caused by the presence of the electric fields. The focusing could still be observed at 100 ma arc current but did not appear as marked. In these experiments it is believed that the electrons are being focused by the traveling fields and the ions are contained in the potential well thus formed. With large structures and higher power it should be possible to focus both electrons and ions. At 1000 Mc/sec the ionization effects of the high-frequency effects were very strong and the plasma could be maintained without a dc discharge. No focusing was observed, but this may have been masked by the intense excitation.

From the experiment to date one cannot say for certain whether the focusing was due primarily to electric fields or primarily to magnetic fields. The slow wave structures were designed to concentrate the magnetic fields in the vicinity of the plasma but the observed excitation indicates that electric fields were also present. Other observations also seemed to indicate the presence of rather strong electric fields.

The circularly symmetric structures used confined the plasma in the transverse direction but not at the ends. A re-entrant plasma column (e.g., toroid or figure 8) may be focused using a re-entrant circuit excited to have only a traveling wave. Excitation may be achieved by the focusing field itself. In this and most other forms the circuit power may be recirculated supplying only the losses in the structure and the plasma.

The reader should note the analogy between the traveling waves discussed by Wuerker, Shelton, Langmuir and Goldenberg.[2]

The authors would like to acknowledge the interesting and helpful discussions they had with G. Kino (of Stanford University) on the general subject of plasma confinement. Dr. Kino and Dr. Chodorow were working on a quadrupole rf system at the time we conceived of our confinement scheme.

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OBSERVATION OF NUCLEAR RESONANCE IN A FERROMAGNET*

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We wish to report the first observation of nuclear resonance in a ferromagnet. A remarkably strong resonance was detected at room temperature in a sample of finely divided face-centered-cubic cobalt (Co^{59}) metal.[1] The resonance frequency was measured to be 213.1 Mc/sec in zero applied field. The observed frequency indicates a magnetic field of 213 400 oersteds at the site of the cobalt nuclei. This very sizable magnetic field arises from both core and conduction electron contributions as has been discussed by Marshall.[2]

The above results are in good agreement with the hyperfine field deduced from specific heat measurements on bulk hexagonal cobalt and cobalt alloys between 0.3 and 1.0°K.[3,4] The specific heat work indicates a nuclear field of 220 000 oersteds in hexagonal cobalt. This work also suggests that the hyperfine field in the cubic phase is about 10 000 oersteds lower than in the hexagonal phase. Only a minor temperature variation in the nuclear field is expected between 0°K and room temperature. Thus the resonance measurements and the specific heat measurements are in good agreement.

A tracing of the resonance line is shown in Fig. 1. The half width at half maximum absorption is 275 kc/sec. We believe that this line width is associated with a static broadening mechanism rather than with relaxation of the cobalt spins. In some respects the line appears to be inhomogeneously broadened. The observed line shape is that of an absorption curve rather than the sum of absorption and dispersion derivatives as is usually observed in metallic resonances. The very similar behavior of the F-center resonance in alkali halides has been established as an adiabatic rapid passage effect.[5] There are differences in detail however in the dependence of the resonance signal on modulation amplitude and frequency. The present signal is strictly proportional to the modulation amplitude over the range of frequencies investigated. At the higher modulation frequencies a decrease in amplitude and a phase shift develop. The amplitude and phase of the resonance signal as a func-

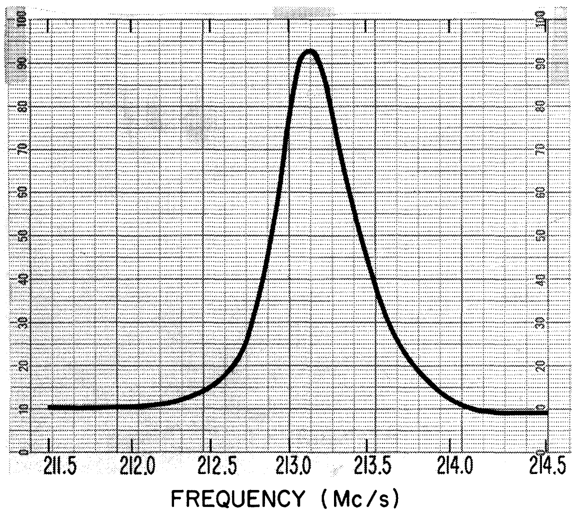

FIG. 1. Recorder tracing of nuclear resonance signal in finely divided fcc Co^{59} metal. The oscillator is frequency modulated at 1.2 kc/sec with an amplitude of 200 kc/sec.

