Role of Spin Exchange in Elastic Electron Scattering from Magnetic Surfaces

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The role of spin-exchange processes in (quasi)elastic electron scattering is investigated by measurement of the changes in polarization of a spin-polarized electron beam scattered in specular geometry from Ni(110) and Ni(110)O(2×1) over an energy range of 5 to 30 eV. Concurrently measuring the scattered intensity as a function of primary spin polarization yields the spin-dependent reflection coefficients. These reflection coefficients entirely account for the changes in polarization. Therefore, it is concluded that spin-exchange processes are negligible ($\leq 3\%$) in the elastic channel.

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Spin-polarized–electron spectroscopies have been immensely successful in the study of ferromagnetic solids and surfaces in recent years. For instance, the addition of spin analysis to energy and angle resolution in photoemission spectroscopy enables direct observation of spin-split electronic states in itinerant-electron ferromagnets.[1] Spin-polarization analysis of low-energy secondary electrons allows the determination of the magnetization at the surface, in magnitude and direction.[2] In these techniques, however, results must be interpreted in light of possible changes of the electron spin polarization due to spin-exchange (spin-flip) scattering during transport and escape of the electrons. From the early days of spin-resolved photoemission there has been a rather persistent concern about the degree to which the electron spin polarization is conserved during emission.[3] The most clear-cut effect is seen as an enhancement by a factor of 2–3 of the spin polarization of very low-energy secondary electrons.[4] This effect is attributed to *inelastic* spin-flip scattering (Stoner excitations).

Also, the question of *elastic* (or quasielastic) spin-flip scattering has been addressed in a variety of circumstances. The most striking are spin-polarized photoemission experiments where significant depolarizations have been observed. For example, Hüfner *et al.* report large depolarization of optically oriented electrons from Ge upon transmission through thin magnetic overlayers (Gd, Ce, Ni), but only slight effects were observed for Au overlayers.[5] Quite recently Schmitt, Kämper, and Güntherodt have observed structures in the spin-polarized photoemission spectra from the Ni(110) oxygen and sulfur adsorbate system,[6] and Carbone and Kisker report on large depolarizations for the system of a monolayer of Gd on Fe.[7] In all these studies it was suggested that elastic spin flip might be responsible for the observed depolarization. However, a difficulty with these methods of characterizing the extent of spin-flip scattering is that the initial spin configuration is not well determined. For an unambiguous decomposition of scattering probabilities, it is necessary to know the initial spin configuration in addition to measuring the scattering intensity and spin polarization.

In this Letter we report on the first direct measurement of the spin-flip contribution to elastic electron scattering from Ni(110) and Ni(110)O(2×1) with high accuracy. This complete experiment measures the spin dependence of the reflection coefficients (asymmetries) from intensity changes upon separate reversal of primary-beam polarization and crystal magnetization. In addition, spin analysis of the scattered beam measures a composite of all elastic (and quasielastic) scattering processes, including spin flip. We find for both Ni(110) and Ni(110)O(2×1) that the spin-orbit and exchange-induced asymmetries account for the changes in measured polarization, without recourse to spin-flip scattering.

The experiments were performed in a UHV system (base pressure $<10^{-10}$ Torr) designed for various spin-polarized–electron spectroscopies. The Ni crystal was a "picture frame" type, exposing the (110) surface. It was cleaned by repeated cycles of heating in oxygen and noble-gas–ion sputtering followed by high-temperature flashes. The surface quality was monitored by LEED. All of the measurements were performed in specular geometry with a 45° angle of incidence and the sample at room temperature. The scattering normal was chosen to be the $[1\bar{1}0]$ direction so that the scattering plane coincided with a mirror plane of the crystal. The details of the apparatus will be described elsewhere,[8] so we restrict our discussion to essential aspects of these measurements.

The spin-polarized primary beam was derived from a GaAs source, producing a spin polarization of $\pm 30\%$. Spin polarization of the scattered beam was measured by a high-energy (115 kV) Mott detector after passing through a hemispherical energy analyzer ($\Delta E = 300$ meV). Primary polarization was measured accurately, to within a few tenths of a percent, by electrostatic deflection of the beam into the energy analyzer and Mott detector. The Mott detector was calibrated to an uncertainty of $\pm 2\%$ (including systematic instrumental errors),[8] and we maintained an overall uncertainty of

$\pm 3\%$ (convoluted with statistics).

The primary-beam polarization and crystal magnetization were oriented perpendicular to the scattering plane. By reversing the direction of each one independently, we measured four intensities I_σ^μ ($\mu,\sigma=\pm$) where μ is the crystal majority-spin direction, and σ is the incident-beam polarization either parallel or antiparallel to the scattering normal. Concurrently, for each configuration we measured the scattered-beam polarization P_σ^μ.

