On the mechanism of spin-dependent (e,2e) scattering from a ferromagnetic surface.

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Abstract. A simple model is suggested for a qualitative analysis of spin-dependent (e,2e) reaction on a ferromagnetic surface. The model is based on the scattering of the primary electron with the average spin projection \( <s_1> \) by the valence electron with the average spin projection \( <s_2> \). To test the model the energy distributions of correlated electron pairs are measured for parallel and anti-parallel orientations of the magnetic moment of the cobalt film and polarization vector of the incident beam. The proposed model explains qualitatively the spin-asymmetry of the measured binding energy spectrum.

1. Introduction
The exchange interaction in electron-electron scattering is a result of the fermionic (spin = \( \frac{1}{2} \)) nature of the electrons. As a consequence, the wave function of an electronic system must be anti-symmetric which implies that an exchange of two electrons of the system results in the change of the wave function sign. To observe the exchange interaction one needs to monitor at least two interacting electrons with well-defined spin states. A spin-dependent scattering experiment includes preparation of the initial spin state of the two electron system and the measurement of the cross section of the scattering for two cases: i) the spin projections of both scattering electrons on the quantization axis are the same (differential cross section is denoted as \( d\sigma^{\uparrow\uparrow} \)); ii) the projections have opposite signs (spin projection of one of the electrons is flipped while the second is unchanged, and the corresponding cross section is \( d\sigma^{\uparrow\downarrow} \)). When such an experiment is performed on a ferromagnetic surface the spin state of the target electrons is defined by the magnetization of the sample, which is anti-parallel to the majority spin states of the sample. The spin state of the second (incident) electron is chosen to be parallel (“spin up”) or anti-parallel (“spin down”) to the majority spins of the target.

The two-electron spectroscopy in reflection with spin-polarized incident beam [1] offers the possibility to probe exchange interaction. The cross section of each of the two above mentioned channels (\( d\sigma^{\uparrow\uparrow} \) and \( d\sigma^{\uparrow\downarrow} \)) is proportional to the number of electron pairs resulting from the interaction of the incident electron beam with the target at a fixed incident current. To test the model we measured (e,2e) spectra from 3 monolayer (ML) cobalt film on W(110) surface.
2. Model.
We present here a qualitative analysis of the spin-dependent electron scattering from a ferromagnetic surface based on a simple model of the ferromagnetic sample. The aim of this analysis is to evaluate the asymmetry parameter that can be measured experimentally and which is defined as:

\[ A = \frac{d\sigma(\uparrow\uparrow)}{d\sigma(\uparrow\downarrow)} \]  \hspace{1cm} (1)

Using a simplified free electron model for the ferromagnetic target one can assume that electrons within binding energy range \( E \) to \( E + dE \) have an average spin projection \( \zeta_1=E \). The incident electron beam with spin polarization \( P \) is characterized by an average spin \( \zeta_1 = \langle \zeta \rangle \). In a very simplified picture one can model our experiment by scattering of an electron with the average spin \( \zeta_1 \) by another electron with average spin \( \zeta_2 \). We will follow Landau [2] for solving this problem. The spin dependence in the cross section \( d\sigma \) must be expressed by the term proportional to the dot-product \( \langle \zeta_1 \cdot \zeta_2 \rangle \). We are looking for the general expression of the cross section in the form:

\[ d\sigma/da = a + b(\zeta_1 \cdot \zeta_2) \]  \hspace{1cm} (2)

To find parameters \( a \) and \( b \) in (2) we consider two particular cases of scattering: i) both electrons in average are unpolarized \( (\zeta_1 = \zeta_2 = 0) \) and ii) completely polarized beam \( (\zeta_1 = \frac{\pi}{4}) \) is scattered by identically completely polarized target \( (\zeta_2 = \frac{\pi}{2}) \). In the first case the second term of (2) is zero, and \( d\sigma/da = a \). On the other hand it is known that for unpolarized electrons the cross section of scattering is the average of the singlet \( d\sigma_{\uparrow\downarrow} \) and triplet \( d\sigma_{\uparrow\uparrow} \) cross sections with their statistical weights:

\[ d\sigma_{\uparrow\uparrow}/d\omega = \frac{1}{4} (d\sigma_{\uparrow\downarrow}/d\omega + 3d\sigma_{\downarrow\uparrow}/d\omega) \]  \hspace{1cm} (3)

In the second case the two scattering electrons are in a triplet state and therefore:

\[ d\sigma_{\uparrow\downarrow}/d\omega = d\sigma/da = a + b/4 \]  \hspace{1cm} (4)

From equations (3) and (4) one can extract \( a \) and \( b \) and substitute them in (2):

\[ d\sigma = \frac{1}{4} (d\sigma_{\uparrow\downarrow} + 3d\sigma_{\downarrow\uparrow}) + (d\sigma_{\uparrow\uparrow} - d\sigma_{\downarrow\downarrow}) (\zeta_1 \cdot \zeta_2) \]  \hspace{1cm} (5)

