current density vs electric field for two large values of strain; the current sensitivity has been adjusted to compensate for the activation energy change (~20%). There is overlap of the two curves for a considerable range of electric field where the nonlinearity in conductivity is due to the velocity dependence of the recombination coefficient σ.[12] It is seen that σ varies by a factor of 3.5 over this range. The (velocity-dependent) recombination cross section is expected to be dependent, not on the acceptor ground-state energy, but rather on a continuum of states ~kT above the valence band edge,[1] which depends in this case on the parameters of the upper band. This expectation is here confirmed experimentally, and is additional strong confirmation that the cascade recombination mechanism of Lax is operative.

We are indebted to Rodney Brown for computational assistance and to Peter J. Price for discussions.

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POLARIZATION OF THE CONDUCTION ELECTRONS IN THE FERROMAGNETIC METALS*

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(Received November 15, 1960)

It has recently been proposed[1] that the polarization of the $4s$ conduction electrons in Fe, Co, and Ni is antiparallel to that of the electrons in the unfilled $3d$ shell; this is the reverse of the usual assumption. There are few ways in which this polarization is manifested. One, however, is in the effective magnetic field at a nucleus, which acts through the contact interaction with the $4s$ electrons. The magnitude of this field has been given by Marshall[2] as

$$H_c = (8\pi/3)\xi_s |\psi(0)|_A^2 \mu n p, \tag{1}$$

where μ is the Bohr magneton, $\xi_s |\psi(0)|_A^2$ is the average probability density of a $4s$ conduction electron evaluated at the nucleus [$|\psi(0)|_A^2$ being the free atom value], n is the number of conduction electrons per atom, and p is their polarization. The sign of the field is positive, i.e., parallel to the direction of magnetization, if the polarization of the $4s$ electrons is parallel to the $3d$ polarization.

Hanna *et al.*[3,4] have measured the magnitude and sign of the field at the Fe nucleus in iron by observing the Zeeman splitting of the 14-kev transition in Fe^{57} and obtain the value -3×10^5 koe. In this case, however, there are other contributions to the field beside H_c; mainly those due to the electrons of the same atom, i.e., the polarized $3d$ electrons. These other contributions almost certainly outweigh the effect of the field H_c alone (H_c is probably of the order of 50 to 100 koe), and it is therefore difficult to draw any conclusion concerning its sign.

In an attempt to measure H_c directly, dilute (1%) solid solutions of Sn in the ferromagnetic metals (Fe, Co, and Ni) have been prepared. Since Sn is basically diamagnetic, we expect that there will be no contribution to the field at the Sn nucleus from its own inner electrons and that the field will be given simply by

$$H_s = (4\pi/3)M + H_c, \tag{2}$$

where $|\psi(0)|_A^2$ in (1) is the appropriate value for a Sn atom. Since H_c is due to an over-all polarization of the conduction electrons, the other terms should remain those appropriate to the solvent atoms.[5]

The Zeeman splitting of the 24-kev transition in Sn^{119} was observed[6] using the Mössbauer effect.[7,8] The transmission through the absorber (the alloy) of the radiation emitted by a moving source was measured as a function of the velocity of the source. The velocity spectrometer has been described in detail elsewhere.[9] The temperature of both the source and absorber were maintained around 100°K. Figures 1, 2, and 3 show the transmission spectra obtained for Fe and Ni and Co. Each member of the doublet is an unresolved triplet caused by the splitting of the excited $\frac{3}{2}^+$ state, while the doublet separation is due mainly to the splitting of the ground $\frac{1}{2}^+$ state. The field strengths H_s listed in Table I were derived using the known values of the magnetic moments. (The excited state moment has been measured as 0.83 ± 0.03 nuclear magneton.[9])

The shifts listed in the table refer to the displacement of the spectra towards negative velocity and are almost entirely due to the chemical shift.[10] In this case, where the source was metallic tin, the magnitude of the shift should be proportional to $(\xi_s - \xi_{\mathrm{Sn}})|\psi(0)|_{\mathrm{Sn}}^2$; ξ_{Sn} and ξ_s refer to metallic tin and the solvent metal, respectively.

The sign of H_s was determined by placing each absorber in a transverse magnetic field of about 7 koe; the magnetization direction is now parallel to the external field. A positive field was observed only in the case of Ni. The final values

Table I. Results derived from the velocity spectra of the absorption of 24-kev γ rays from Sn^{119m} in absorbers containing 1% of Sn^{119} dissolved in Fe, Co, and Ni. The shift is the displacement of the spectra towards negative velocity due to chemical effects, H_s is the field at the Sn nucleus, and $(4\pi/3)M$ is the usual Lorentz field.