The spin dependence of the reflection coefficients is typically described by the experimentally derived asymmetries[9] A^+, A^-:

$$A^\mu = \frac{1}{|P_0|}\frac{I_+^\mu - I_-^\mu}{I_+^\mu + I_-^\mu}.$$

It has been shown that for Ni, the exchange and spin-orbit contributions may be described independently to a very good approximation[9] by

$$A_{\rm s.o.} \simeq \tfrac{1}{2}(A^+ + A^-), \quad A_{\rm ex} \simeq \tfrac{1}{2}(A^+ - A^-).$$

We show our results for the spin-orbit and exchange-induced asymmetries in Fig. 1. For clean Ni, it is clear that both spin-orbit and exchange contribute significantly to the spin dependence. For the reconstructed $O(2\times1)$ surface, the exchange contribution is suppressed with respect to the spin-orbit. To the extent that the exchange asymmetry reflects the surface magnetization,[10] we see that the Ni-O(2×1) magnetization is greatly reduced. This result is consistent with previous observations of the decrease of the spin polarization of secondary electrons.[11]

The spin polarization as a function of kinetic energy for the clean Ni(110) is shown in Fig. 2 for the four beam/magnetization orientations. Since exchange scattering is expected to be strongly energy dependent, we carried out the measurements to as low primary energies

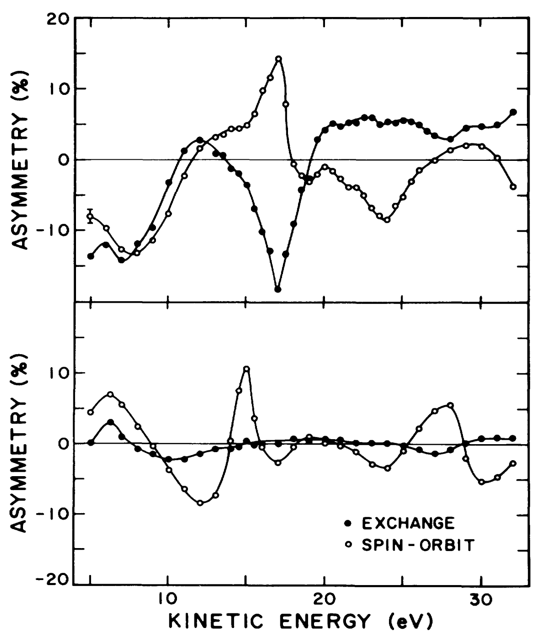

FIG. 1. Spin-orbit and exchange contributions to the scattering asymmetry as functions of kinetic energy. Top: Ni(110); bottom: Ni(110)O(2×1).

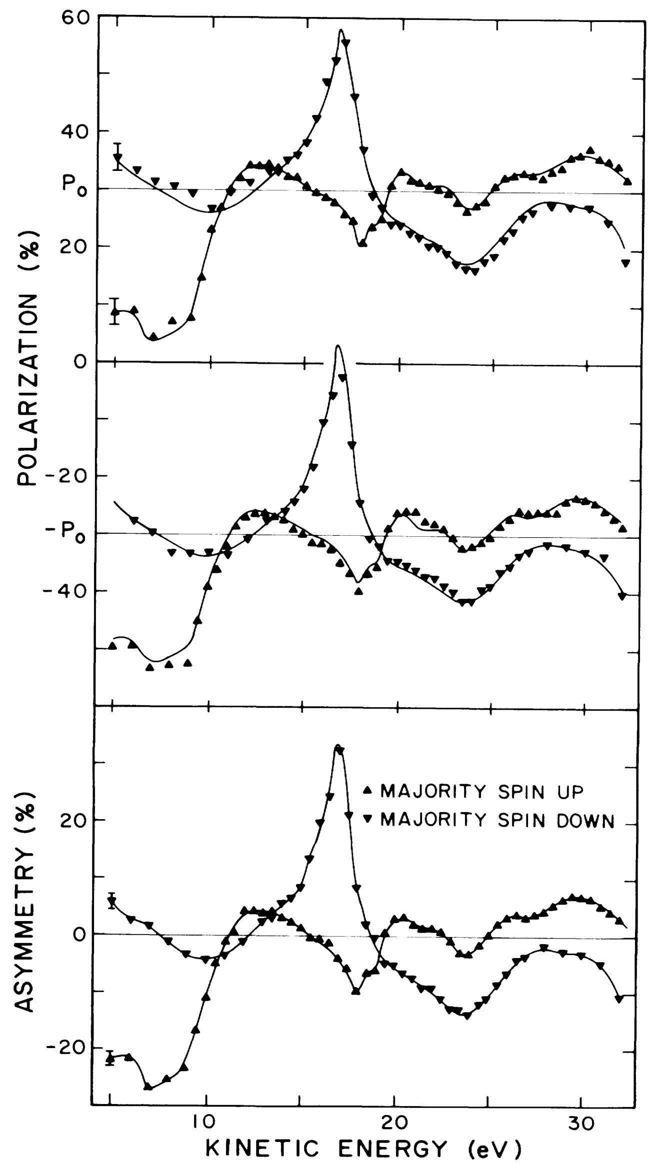

FIG. 2. Polarization after scattering (top panel) from the Ni(110) surface for primary beam polarizations, $\pm P_0$ (shown with baselines at $\pm 30\%$) and for magnetizations up (inverted triangles) and down (triangles). Below it are the scattering asymmetries for each magnetization (A^+,A^-) (the solid lines are guides to the eye). With the polarization values are smooth lines indicating the calculated values based on the scattering asymmetries only, according to Eq. (1).

