cord with theory. We are presently extending the work to lower temperatures where the theory used here is no longer valid.

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Magneto-optic Kerr Effect in Ni, Co, and Fe

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Magneto-optic Kerr-effect spectroscopy of Ni, Co, and Fe is used to study d-band widths and electron spin polarization (ESP). The d-band widths determined on the basis of magneto-optic Kerr-effect spectra are wider than those established by photoemission, and the sign of ESP of electrons near the Fermi level in Ni is found to be negative, as predicted by band theory. We discuss the relationship between this work and other recent studies of ESP.

Recent experimental studies of Ni, Co, Fe, and Gd have created new interest in the electronic structure of ferromagnets. Photoemission spectroscopy has been used to study the widths and general shapes of occupied d bands in Ni, Co, and Fe[1] and in Gd,[2] and to study $4f$ levels in rare-earth metals.[3,4] Spin-polarized photoemission spectroscopy has been recently introduced and applied to Ni, Co, and Fe[5] and to Gd,[6] and spin-polarized field-emission spectroscopy has been applied to the study of Gd[7] and Ni.[8] In addition, an interesting experimental investigation of the electron spin polarization (ESP) of Fermi level electrons in Ni, Co, Fe, and Gd using spin-dependent tunneling techniques has been recently reported.[9]

These experimental studies have produced some rather interesting results: The spin-dependent tunneling experiments measure a positive ESP of electrons within 0.001 eV of the Fermi level E_F in Ni, Co, Fe, and Gd. This is rather surprising in the case of Ni since the Stoner-Wohlfarth-Slater (SWS) band model of ferromagnetism applied to Ni predicts a net *negative* ESP for electrons near E_F. The spin-polarized photoemission experiments (which probe a depth between 0.4 and 0.8 eV below E_F) also measure a positive ESP in Ni, Co, Fe, and Gd, with a degree of polarization in each case in good agreement with the tunneling results. Several theoretical papers[10-13] have attempted to account for the positive ESP observed in the photoemission experiments, and these papers demonstrate that the spin-polarized photoemission results are not necessarily in disagreement with the SWS theory. However, in Ni, in particular, apparently contradictory experimental results exist which make clear that unanswered questions remain. Spin-

polarized field-emission studies of Ni (which probe a depth of about 0.1 eV below E_F) measure a negative ESP in both polycrystalline and single crystal Ni samples [a small positive ESP is observed from the (001) face], and it has been shown that this result is consistent with the SWS band theory.[14] In short, the present explanations do not seem to explain all experimental data on the ESP in Ni.

In this Letter we discuss magneto-optic Kerr-effect (MOKE) spectroscopy of Ni, Co, and Fe. This type of spectroscopy not only provides information about the joint density of states (in analogy to photoemission and ordinary optical measurements) but also yields information about the ESP of states participating in the MOKE transitions. In our discussion of the experimental data we compare predictions based on MOKE spectroscopy with the work referred to in the preceding paragraphs. We find the MOKE results for Ni are in agreement with the field emission experiments, and with a stretch of interpretation perhaps also with the photoemission experiments but not with the tunneling experiments. We find d-band widths predicted from the MOKE spectra of Ni are appreciably wider than those predicted by photoemission.

Magneto-optic Kerr-effect spectroscopy provides a unique experimental technique for probing the electronic structure of ferromagnets offering several advantages over other methods. The MOKE is much less sensitive to surface effects than electron emission and tunneling experiments since the optical penetration depth is typically hundreds of angstroms rather than tens of angstroms which characterize electron escape depths. The work function does not enter into the interpretation of MOKE data, and this eliminates one uncertainty in the energy range of states being probed. The MOKE is proportional to the product of spin-orbit coupling strength and net ESP of states excited by the incident light. These features result in the MOKE being primarily sensitive to the "magnetic" electrons, namely, d states in the transition metal ferromagnets and d and f states in the rare-earth metals. The dependence on spin-orbit coupling strongly discriminates against s-p states even if they exhibit some spin-polarization. Therefore, MOKE measurements are particularly suited to study magnetic electronic states.

The MOKE is described by off-diagonal elements in the optical conductivity tensor $\tilde{\sigma}(\omega)$. In standard notation[15] the real component of diagonal elements, $\sigma_{xx}^{(1)}(\omega)$, describes the ordinary optical absorption which is always positive, and the imaginary component of off-diagonal elements, $\sigma_{xy}^{(2)}(\omega)$, describes MOKE absorption. The MOKE absorptive component can have either positive or negative sign since it is proportional to the difference in absorption of right- and left-circularly polarized light. The sign of $\sigma_{xy}^{(2)}(\omega)$ is directly related to the ESP of states which contribute to MOKE absorption.