tion of modulation frequency are shown in Fig. 2. The theoretical curves are for exponential relaxation with a relaxation time of 0.13 milliseconds. This time is somewhat shorter than the relaxation time expected from interaction with conduction electrons.[6] Still, the interaction of the nuclear spins with spin waves is expected to have an even smaller effect.[7] There exists the possibility that the observed relaxation time is associated with spin-spin interaction. A strong coupling of the cobalt nuclear spins through spin waves can be expected.[8]

We would next like to comment on the remarkable strength of the resonance. Ordinarily only a very small absorption might be expected from samples with line widths as large and radio-

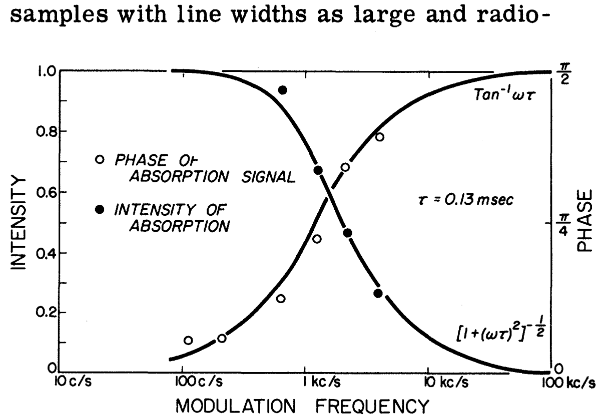

FIG. 2. Amplitude and phase of resonance absorption as a function of modulation frequency. The theoretical curves shown are for exponential relaxation.

frequency penetration as low as in cobalt metal. However, built into the ferromagnetic sample is a mechanism which increases the strength of the nuclear resonance absorption by four orders of magnitude. It is this mechanism which is responsible for the tremendously enhanced signal which we have observed. It can be seen that the resonance is excited predominantly by the hyperfine coupling itself rather than by the external rf field and this leads to the enhancement. Since the magnetization relaxes rapidly, it can be presumed to follow the rf field. A transverse field H_1 should produce an internal field $H_1/(1+N\chi)$ where N is the demagnetizing factor. We can then expect the magnetization to rotate through an angle $H_1/(1+N\chi)H_A$ where H_A is the anisotropy field. The rotation of the magnetization at the radio frequency should produce a transverse rf field of magnitude $[H_N/(1+N\chi)H_A]H_1$ where H_N is the hyperfine field at the cobalt nuclei. We estimate the factor $H_N/(1+N\chi)H_A$ to be of the order of 10^2. Then the resonance intensity which is proportional to this factor squared should be enhanced by some four orders of magnitude as observed. One would expect that this enhancement factor would decrease in a static magnetic field as shown in Fig. 3. For comparison we have also measured the field dependence of the transverse susceptibility of our sample. One would expect that at low fields both domain wall displacement and domain rotation would contribute to the transverse magnetization. At high

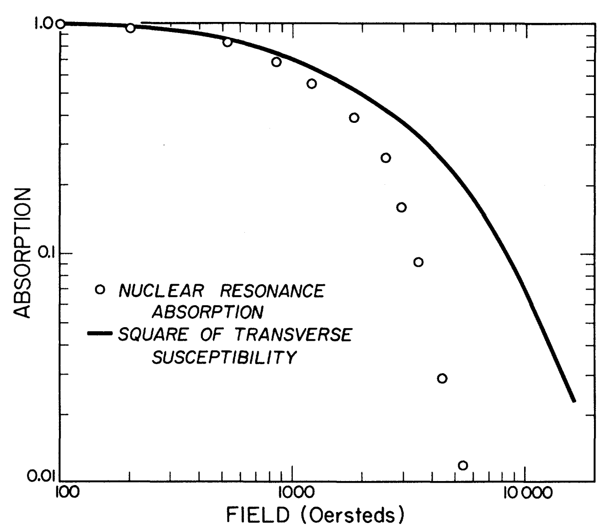

FIG. 3. Comparison between the strength of the absorption signal and the square of the transverse magnetic susceptibility as a function of static applied field.

fields only domain rotation should make an appreciable contribution. One can consider that the resonance signal measures the domain-rotation contribution to the magnetization. From the fact that the resonance signal drops off much more rapidly than does the square of the susceptibility we must conclude that domain wall processes play an important role out to the highest fields in which the resonance could be detected.

