TEMPERATURE DEPENDENCE OF THE INTERNAL FIELD IN FERROMAGNETS*

D. E. Nagle, H. Frauenfelder,† R. D. Taylor, D. R. F. Cochran, and B. T. Matthias‡
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received September 22, 1960)

The saturation magnetization of a ferromagnet varies with temperature in a characteristic and well-investigated manner; it reaches a limiting value at temperatures well below the Curie temperature T_C and vanishes at and above T_C. The behavior of the internal magnetic field, however, is much less well known. Because the theories of internal fields in ferromagnets are still far from satisfactory,[1] accurate and detailed measurements of these internal fields over a wide temperature range are important; the effects near the Curie point are particularly revealing. Preliminary work on such problems has been discussed by the Argonne group.[1] In the present Letter, we report a determination of the temperature variation of the internal magnetic field in Fe ($T_C = 1043°K$) and in a CoPd alloy ($T_C = 275°K$) by means of the Mössbauer effect.

That the Mössbauer effect is well suited for the investigation of internal fields no longer needs any justification.[1] The radioisotope Fe^{57} is very convenient for such experiments, since Fe itself is a ferromagnet and since the Mössbauer spectrum of its 14.4-kev gamma ray is well known.[2] The emission spectrum of an Fe source at room temperature consists of six lines, well separated by the Zeeman effect due to the internal magnetic field. With an Fe absorber of identical internal field, these lines give rise to a Mössbauer spectrum consisting of a prominent central absorption line and five strong satellites on either side, two of them doublets. The internal field has been deduced from the splitting of these lines.[2]

Complications arise when the source and the absorber have different internal fields. The six emission and six absorption lines of different spacing then give rise to as many as 36 lines; the Mössbauer spectrum becomes harder to find and harder to identify. There are three ways to circumvent this difficulty. One can employ a source having no effective internal field where the six emission lines are collapsed into one,[3] one can utilize a single line absorber,[4,5] or one can reduce the number of lines by selecting plane[2] or circularly[6] polarized gamma rays. The best method will depend on the particular problem. We have chosen the first approach for Fe and the third one, with selection of circularly polarized gamma rays, for CoPd.

A CoPd source was prepared by electroplating Co^{57} onto a CoPd alloy (92% Pd, 8% Co) and heating the CoPd foil in a vacuum furnace at 1000°C for two hours. The source was then placed in a cryostat which allowed the source temperature to be varied from 88°K to room temperature. The Mössbauer spectrum was observed with an Fe absorber, enriched to 75% Fe^{57} and of equivalent thickness 2.2 mg/cm^2. This absorber was mounted on a Jensen 8-inch Flexair woofer and moved sinusoidally at a frequency of 11 sec^{-1}. The output pulses from a scintillation counter were energy selected by a single-channel analyzer and modulated with a saw tooth voltage, which was locked in with the speaker drive. The modulated pulses were displayed on a 400-channel RIDL analyzer and thus yielded directly the desired Mössbauer spectrum,[4] as shown in Fig. 1. Due to the sinusoidal drive and linear display, the velocity scale in Fig. 1 is sinusoidal. The slight drop to the right in each spectrum is caused by dead-time effect in the 400-channel analyzer.

A series of measurements was taken in which the temperature of the CoPd source was varied and the temperature of the Fe absorber was 24°C.

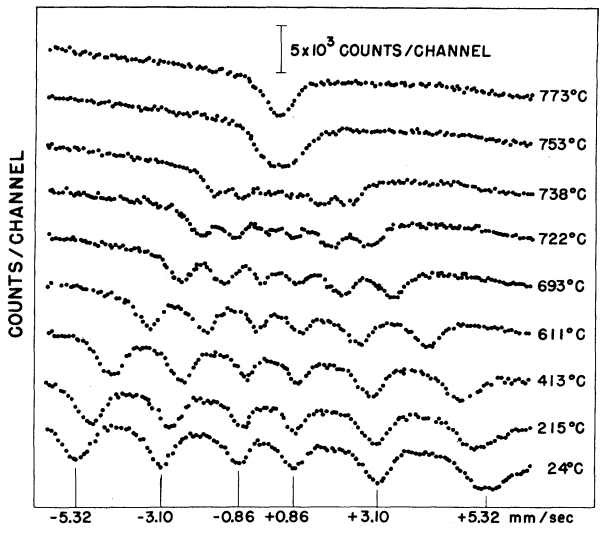

FIG. 1. Mössbauer spectra of a CoPd source at 24°C and an Fe absorber as functions of the absorber temperature. Positive velocity is taken to mean source moving away from absorber.

