actions and subsequent high migration rates[20,3] in concentrated systems suggests that the processes are of the type described by Dexter.[21] The present experiments cannot distinguish this from the process whereby spontaneous emission is absorbed by ions in excited states. Experiments are planned to study this and other aspects of the effect.

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[1]V. V. Ovsyankin and P. P. Feofilov, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 3, 494 (1966), and 4, 471 (1966) [translations: JETP Letters 3, 322 (1966), and 4, 317 (1966)]; P. P. Feofilov and V. V. Ovsyankin, Appl. Opt. 6, 1828 (1967).

[2]M. R. Brown and W. A. Shand, Phys. Letters 18, 95 (1965); R. J. Woodward, J. M. Williams, and M. R. Brown, Phys. Letters 22, 435 (1966).

[3]William B. Gandrud, Technical Report, U. S. Army Research Office Contract No. DA-31-124-ARO-D-339 (1968); William B. Gandrud and H. W. Moos, to be published.

[4]N. A. Tolstoi and A. P. Abramov, Opt. i Spektroskopiya 20, 496 (1966), and 22, 501 (1967) [translations: Opt. Spectry. (USSR) 20, 273 (1966), and 22, 272 (1967), and Fiz. Tverd. Tela 9, 340 (1967) [translation: Soviet Phys.—Solid State 9, 255 (1967)].

[5]R. G. Kepler, J. C. Caris, P. Avakian, and E. Abramson, Phys. Rev. Letters 10, 400 (1963).

[6]M. Silver, D. Olness, M. Swicord, and R. C. Jarnagin, Phys. Rev. Letters 10, 12 (1963).

[7]Joseph Murphy and F. M. Ryan, Bull. Am. Phys. Soc. 13, 415 (1968).

[8]S. Singh and J. E. Geusic, in Optical Properties of Ions in Crystals, edited by H. M. Crosswhite and H. W. Moos (Interscience Publishers, Inc., New York, 1966), p. 493.

[9]E. H. Carlson and G. H. Dieke, J. Chem. Phys. 34, 1602 (1961).

[10]F. Varsanyi and G. H. Dieke, J. Chem. Phys. 33, 1616 (1960).

[11]G. A. Prinz, dissertation, Johns Hopkins University, 1966 (unpublished).

[12]Energies for $NdCl_3$ levels when not avaiable in Ref. 11 were extrapolated from the low-concentration data of Ref. 9 on the basis of a systematic shift of the optical levels by 0.08% to lower energies.

[13]W. D. Partlow and H. W. Moos, Phys. Rev. 157, 252 (1967).

[14]C. K. Asawa and M. Robinson, Phys. Rev. 141, 251 (1966).

[15]G. E. Barasch and G. H. Dieke, J. Chem. Phys. 43, 988 (1965).

[16]The lifetimes of R and W in these measurements are in fair agreement with previous measurements given in Refs. 3, 13, and 14, although those measured here are consistently shorter. Gandrud and Moos have shown that migration to trace impurities strongly affects the lifetimes of rare-earth infrared states and leads to variation from sample to sample. Barasch and Dieke have attributed other such variations to resonance radiation trapping.

[17]It is difficult to rule out the presence of faster decay components at early times since a small amount of scattered pump light reaches the detector. If present, however, the intensity of these components is never greater than 10% of the main component.

[18]L. A. Riseberg and H. W. Moos, Phys. Rev. Letters 19, 1423 (1967).

[19]E. Cohen and H. W. Moos, Phys. Rev. 161, 258 (1967).

[20]L. G. Van Uitert, E. F. Dearborn, and J. J. Rubin, J. Chem. Phys. 45, 1578 (1966).

[21]D. L. Dexter, Phys. Rev. 126, 1962 (1962).

rf-INDUCED SIDEBANDS IN MÖSSBAUER SPECTRA*

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We report the first clear evidence that rf magnetic fields generate acoustical sidebands in the Mössbauer spectra of metallic Fe^{57}. We advance an explanation of this magnetoacoustic effect in terms of magnetostriction, and suggest that this effect provides a consistent explanation of the results of several earlier workers who observed rf resonance effects seemingly associated with hyperfine transitions.

Additional distinct lines in the Mössbauer absorption of metallic Fe^{57} have been generated by subjecting the iron absorber foil to an rf magnetic field. These additional lines are interpreted as acoustically modulated sidebands arising from magnetostrictive effects within the iron. It should be emphasized that the present experiments do not involve an absorber fastened to a piezoelectric oscillator, but deal with internal vibrations in the absorber itself.