The resonance signal has been observed in static magnetic fields up to 5400 oersteds. Above 5400 oersteds the signal intensity drops below the noise level. Over this range of applied fields the resonance frequency holds constant to within 100 kc/sec. This is somewhat surprising since one might expect a field of 5400 oersteds to produce a frequency shift of some 5.4 Mc/sec. However the cobalt particles because of their high demagnetizing fields are still relatively permeable up to the highest fields at which the resonance could be observed. A plot of the sample magnetization obtained by integrating the apparent longitudinal susceptibility is shown in Fig. 4. At 5400 oersteds the magnetization is still only 70% saturated. We must conclude that variations in internal field are kept below a few hundred oersteds over the range of fields investigated.

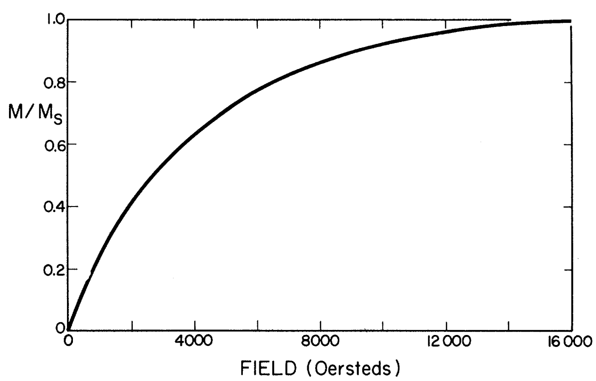

FIG. 4. Magnetization vs applied magnetic field for finely divided fcc cobalt as obtained from an integration of the longitudinal ac susceptibility.

The measurements reported in this Letter were made by placing the sample at the shorted end of a quarter-wavelength coaxial cavity. The cavity forms the resonant element of a 464A lighthouse-tube oscillator. Our spectrometer is very similar to a unit developed independently by Kojima et al.[9] The spectrometer is frequency-modulated by vibrating a small capacity across the high voltage end of the cavity. Modulation frequencies from a few cycles up to 10 kc/sec and modulation amplitudes up to 3 Mc/sec are possible with this design. Further studies both of the static and dynamic interaction between nuclear and electron spins in a ferromagnet are in progress.

We wish to acknowledge very helpful conversations with Dr. W. Marshall, Dr. P.-G. de Gennes, and Professor C. Kittel. Our very deep gratitude is due Dr. Nicholas Kurti who aroused our interest in this problem during his stay in Berkeley. We are indebted to Mr. Harry Robinson for advice on the construction of the spectrometer.

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[1]We are indebted to Dr. J. Crangle for making this sample available to us.

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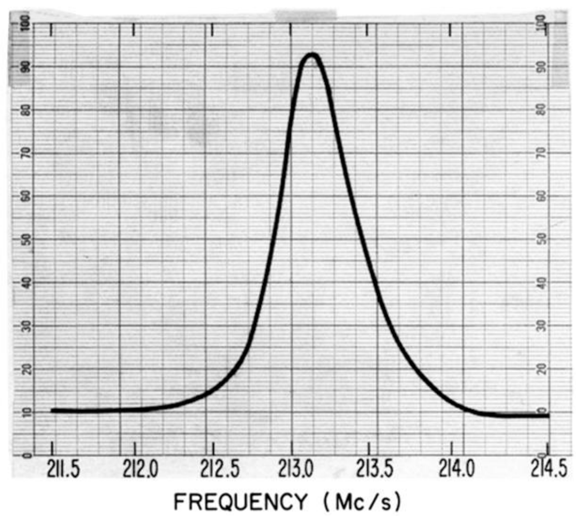

FIG. 1. Recorder tracing of nuclear resonance signal in finely divided fcc Co^{59} metal. The oscillator is frequency modulated at 1.2 kc/sec with an amplitude of 200 kc/sec.