When the CoPd was above its Curie point of 275°K, the six-line spectrum was obtained, similar to the lowest curve of Fig. 1; such a spectrum is typical of a single-line source with an Fe absorber. Thus CoPd above its Curie point possesses only a very small effective magnetic field: From the position of the lines and from the line widths, an upper limit of 2000 oersteds is obtained. Below the Curie point, the splitting pattern changes rapidly, indicating the appearance of an internal magnetic field. At 88°K, astonishingly enough, the pattern is typical of source and absorber with identical fields. Hence at 88°K, the field at the Fe^{57} nucleus in CoPd is 3.3×10^5 oersteds,[2] the same as that of Fe^{57} in Fe at temperatures well below the Curie point. Details of these measurements will be published elsewhere.[7]

The single emission line of the CoPd source above its Curie point now offers a convenient tool for the investigation of the internal field in Fe. For this experiment, an absorber (5 mg/cm² Fe^{57}, 75% enriched) was placed in a furnace equipped with thin entrance and exit windows and containing an atmosphere of hydrogen. The CoPd source was mounted on the speaker and the transmission spectrum recorded as a function of the absorber temperature. Some typical spectra obtained in this way are shown in Fig. 1.

The curves in Fig. 1 show the decrease in the internal magnetic field, the temperature shift[8,9] of the center of the spectrum, the decrease in Mössbauer absorption due to the Debye-Waller factor, and finally the disappearance of the effective magnetic field in the Fe absorber at the Curie point.

The relative magnetic field at the Fe^{57} nucleus, as deduced from the curves in Fig. 1 and some additional data, is plotted in Fig. 2 as a function of T/T_C. For comparison, the relative saturation magnetization[10] is indicated by the solid line.

We thank Dr. R. M. Bozorth for determining the Curie point of our CoPd alloy, Dr. C. E. Olsen for the preparation of the CoPd alloy and the annealing of the source, and Dr. W. E. Keller for the loan of his DYNA amplifier. We are grateful to Dr. P. P. Craig and Dr. J. G. Dash for stimulating discussions and to Mr. R. Hanft for his tireless efforts during the experiment.

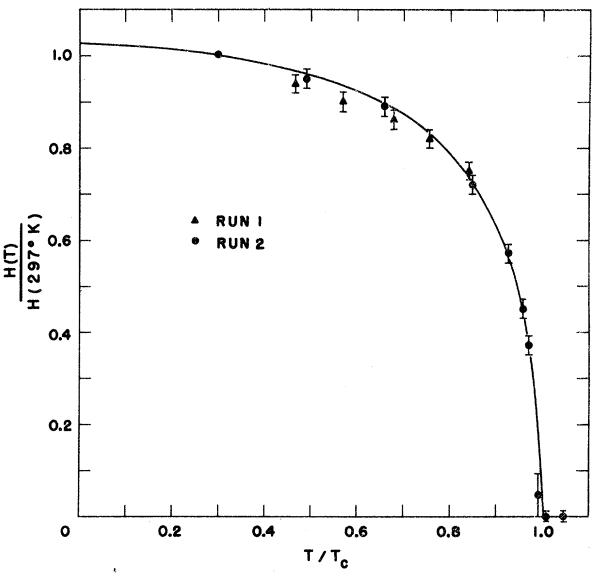

FIG. 2. Relative internal magnetic field $H(T)/H(297°K)$ at the Fe^{57} nuclei in an Fe absorber, as deduced by Mössbauer effect. The solid line indicates the relative saturation magnetization, $\sigma(T)/\sigma(297°K)$, of Fe.

*Work done under the auspices of the U. S. Atomic Energy Commission.

†Consultant, University of Illinois, Urbana, Illinois.

‡Consultant, Bell Telephone Laboratories, Murray Hill, New Jersey.

[1]Mössbauer Effect, Allerton House Conference, edited by H. Frauenfelder and H. Lustig (University of Illinois, Urbana, 1960).

[2]S. S. Hanna, J. Heberle, C. Littlejohn, G. J. Perlow, R. S. Preston, and D. H. Vincent, Phys. Rev. Letters 4, 177 (1960).

[3]O. C. Kistner and A. W. Sunyar, Phys. Rev. Letters 4, 412 (1960).

[4]S. L. Ruby, L. M. Epstein, and K. H. Sun, Rev. Sci. Instr. 31, 580 (1960).

[5]G. K. Wertheim, Phys. Rev. Letters 4, 403 (1960).

[6]H. Frauenfelder, D. E. Nagle, R. D. Taylor, D. R. F. Cochran, and W. M. Visscher (to be published).

[7]R. D. Taylor, D. E. Nagle, H. Frauenfelder, and D. R. F. Cochran (to be published).

[8]R. V. Pound and G. A. Rebka, Jr., Phys. Rev. Letters 4, 274 (1960).

[9]B. D. Josephson, Phys. Rev. Letters 4, 341 (1960).

[10]American Institute of Physics Handbook (McGraw-Hill Book Company, New York, 1957), p. 5-208.