The influence of rf magnetic fields on Mössbauer spectra was first investigated by Perlow,[1] who observed a change in recoilless absorption at 25.98 MHz, the hyperfine resonant frequency of the 14.4-keV level of metallic Fe^{57}. Recently Matthias[2] obtained similar results and noted a change in recoilless absorption at 45.44 MHz, the ground-state hyperfine resonant frequency. In each of these experiments a split source was rigidly attached to a split absorber, and various combinations of rf and static fields were applied to this source-absorber sandwich. The 14.4-keV gamma rays emitted from the source through the absorber were detected as a function of the frequency of the applied field. In both experiments the application of the rf field produced large changes in the count rate, even at nonresonant frequencies. These effects could not be satisfactorily explained at the time, although both authors have since suggested that magnetostrictive effects in the iron might be responsible.

Each author attempted to verify this hypothesis. Matthias[2] observed no sideband effect in a velocity spectrum taken with a single-line source and an unpolarized split absorber subjected to a 14.9-MHz field of about 4 G. Perlow[3] performed a similar experiment with a split source and a single-line absorber, using rf fields of 4.2 and 6.5 MHz. He obtained a general washing out of the Mössbauer pattern, which he attributed to the random flipping of the hyperfine field due to domain wall motion.

The present Letter provides for the first time clear evidence that rf magnetic fields generate acoustical sidebands in iron. In addition, we believe that the sideband effects reported here provide a consistent explanation for the changes in count rate seen in the split-split experiments referred to above. The generation of sidebands spreads the recoilless gamma rays among many more lines, and this reduces the effective Mössbauer absorption. At the resonant frequency, however, the sidebands overlap the normal Mössbauer lines, resulting in a partial restoration of the absorption. We suggest that this restoration due to sideband overlap is responsible for the resonance effects seen by Matthias. We also suggest, as a general caution, that this magnetoacoustic effect should be considered in any experiment involving radiation emanating from a ferromagnetic sample subjected to rf fields.

Unless otherwise stated, all of our experiments were performed in standard transmission geometry. A 30-mCi Co^{57} source in a Cr matrix was attached to a Mössbauer transducer; an enriched Fe^{57} foil (thickness $= 2.4\times10^{-4}$ cm) was placed normal to the well-collimated gamma beam. An rf magnetic field in the plane of the foil was obtained by wrapping an eight-turn, flattened, rectangular coil about the iron. To provide cooling the foil was attached to a glass slide and mounted in a Lucite chamber in such a way as to allow flowing water to cool both the absorber and coil. A screened cage enclosed the transducer and associated electronics, and great care was taken to insure that rf interference did not lead to spurious results.

The results are presented graphically in Figs. 1 and 2. Figure 1 shows transmission spectra taken at various field strengths with an rf field of 13.0 MHz. Figure 2 shows the transmission spectra as a function of frequency. For these data the field strength was held constant at approximately 10 G. The solid lines in both figures are least-squares fits to data obtained using the following simplifying assumptions: (1) All lines are Lorentzian; (2) the standard Mössbauer lines are reduced in size by the rf field; and (3) each of the six Mössbauer lines has a number of symmetric pairs of sidebands located relative to the main line at velocity positions corresponding to integral multiples of the applied frequency, that

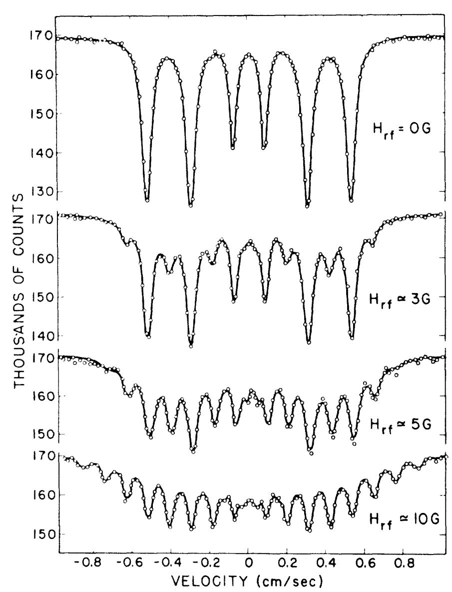

FIG. 1. The effect of a 13-MHz magnetic field on a metallic Fe^{57} Mössbauer absorber as a function of field strength. The solid line is a theoretical curve generated on the basis of FM theory. The modulation index m for each curve is, from top to bottom, $m=0$, $m=0.75$, $m=1.13$, and $m=1.4$. The error bars for the data points are approximately the size of the open circles. The error bar associated with the magnitude of H_{rf} is about ±25%.