Solvent	Shift (mm/sec)	H_s (koe)	$(4\pi/3)M$	$H_s - (4\pi/3)M$
Fe	1.1	-81 ± 4	7.5	-88
Co	1.1	-20.5 ± 1.5	6.1	-26.5 ± 1.5
Ni	1.1	$+18.5 \pm 1$	2.0	$+16.5 \pm 1$

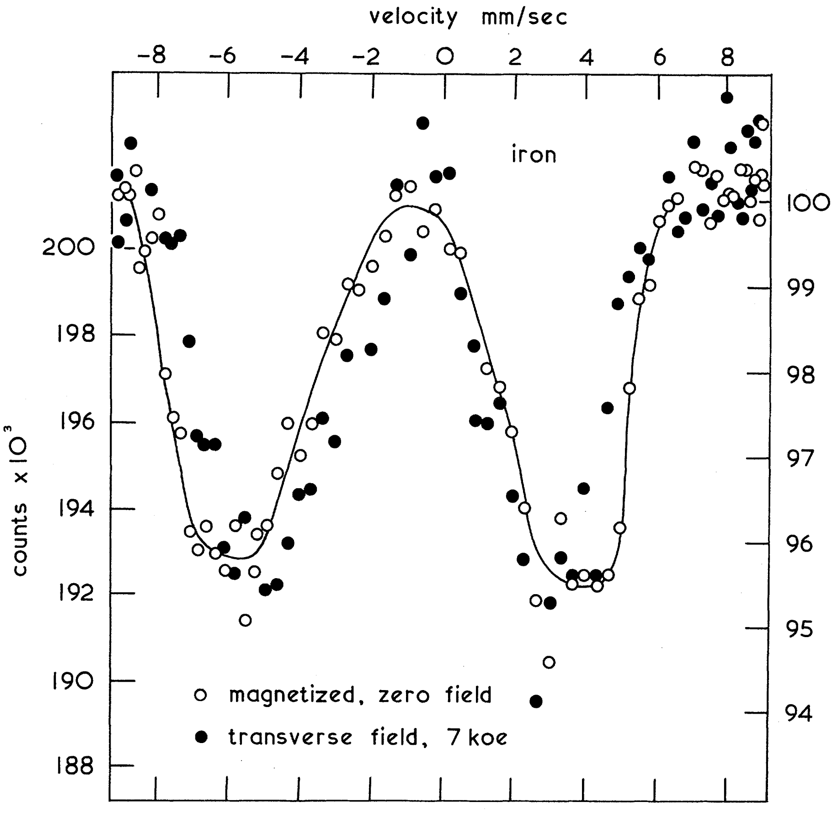

FIG. 1. The absorption spectra obtained with 1% Sn^{119} in Fe. Left scale, ○ ; right scale, ●.

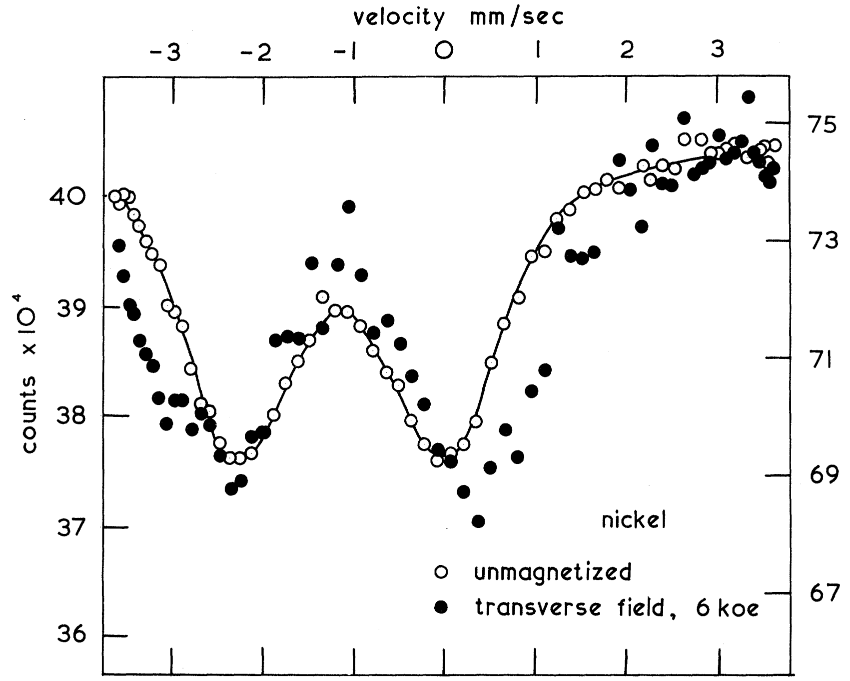

FIG. 2. The absorption spectra obtained with 1% Sn^{119} in Ni. Left scale, o; right scale, ●.