as possible.[12] The scattered-beam polarization shows significant deviations from the incident polarization (indicated here by baselines at ±30%). Shown below it are the scattering asymmetries A^μ measured for each magnetization (as opposed to the $A_{\rm s.o.}, A_{\rm ex}$ of Fig. 1). Not only are the deviations from P_0 very striking; they reflect the asymmetries quite closely. In the absence of any spin flip, it is easily seen that with a primary beam of polarization P_0 [composed of $I_\uparrow = \frac{1}{2}(1+P_0)$ and $I_\downarrow = \frac{1}{2}(1-P_0)$] and spin-dependent reflection coefficients (which lead to asymmetries A^μ), the polarization of the scattered beam is given by[13]

$$P^\mu = (P_0 + A^\mu)/(1 + P_0 A^\mu). \qquad (1)$$

If we consider the possibility of spin-flip scattering rates F^μ_+, F^μ_-, in addition to the intensity asymmetries, as causing the changes in polarization, the measured polarization would be

$$P^\mu = (P_0 + A^\mu)/(1 + P_0 A^\mu) - 2(F^\mu_+ - F^\mu_-)/I^\mu_s, \qquad (2)$$

where $I^\mu_s = I^\mu_+ + I^\mu_-$ is scattered intensity. For an unpolarized primary beam ($P_0 = 0$) this leads to $P = A$, a result which has been shown to be valid in spin-orbit-induced scattering asymmetries from high-Z materials.[14]

Shown with the polarization data are smooth lines indicating the locus of calculated polarizations based on the *measured asymmetry only*, i.e., according to Eq. (1). Within experimental uncertainty, there are no systematic deviations from the calculated values which would indicate spin-flip scattering. It is apparent that over the entire energy range considered, the elastic-scattering *asymmetry* is sufficient to account for the polarization of the scattered beam. Figure 3 shows the spin polarization as a function of kinetic energy for the Ni(110)O(2×1) surface. Since the exchange-induced asymmetry is a small contribution, there is very little change when the sample magnetization is reversed. For clarity, the data for opposite magnetizations are shifted. We note the same *qualitative* agreement between the deviations from P_0 and the asymmetry. Furthermore, there is also no evidence for spin-flip scattering on the basis of good agreement between the calculated polarizations [again, from Eq. (1)] and the directly measured polarization.

Our results seem to be at variance with the observations cited earlier.[5–7] We consider the possibility that with a suitably high energy bandwidth, some quasielastic spin-flip processes may become significant; however, this effect is not evident here. Extending our measurements to off-specular directions may enhance the relative contribution of any quasielastic flip processes already present.[15] Another natural extension of this technique is to probe spin-dependent loss processes in Ni with high-energy resolution, as has already been carried out for Fe.[16]

In summary, we have shown that elastic spin-flip processes at the Ni(110) and Ni(110)O(2×1) surfaces are negligible over the kinetic-energy range of 5 to 30 eV. We arrive at this result by directly observing the spin-flip rates with a complete spin-polarized electron-scattering experiment. The spin polarization after scattering is accounted for entirely by the intensity asymmetry.

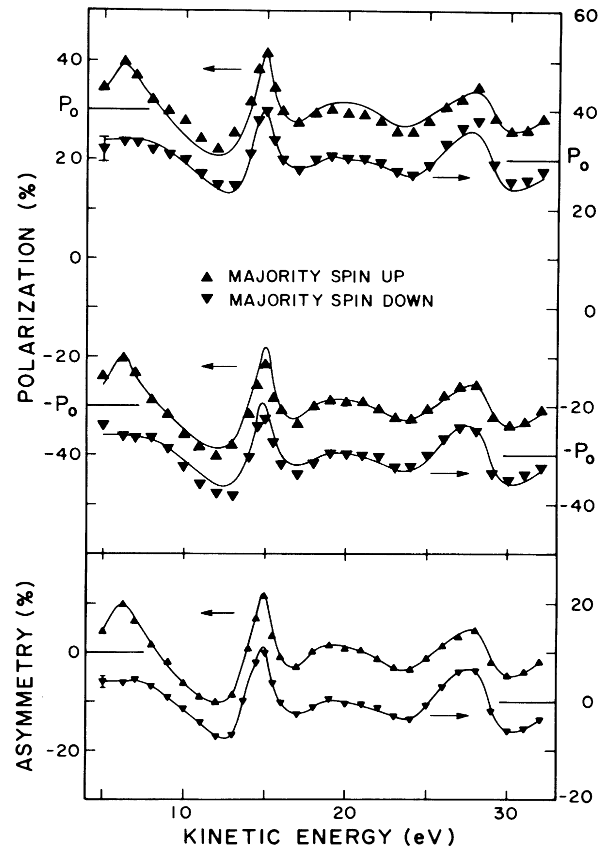

FIG. 3. Same as Fig. 1 for Ni(110)O(2×1). Heavy bars indicate the incident polarization, $P_0 = \pm 30\%$. Note here a shift in scale between the two magnetizations, for clarity.

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