is,

$$\pm n\nu \frac{2.245 \text{ mm/sec}}{25.98 \text{ MHz}}.$$

Standard FM theory shows that a carrier frequency ω_0 modulated sinusoidally at a frequency ω gives rise to a spectrum consisting of the original carrier and an infinite set of sidebands. These sidebands are located at $\omega_0 \pm n\omega$, and their relative amplitudes are given by $I_n^2(m)$, where J_n is the nth Bessel function and m is the modulation index. Modulation effects of this type have been seen before in Mössbauer experiments. Ruby and Bolef[4] obtained sidebands by using a piezoelectric quartz crystal to vibrate an unsplit Co^{57} source mechanically in a sinusoidal manner. This method was also used in the more recent work of Cranshaw and Reivari.[5]

The rf magnetically induced sidebands reported here also seem to be describable in standard FM terms. We point out, for example, that the sidebands occur precisely where FM theory predicts. The overlapping of sidebands from the several hyperfine lines in the spectrum makes it somewhat difficult to decide whether the sideband amplitudes are given by $J_n^2(m)$ with a single m, or whether a distribution of m's should be used. A very satisfactory fit to the data can be obtained with a single m as is indicated in the figures.

To further investigate this phenomenon the following additional experiments were performed: (a) The absorber and coil were rotated so that $\vec{H}_{rf}$ was oriented 45 deg to the gamma beam. This resulted in a significant increase in the sideband effect. (b) The experiment was performed with a natural-iron powder absorber (30 mg/cm^2) in place of the iron foil. Particle diameters were less than 10^{-3} cm. No sidebands were observed. (c) The experiment was performed with a natural Fe_2O_3 powder absorber (30 mg/cm^2) in place of the foil. Particle diameters were less than 10^{-3} cm. No sidebands were observed. (d) The experiment was performed with a 310 stainless-steel foil (thickness $= 3.6 \times 10^{-4}$ cm) in place of the iron foil. No sidebands were observed. (e) An experiment in 90° scattering geometry was performed, using a large sample of Fe_2O_3 in hematite form (4.0 cm $\times$ 0.3 cm). A strong sideband effect was observed with an rf field of only 1.5 G.

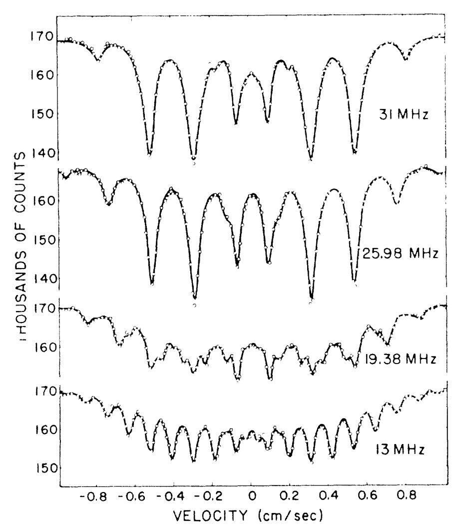

FIG. 2. The effect of a 10-G rf magnetic field on a metallic Fe^{57} Mössbauer absorber as a function of frequency. Once again the solid line is the theoretical FM fit. The modulation index m from the top to bottom is $m = 0.75$, $m = 1.01$, $m = 1.30$, and $m = 1.4$.

The powder experiments (b) and (c) strengthened our belief in the acoustic nature of the effect, as the sidebands disappeared when the particle sizes in the absorber were smaller than the wavelength of the acoustic vibrations at the applied frequency. The stainless-steel experiment (d) shows that the effect is not simply the result of the bulk nature of the material, but also depends strongly on its magnetic properties. Finally, experiment (e) which was done in scattering geometry shows that the internal acoustic vibrations couple to the Fe^{57} nuclei in gamma-ray emission as well as in absorption.