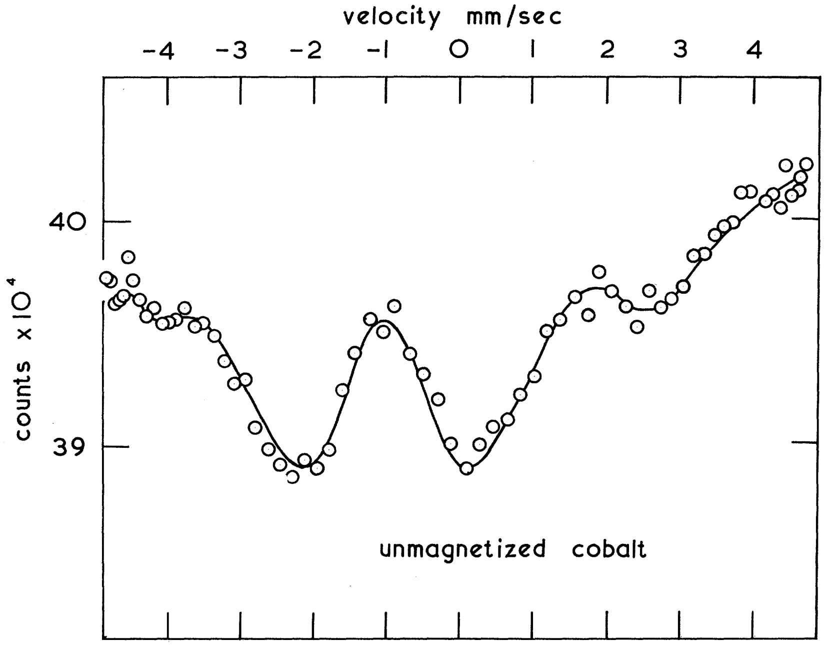

FIG. 3. The absorption spectrum obtained with 1% Sn^{119} in Co.

of $[H_S - (4\pi/3)M]$ are listed in the table, where the values of M have been corrected for the quenching of the atomic moments by the added valence electrons of Sn. This is most significant in Ni, and, since it will occur predominantly amongst the nearest neighbors, will undoubtedly result in a lowered value of the observed field.

The results are obviously inconsistent with the existence of the single field H_c; firstly because of the different signs and secondly because of the relative magnitudes of the fields. Since p is very closely proportional to M,[2] the expression (1) for H_c can be written simply, $H_c = \text{const}\ \xi_S M$. Further, we can conclude from the chemical shifts that ξ_s is practically constant for Fe, Co, and Ni, and therefore H_c will be roughly proportional to M.

There is another mechanism[11] by which an effective field might be produced at the Sn nucleus in this situation. The wave function for the 4s electrons of the Sn atom will overlap with those of the 3d electrons of the surrounding solvent atoms, and the polarization of the latter will result in a change in the relative spatial distribution of the 4s electrons in respect of their spin orientation. In the region of the Sn nucleus, electrons with spin antiparallel to the 3d polarization will predominate, producing a negative effective field H_p.

Evidence for the existence of such a field is provided by the results for Co (Fig. 3) which indicate the presence of a second field of -50 koe with the same chemical shift. X-ray analysis of the sample showed that both cubic and hexagonal structures were present in the rough proportion 40:60. Since neither ξ_s nor p depends on the structure, the two values of the field cannot be associated with H_c; however, since the distribution of the 3d orbitals will probably differ for the two structures,[12] H_p would also differ.

We have no estimate of H_p, but its magnitude should depend not only on M but also on the mean radius of the 3d shell and thus will decrease more rapidly from Fe to Ni than does the field H_c which depends only on M. In the absence of any further contributions, combination of such a field H_p with a positive value of H_c would therefore provide a qualitative interpretation of the present results.

It is interesting to compare the present results for the field at a Sn nucleus in Fe with those of Samoilov et al.[13] From measurements of the nuclear polarization these authors obtain values of 250 koe and 280 koe, respectively, for the field at In^{114} and Sb^{122} dissolved in Fe.

We are indebted to Dr. C. Johnson for drawing our attention to the results of Samoilov et al. and we are grateful to many people for valuable discussion, particularly Dr. Lomer, Dr. W. Marshall, Dr. S. F. Edwards, and Dr. H. E. Hall. Much helpful advice in the preparation of the alloys has been given by Dr. J. Stubbles. We would also like to thank Dr. J. Zussman for performing the x-ray analysis.

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*Supported financially by the Department of Scientific and Industrial Research.

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