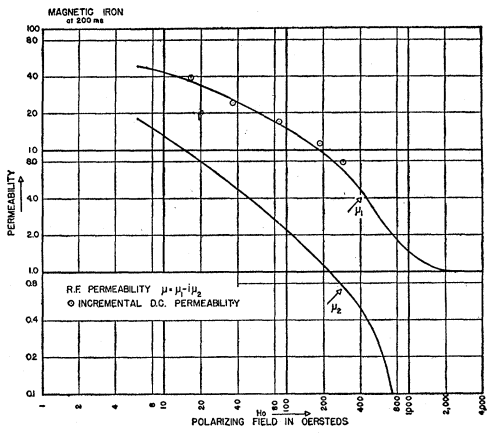

FIG. 2. Experimental permeabilities as a function of the polarizing field H_0.

cannot be explained by a longer relaxation time in these fields. (With $\mu_2=0.5\ \mu_1$ the maximum discrepancy could be 15 percent instead of the observed factor 3.) The small increase in μ_1 below 6.25 oersteds could be entirely due to magnetization by rotation of the spin directions. We therefore conclude that *at* 200 mc *magnetization by the displacement of domain boundary walls is greatly reduced and is almost wholly out of phase with the magnetizing field, and that magnetization by rotation is the dominant effect.*

This investigation is being extended to other materials and to other wave-lengths.

[1] Abstracts L4 and L5, Bull. Am. Phys. Soc., Jan. 30, 1947.
[2] We are indebted to Mr. R. A. Chegwidden of the Bell Telephone Laboratories for samples of several magnetic materials.
[3] In practice the frequency is held constant and the resonant wavelength of the cavity altered linearly by displacing a dielectric bead.
[4] We are much indebted to Mr. E. A. Gaugler of the Naval Ordnance Laboratory for the preliminary measurements of d.c. incremental permeability shown in Fig. 2.

A Defense of the Cauchy Relations

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EPSTEIN[1] has recently presented a theoretical analysis of the Cauchy relations between the coefficients of elasticity. From this analysis he concludes that the assumption of central forces does not necessarily lead to relations of the Cauchy type, and implies that the failure of the Cauchy relations in particular lattices has no theoretical significance. The purpose of the present letter is to point out that the Cauchy relations do follow when in addition to the assumption of central forces we assume that each atom is at a center of symmetry of the lattice. Since many metals and salts satisfy this symmetry condition, namely simple cubic, face centered cubic, and body centered cubic crystal structures, a failure of the Cauchy relation between their coefficients of elasticity is of theoretical significance, namely this failure implies that all the forces are not of the central type acting along lines joining lattice points.

The proof that the Cauchy relation follows from the above two assumptions has been given by Love.[2] An alternative proof is in fact furnished by Epstein's own analysis. Epstein shows that the correct relations are identical with the Cauchy relations save for the presence of certain expression of the type

$$v_{jk}=\Sigma_{\mu\nu}A_{\mu\nu}a_{\mu\nu j}a_{\mu\nu k},$$

where the symbols in the right member are defined in reference 1. The above expression may be written in the more familiar form

$$v_{jk}=\tfrac{1}{2}\Sigma_{\mu\nu}l_{\mu\nu}m_{\mu\nu}a_{\mu\nu}\phi'(a_{\mu\nu}),$$

where $l_{\mu\nu}$ and $m_{\mu\nu}$ are the direction cosines of the vector passing from the lattice point μ to the lattice point ν, referred to the j and k axes, respectively. Love[2] has given a very simple interpretation to this second expression for v_{jk} in the case of central forces when each atom is at a center of symmetry; namely, he has shown that aside from a multiplicative constant, v_{jk} is simply jk, the stress acting across a plane normal to the j axis in the direction of the k axis. Under these two conditions the Cauchy relations are therefore valid, provided the specimen is under no initial stress.

[1] Paul S. Epstein, Phys. Rev. **70**, 915 (1946).
[2] A. E. H. Love, *Mathematical Theory of Elasticity* (Cambridge University Press, 1906), second edition, p. 535.

The Upper Energy Limit of the K^{40} Beta-Ray Spectrum

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KONOPINSKI[1] has discussed the disintegration on K^{40} in terms of the selection rules, which are assumed to hold during the beta-decay. The nuclear transition involved is a highly forbidden one, and therefore interesting from the theoretical point of view. However, no decision could be made between the Gamow-Teller and Fermi selection rules because of the conflicting experimental values for the upper limit of the spectrum. For this reason it is felt that a fuller account of my measurements[2] of the upper limit may be of interest.

The measurements were made by the absorption method wherein the absorption of the K^{40} beta-rays in copper was compared with the absorption of radium E and uranium X_2 beta-rays under the same experimental conditions. Since the activity of potassium is very small, a large solid angle and a sensitive detector are required. A cylindrical Geiger-Müller counter of diameter 1.7 cm and length 5 cm of Dow-metal wall, of 0.0354 g/cm^2 was surrounded by a cylinder of KCl, of inner diameter 3.2 cm and 2.3 cm thick. In this arrangement the initial count, with only the counter walls absorbing, was 500 per minute. The absorption curve obtained by dropping copper tubes over the counter is shown in Fig. 1. After the beta-rays have been stopped at a range of 0.375 g/cm^2 of copper, there remains a constant background due to the gamma-radiation of energy 2.0×10^6 volts emitted[3] by potassium, with an intensity of 3 quanta per 100 disintegrating potassium atoms.

With the ordinary radioactive bodies, where the intensity is much greater, it is customary to use some empirical relation[4,5] to calculate the upper energy limit from the range or the absorption coefficient. Such a procedure is not permissible in the case of potassium because of the low initial activity, and the range 0.375 g/cm^2 must be corrected by comparison with other radioactive bodies where the energy distribution is known. The measurements were therefore repeated using identical sized sources of radium E and U_3O_8 mixed with NaCl as filler to make up the same mass per unit area as the KCl source. In each case the strength was adjusted so that the initial intensity was approximately the same as the KCl—i.e., 500 counts per minute. The radium E and uranium X_2 curves are included in Fig. 1. From these absorption curves the apparent ranges of the radium E and uranium X_2 beta-rays are 0.310 g/cm^2 and 0.865 g/cm^2, respectively. The correct ranges of the beta-rays from these bodies are very well known,[6–8] and are 0.475 g/cm^2 and 1.10 g/cm^2. It is apparent that the ranges measured with low intensity sources are too small, and the usual relations cannot be used to