Ordinary optical absorption contains an intraband (Drude) component and an interband component. In analogy to this, the MOKE absorptive component also contains an intraband contribution and an interband contribution. The interband MOKE absorptive component is related to the joint density of states,[16] analogous to ordinary optical absorption. It is possible to estimate the intraband contribution and separate it from the data to obtain the interband absorptive component.[16]

Experimental MOKE data for Ni, Co, and Fe are shown in Fig. 1. These data were reported by Krinchik and Artemev[17] who studied the MOKE in both polar and transverse optical configurations using bulk samples prepared by a sequence of mechanical polishing, annealing, and electro-

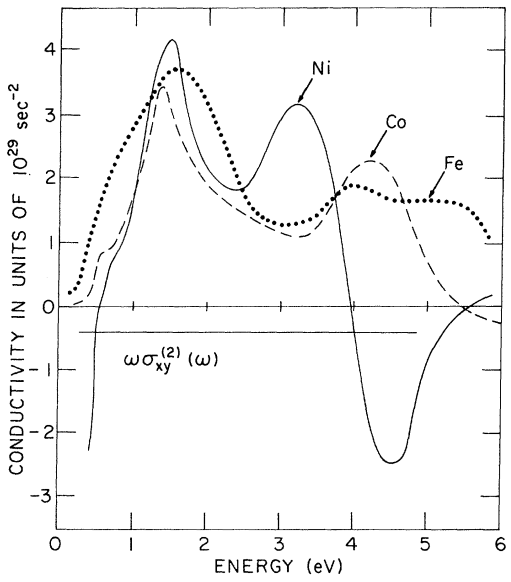

FIG. 1. Magneto-optic Kerr absorptive components for Ni, Co, and Fe. The quantity plotted is $\omega\sigma_{xy}^{(2)}(\omega)$, where $\sigma_{xy}^{(2)}(\omega)$ is the absorptive component of the magnetic contribution to the conductivity. The vertical scale is correct for Ni. To correct the scale for Co and Fe, the existing scale should be multiplied by a factor of 5. The horizontal line shows the estimated intraband contribution in Ni.

polishing. We have independently studied MOKE effects in Ni using the longitudinal optical configuration and a precision ellipsometric technique.[16,18] Our samples were prepared by vacuum evaporation of 99.9% pure Ni onto glass microscope slides and were studied *in situ* under ultrahigh vacuum conditions. Our results are in agreement with the work of Krinchik and Artemev[17] aside from a small scale factor which probably resulted from the massive samples not being magnetized to saturation in their experiments. We found that the Ni results were not sensitive to short time exposure to air.

To interpret the experimentally determined interband structure of $\sigma_{xy}^{(2)}(\omega)$, we use a modified atomic model which has been previously applied to the magneto-optic spectrum of Gd.[16] Application of this model to Ni correctly predicts the general characteristics shown by $\omega\sigma_{xy}^{(2)}(\omega)$ in Fig. 1; i.e., a negative peak followed by two positive peaks, and finally a negative peak.[19] This general shape of $\omega\sigma_{xy}^{(2)}(\omega)$ predicted by our model is reasonably independent of the shape of the optical joint density of states (p and d states for Ni) as long as the joint density of states function can be approximated by basically a single peak rather than, for example, two peaks separated by a broad deep valley.

The negative sign of $\omega\sigma_{xy}^{(2)}(\omega)$ for Ni below 0.5 eV, shown in Fig. 1, is characteristic of transitions involving *minority* spin electrons. This result is model *independent* for states near the top or bottom of the band, as in Ni, and depends solely on the sign of the spin-orbit coupling, a quantity known from atomic calculations. MOKE measurements of f levels in Dy show agreement with this result.[20] Cooper[21] has theoretically studied the low-energy MOKE spectrum of Ni in detail and has attributed the low-energy structure to transitions between minority spin bands at the symmetry point L_2. His calculation had a sign uncertainty which our analysis supplies. According to our analysis, minority-spin transitions dominate from zero energy up to a point where the experimental data cross the intraband contribution (the straight line in Fig. 1) which occurs at 0.5 eV. From this, we argue that MOKE spectroscopy of Ni predicts a net *negative* ESP of the d electrons below 0.5 eV and a net *positive* ESP of the d electrons above 0.5 eV. If the photoemission experiments (probing 0.4–0.8 eV below E_F) weight the higher energies more strongly, or if the energy range believed covered is in error by several tenths of an electron volt (due to uncertainty in the work function, for example), then the MOKE experiments may agree with photoemission on the sign of ESP in Ni, but it is hard to understand the magnitude.

