The line shape therefore should consist of maxima corresponding to the transitions between Landau levels. The exciton line shape is also similar and is hence favorable for accurate determination of the various parameters. The exciton Zeeman pattern should give discrete resolvable lines for all crystal directions and allow the measurement of the anisotropic g factors. This pattern in the [110] plane will have three branches due to the spin alone.

The above transition should be extremely attractive for use in an optically excited cyclotron resonance maser since the fundamental excitation is in a very desirable range of the optical spectrum where pulsed line sources of the order of several watts or more are possible. Furthermore, this transition fulfills the necessary requirements for such a maser.[11] The direct transition permits selective excitation to discrete magnetic levels deep into the bands allowing population inversion of holes or electrons relative to Landau levels of lower quantum number. Due to the interaction of the spin-orbit split L_3, valence bands, these should have large change of curvature. This will permit unequally spaced magnetic levels so that selective transitions downward in energy between only two unique levels can be chosen by the resonant radiation in an interferometer tuned to this frequency. Thus the induced electric dipole cyclotron resonance transition will be emissive. From the values estimated in this paper for H along a [111] direction, with fields of the order of 4×10^4 gauss or larger which are available and desired for the interband transitions, the maser should be operable in the submillimeter or far infrared region at approximately 600 microns.

The author is grateful to Dr. Laura Roth for several suggestions and for checking the estimates of the effective-mass values. He has also benefitted from discussions with Professor G. F. Koster, Dr. H. J. Zeiger, and Dr. S. Zwerdling.

*Operated with support from the U. S. Army, Navy, and Air Force.

[1]L. M. Roth and B. Lax, Phys. Rev. Letters 3, 217 (1959).

[2]J. C. Phillips, J. Phys. Chem. Solids 12, 208 (1960)

[3]K. J. Button, L. M. Roth, W. H. Kleiner, S. Zwerdling, and B. Lax, Phys. Rev. Letters 2, 161 (1959).

[4]G. Feher, D. K. Wilson, and E. A. Gere, Phys. Rev. Letters 3, 25 (1959).

[5]H. R. Philipp and E. A. Taft, Phys. Rev. 113, 1002 (1959).

[6]L. M. Roth (to be published).

[7]M. Lampert, Phys. Rev. 97, 352 (1955).

[8]S. Zwerdling, B. Lax, L. M. Roth, and K. J. Button, Phys. Rev. 114, 80 (1959).

[9]R. J. Elliott, J. P. McLean, and G. G. Macfarlane, Proc. Phys. Soc. (London) 72, 553 (1958).

[10]L. M. Roth, B. Lax, and S. Zwerdling, Phys. Rev. 114, 90 (1959); B. Lax and S. Zwerdling, Progress in Semiconductors (to be published).

[11]B. Lax, Conference on Quantum Electronics-Resonance Phenomena (Columbia University Press, New York, 1960).

DIRECTION OF THE EFFECTIVE MAGNETIC FIELD AT THE NUCLEUS IN FERROMAGNETIC IRON†

S. S. Hanna, J. Heberle, G. J. Perlow, R. S. Preston, and D. H. Vincent
Argonne National Laboratory, Argonne, Illinois
(Received April 28, 1960)

In a recent experiment[1] it was shown that in ferromagnetic iron the effective magnetic field at the iron nucleus is strongly correlated with the magnetization. The sense of the correlation, however, was not determined, i.e., it was not known whether the effective field was parallel or antiparallel to the magnetization. The sense of the correlation has now been established by observing the change in the hyperfine splitting of the nuclear energy levels of Fe^{57} on application of an external field of 17 to 20 koe.

In an earlier paper[2] we presented the hyperfine spectrum obtained in the resonant Mössbauer[3] absorption in Fe^{57}. The interpretation given to the spectrum has since been confirmed in detail. Several groups have shown the correctness of the hyperfine pattern by observing the spectrum when different alloys and compounds of iron are used.[4] Gossard, Portis, and Sandle[5] have observed the nuclear magnetic resonance in the ground state of Fe^{57} at a frequency corresponding to a value of the effective field in close agreement with the value of 333 koe deduced in reference 2. In addition, Ewan, Graham, and Geiger[6] have

found that the $E2$ admixture in the $M1$ radiation is less than 10^{-4}, which confirms that the effect of $E2$ radiation in the spectrum is indeed negligible.[2]

Experimentally it was feasible to apply a large magnetic field only to the source of the resonant radiation. The absorber was either in the fringing field of the electromagnet holding the source or in a small parallel magnetic field of its own, applied to produce a definite magnetization in the absorber. At the top of Fig. 1 is shown the velocity spectrum which is applicable if the hyperfine splittings in source and absorber are identical. The intensities are appropriate to the emission of polarized radiation from the source but to an unpolarized absorption process. If, on the other hand, the hyperfine splittings in the emitter are about 10% greater (for example) than those in the absorber, then the complex spectrum at the bottom of Fig. 1 is obtained. It is clear that a study of the singlet line 6 affords the best means of determining the change that an external field produces in the hyperfine splitting.