These initial experiments are consistent with the interpretation that internal acoustic vibrations are generated in the sample by bulk magnetostriction or by motion of the domain walls in response to the rf magnetic field. An effort is underway to clarify the details of these mechanisms through further experimentation involving static fields, orientation of the foil, magnetic ordering, and particle size. Unfortunately, theories of domain wall motion do not readily provide any quantitative predictions with which to compare our present data. Certain quantitative predictions can be made in the case of bulk magnetostriction, however, using a simple model.

One expects[5] that the modulation index $m = (\omega_0/c)A$, where A is the amplitude of vibration. The relation between m and the magnetostrictive constant Λ can be made through the approximate formula[6] for bulk magnetostriction in a polycrystalline sample:

$$\delta l/l = \tfrac{3}{2}\Lambda(\cos^2\theta - \tfrac{1}{3}),$$

where $\cos\theta$ is the ratio of the actual bulk magnetization to the saturation value, i.e., $\cos\theta = M/M_s$. Combining these equations and assuming that M is made up of a component of permanent magnetization M_0 and a component of magnetization induced by the rf field M_{rf}, one obtains

$$m = \frac{3}{2}\frac{\omega_0}{c}\Lambda l\left(\frac{2M_0M_{rf}+M_{rf}^2}{M_s^2}\right).$$

Using $l = 1.2\times10^{-4}$ cm (i.e., the half-thickness of the foil), $\Lambda = 2\times10^{-5}$, and reasonable values for M_0 and M_{rf}, we can obtain values for the modulation indices which are in good agreement with our data.

On the basis of ideal magnetostriction, one would expect the sidebands to occur at $\pm 2n\omega$, since the sample contracts regardless of the sense of the magnetic field. This difficulty is resolved by inserting the time dependence in the above equation and assuming that $M_0 \gg M_{rf}$. Then

$$m = \frac{3}{2}\frac{\omega_0}{c}\frac{\Lambda l}{M_s^2}[2M_0M_{rf}e^{i\omega t} + M_{rf}^2e^{i2\omega t}].$$

The dominating term leads to sidebands at $\pm n\omega$, with the last term contributing only slightly to even numbered sidebands. The metallic iron foil in our experiment was strongly magnetized, as may be deduced from the relative intensities of the lines in the calibration spectrum. Thus the assumption that $M_0 \gg M_{rf}$ is reasonable considering the small values of H_{rf} used. It appears, therefore, that the sidebands observed may be understood on the basis of this simple magnetostriction model.

Finally, it should be remarked that the Mössbauer technique clearly provides a sensitive new method for studying magnetoelastic effects.

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[1]G. J. Perlow, University of Illinois Report No. ASOSR 60-698, 1960 (unpublished).

[2]E. Matthias, in Hyperfine Interactions and Nuclear Radiation edited by E. Matthias and D. A. Shirley (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968).

[3]G. J. Perlow, "Influence of Radiofrequency Magnetic Fields on the Mössbauer Effect in Magnetic Co^{57} Sources" (to be published).

[4]S. L. Ruby and D. I. Bolef, Phys. Rev. Letters 5, 5 (1960).

[5]T. E. Cranshaw and P. Reivari, Proc. Phys. Soc. (London) 90, 1059 (1967).

[6]See, for example, A. H. Morrish, Physical Principles of Magnetism (John Wiley & Sons, Inc., New York, 1965), p. 325.

OPTICAL CONSTANTS OF SODIUM AND POTASSIUM FROM 0.5 TO 4.0 eV*

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Ellipsometric experiments have been performed on thick evaporated films of Na and K both by single reflection at free surfaces and by multiple reflection at metal-fused silica interfaces. The results are in qualitative agreement with the nearly-free-electron model, exhibiting no anomalous peaks and showing interband transitions with thresholds at the expected frequencies. The values deduced for the optical masses are 1.14m for Na and 1.17m for K.

New measurements have been made of the optical constants of Na and K as part of a larger project to investigate the optical and photoemission properties of the alkali metals. We believe that these first results will be of immediate interest since they do not show the anomalous effects reported by Mayer and coworkers.[1,2] The results are in fair accord with the predictions of the nearly-free-electron model.

Apart from the obvious problems associated with the preparation of uncontaminated surfaces, the alkali metals present the following additional experimental difficulty. The ellipsometric method, usually regarded as the most sensitive, consists of determining ρ and Δ at some large angle of incidence φ; $\rho\exp(i\Delta)$ is defined as the ratio of the amplitude reflection coefficients for the components of polarization parallel and perpen-