We can also apply our model to extract from the experimental data of Fig. 1 the width of both minority- and majority-spin bands in Ni. Minority-spin transitions produce the first negative peak and the second positive peak; majority-spin transitions produce the first positive peak and second negative peak. From this we estimate in Ni the minority-spin band to be approximately 4.0 eV wide, and the majority-spin band to be approximately 4.5 eV wide with an average exchange splitting of 0.5 eV. It is interesting to note that photoemission experiments[1] predict a much narrower width (3.3 eV). The large difference may be due to the surface sensitivity of photoemission experiments as suggested by Haydock *et al.*[22] Another possibility is broadening in our data introduced by the p band since $p \rightarrow d$ transitions are involved. This broadening appears to be less than 0.5 eV from the sharpness of the MOKE structure in Fig. 1. The possibility still remains that transitions from two or more narrow p-type regions in energy could give a greater overall width by the energy separation between these regions. The data do not appear to indicate that this is occurring since one would expect the narrow peak at 2.5 eV to split by the amount of this energy separation.

Application of our model is not as straightforward in the case of Co and Fe. Inspecting Fig. 1 one observes that although there is similarity between the MOKE spectra of Ni and Co, in the case of Fe, only a vague similarity persists. The reason for this is that the location of E_F in Ni is near the top of the band whereas in Co and Fe, E_F progressively moves towards the middle of the band. Therefore, although in Ni, $p \rightarrow d$ transitions do not contribute appreciably to MOKE absorption, these effects become more important in Co and Fe as more unfilled states are available. In Co and Fe, calculation of the intraband component is further complicated by the fact that the details of the band structure enter in determining both the sign and magnitude of σ_{xy} while in Ni these details determine only the magnitude and not the sign. The MOKE spectrum of Co is similar enough to that of Ni to predict a minority-spin d-band width of approximately 5 eV. The data do not extend to high enough energies to estimate the majority bandwidth in Co, but it is clearly greater than 5 eV.

There appears to be a contradiction in the present interpretation of experimental data on Ni, especially in regard to the ESP. A straightforward interpretation of photoemission and tunneling experiments indicates that the electron spins near the Fermi surface are predominantly majority spins while the MOKE and field emission indicate the opposite result in agreement with band theory. None of the proposed explanations[10-14] appear to be consistent with all of the measurements of ESP in Ni. We would like to suggest that the apparent contradiction may arise from an oversimplified interpretation of some of the experiments. In the tunneling, photoemission, and field-emission experiments, both s-p and d electrons are involved. In the interpretation, it is assumed the d electrons dominate, yet this is not obviously so. It is true that the density of states is dominated by the d electrons, but the processes of interest also depend on matrix elements which typically favor the s-p electrons. For example, we estimate for Gd that the $s \rightarrow p$ dipole matrix squared is about 20 times that of the $d \rightarrow p$ one.[17] Secondly, it is assumed that the tunneling probability or surface escape probability is independent of spin polarization. Again this is not obvious. For instance, for Ni near the Fermi energy, band theory indicates that the density of states of minority spins is much greater than that of majority spins. This immediately indicates the minority-spin electrons will have smaller mean free paths due to scattering and consequently will have a smaller escape probability than majority-spin electrons. Thus the spin distribution of escaped electrons will not reflect their distribution inside the sample. Finally, as mentioned before, surface effects may be important in the interpretation of these experiments.

The strength of the MOKE experiments is that they do not suffer from these uncertainties in interpretation. Because of the proportionality to spin-orbit interaction and net spin polarization, MOKE preferentially senses the magnetic electrons, the d electrons in Ni. We have experimentally shown that bulk properties are being measured in MOKE. The sign of the $\sigma_{xy}^{(2)}$ at low frequencies in Ni is determined entirely by the sign of the spin-orbit coupling known from atomic properties. In view of this we conclude that the ESP in Ni at the Fermi energy is dominated by minority carriers, in agreement with SWS band theory.

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