For the effective field at the nucleus we write

$$\vec{H}_n = H_{n0}\vec{M}_0 + \vec{H}_{ext}, \qquad (1)$$

where $\vec{M}_0$ is a unit vector along the direction of magnetization in a ferromagnetic domain, and H_{n0} is the magnitude of the effective field in the absence of the external field $\vec{H}_{ext}$. The latter quantity includes the demagnetizing field which is negligible for the planar samples used. Since $H_{ext}/H_{n0} \ll 1$ in the present experiment, it is assumed in Eq. (1) that H_{n0} is not appreciably influenced by $\vec{H}_{ext}$. The quantity of interest is the sign of H_{n0}. Since $\vec{M}_0$ and $\vec{H}_{ext}$ are parallel under saturation conditions, the sign can be determined by observing whether the hyperfine splitting increases or decreases on application of a field. With a field of 17.6 koe a shift of $\pm 2.65\%$ is expected in line 6.

The experimental technique was similar to that in our earlier work.[1,2,7] The carriage of a lathe was used to provide velocities by means of which the spectrum was scanned. The source was mounted in the narrow gap of an electromagnet capable of producing fields up to 20 koe. The magnet was attached rigidly to the end of the lathe and the absorber was mounted on the carriage. The result obtained for line 6 is shown in Fig. 2. On application of the field to the source, a shift to lower energy is unmistakable. The correlation

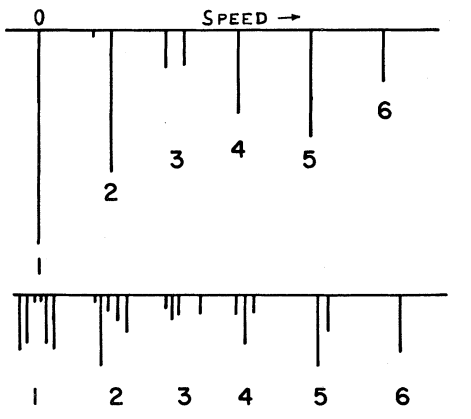

FIG. 1. Theoretical absorption spectra of 14.4-kev resonance radiation from Fe^{57}. Top: metallic source and absorber with identical hyperfine splittings. Bottom: same source and absorber but with the splitting in the source increased by 10%.

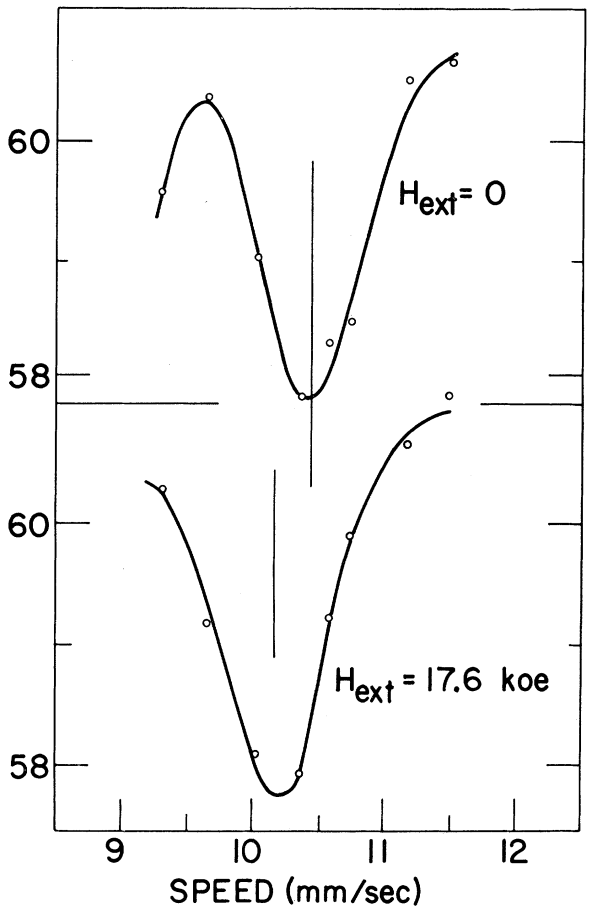

FIG. 2. Line 6 observed with $H_{ext} = 0$ and $H_{ext} = 17.6$ koe, where H_{ext} is the external field applied to the source of resonance radiation. The ordinate is in units of 10^3 counts.

is therefore negative. The magnitude of the observed shift is $(2.7 \pm 0.4)\%$ which is compatible with the linear relation $H_n = H_{n0} - H_{ext}$. A negative shift of about the correct magnitude was also observed in line 4. The multiplet structure in line 4 is symmetrical (Fig. 1) and so does not seriously interfere with the observation of a shift of its central member.

The effective field at the iron nucleus has now been determined both in sign and magnitude. The existence of such a large negative field (-333 koe) was unexpected. Marshall[8] has discussed a number of sources of the effective nuclear field. These consist mainly of direct effects of the $3d$ electrons and indirect effects of polarization of the various s electrons, which then contribute to the field via the Fermi contact interaction. The polarization of inner shells of electrons results in negative contributions to the field. In view of the experimental result these negative terms must completely dominate the other contributions.

We are grateful to S. Raboy for loan of the magnet. We wish also to thank M. R. Perlow for preparation of the source; F. J. Karasek for continuing to supply us with thin rolled iron foils; and E. Kowalski for assistance in taking the data. We have profited from a stimulating discussion with W. Marshall.

†This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1]G. J. Perlow, S. S. Hanna, M. Hamermesh, C. Littlejohn, D. H. Vincent, R. S. Preston, and J. Heberle, Phys. Rev. Letters 4, 74 (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]R. L. Mössbauer, Z. Physik 151, 124 (1958).

[4](Ferrocyanide) S. L. Ruby, L. M. Epstein, and K. H. Sun (to be published); (ferrocyanide, stainless steel) G. K. Wertheim, Phys. Rev. Letters 4, 403 (1960); (Fe_2O_3) O. C. Kistner and A. W. Sunyar, Phys. Rev. Letters 4, 412 (1960).

[5]A. C. Gossard, A. M. Portis, and W. J. Sandle (to be published).

[6]G. T. Ewan, R. L. Graham, and J. S. Geiger (to be published).

[7]S. S. Hanna, J. Heberle, C. Littlejohn, G. J. Perlow, R. S. Preston, and D. H. Vincent, Phys. Rev. Letters 4, 28 (1960).

[8]W. Marshall, Phys. Rev. 110, 1280 (1958), and private communication.

RESONANCES IN C^{12} ON CARBON REACTIONS

E. Almqvist, D. A. Bromley, and J. A. Kuehner
Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, Ontario, Canada
(Received March 28, 1960)

The reaction yield from C^{12} on carbon in the laboratory energy range 9-29 Mev has been investigated using C^{12} beams of precisely defined energy from the Chalk River tandem accelerator. The measured excitation curves for all reaction products studied reveal unexpected, sharp, isolated resonances at incident energies just below the Coulomb barrier corresponding to excitations in $Mg^{24} \approx 20$ Mev. At higher energies where strong interference structure was previously observed in the elastic scattering,[1] the reaction resonance structure is considerably less marked. In contrast to these results for the $C^{12} + C$ system, similar measurements for O^{16} ions on oxygen targets show no such resonant behavior; in this case the incident energy required to reach the top of the Coulomb barrier is somewhat higher and corresponds to 27-Mev excitation in S^{32}. It is noted that both reactions are restricted to only those states allowed to a system of two identical spin-zero Bosons.

The various excitation curves for C^{12} on carbon in Fig. 1 show marked similarity; particularly for incident energies below 6.5 Mev (center-of-mass system), sharp resonances appear in all curves at energies of 5.68 Mev, 6.00 Mev, and 6.32 Mev. The observed widths of these peaks are equal to the energy loss in the 40-$\mu g/cm^2$ carbon targets. This amounts to 100 kev in the c.m. system; consequently, in each case the true resonance width is almost certainly less than this. Additional measurements not shown in the figures on alpha particles detected[2] at 27° and 62° and protons detected[2] at 62° in the laboratory and on all gamma radiation of energy greater than 2.8 Mev also show these same sharp resonances below the Coulomb barrier. The fact that these resonance peaks appear at the identical incident energies for all reaction products independently of the angle of observation