Having the expression for the cross section (5) we can return now to the problem of the polarized electron beam scattering by a ferromagnetic target. The average spin of the incident electron is \( \zeta_1 = \frac{\pi}{2} \), where \( P \) is degree of polarization of the incident electron beam. For our model of the target the average spin \( \zeta_2 \) can be expressed using the majority \( \rho_{\text{maj}}(E) \) and minority \( \rho_{\text{min}}(E) \) density of states and the unit vector \( m \), which is parallel to the spin of majority of electrons (i.e. opposite to the magnetization direction of the sample):

\[ \zeta_2 = \frac{\pi}{2} \left[ (\rho_{\text{maj}} - \rho_{\text{min}})/(\rho_{\text{maj}} + \rho_{\text{min}}) \right] m \]  \hspace{1cm} (6)

The experimentally measured quantity of interest is the asymmetry of the scattering cross section, defined by (1) as:

\[ A = (d\sigma_{\uparrow\uparrow} - d\sigma_{\downarrow\downarrow})/(d\sigma_{\uparrow\uparrow} + d\sigma_{\downarrow\downarrow}) \]  \hspace{1cm} (7)

The asymmetry normalized to the polarization of the incident beam is then:

\[ A/P = (\rho_{\text{maj}} - \rho_{\text{min}})/(\rho_{\text{maj}} + \rho_{\text{min}}) \left[ (d\sigma_{\uparrow\uparrow} - d\sigma_{\downarrow\downarrow})/(d\sigma_{\uparrow\uparrow} + 3d\sigma_{\downarrow\downarrow}) \right] \]  \hspace{1cm} (8)

This expression is similar to the one obtained in [3] from first principles. The term \( (d\sigma_{\uparrow\uparrow} - d\sigma_{\downarrow\downarrow})/(d\sigma_{\uparrow\uparrow} + 3d\sigma_{\downarrow\downarrow}) \) in the product (8) is the so called “exchange asymmetry” and the \( (\rho_{\text{maj}} - \rho_{\text{min}})/(\rho_{\text{maj}} + \rho_{\text{min}}) \) is the spin asymmetry of the valence electrons. In symmetric kinematics (normal incidence and symmetric detection), when the momenta of both detected electrons are equal, the triplet cross section vanishes \( d\sigma = 0 \) because of the symmetry consideration [this statement is strictly correct only if the valence electron state involved in the scattering is even with respect to the mirror plane perpendicular to the scattering plane and to the surface]. Consequently, the asymmetry of the scattering cross section \( A \) is determined only by the asymmetry of the density of states at \( k_0 \), where \( k_0 \) is valence electron wave vector:
\[ A/P = - \frac{(\rho_{maj} - \rho_{min})}{(\rho_{maj} + \rho_{min})} \] (9).

The minus sign before the parenthesis means that if the majority density of states is larger at the binding energy where the valence electron is excited from, then the cross section of the (e,2e) reaction is larger for the “down” polarization of the incident electron. It simply means that the cross section for two-electron scattering is larger when the two electrons have opposite spin projections on the quantization axis.

3. Experiment.

The experiment was performed in the UHV conditions with the base pressure in the $10^{-11}$ Torr range. The residual magnetic field within the vacuum chamber was reduced to less than 5 mG using a combination of static and dynamic Helmholtz coils. The W(110) substrate was cleaned using standard procedure including oxygen treatment at 1400 °C followed by high temperature flashes. The cleanliness of the sample was monitored by Auger Electron Spectroscopy and Low Energy Electron Diffraction. A 3 ML cobalt film was deposited using Omicron evaporator with the deposition rate of 0.5 ML per minute. The quality of the film was monitored by Low energy electron diffraction (LEED) and Auger electron spectroscopy. The LEED picture shows that the grown film was epitaxial with \textit{hcp} structure and (0001) axis perpendicular to the sample surface.

![Figure 1. Geometry of the experiment. M1 – magnetization direction.](image)

We applied spin-polarized two-electron spectroscopy in reflection geometry (referred to as (e,2e) spectroscopy) [4] for measuring energy distributions of correlated electron pair excited from the cobalt film by spin-polarized incident electrons. The geometrical arrangement of the experiment is shown in Figure 1. The 25 eV incident electron beam was spin-polarized with (60-70) % degree of polarization (measured in separate experiment).

4. Results and discussion

The energy conservation law in the (e,2e) reaction allows to determine the binding energy $E_b$ of the valence electron involved in the scattering using measured energies of two correlated electrons: $E_b = (E_1 + E_2) - E_o$, where $E_o$ is the incident electron energy, $E_1$ and $E_2$ are the two detected electrons energies. Two-dimensional energy distributions of correlated electron pairs from 3 ML cobalt film has been recorded with spin-up and spin-down polarization of the incident beam. As was mentioned in the model description for a particular selection of correlated electron pairs when both of the electrons are detected with equal energies and at symmetric angles the asymmetry of the binding energy spectrum represents the asymmetry (with “minus” sign) of majority and minority densities of states in the valence band. We plot this asymmetry and compare it with the asymmetry calculated using spin-up and spin-down densities of states from [5]. This comparison is presented in Figure 2.
Figure 2. Comparison of measured and calculated asymmetries of binding energy spectrum.

The theoretical curve is scaled down by a factor of 3 to be compared with the experimental curve. Both curves show similar tendency: they have negative value just below the Fermi level (zero on the x axis) and then cross the x-axis and go positive. The theoretical curve oscillates and actually crosses the x-axis three times. Our experimental curve does not show such oscillations. This might be due to an insufficient energy resolution in the experiment that is estimated to be 0.5 eV and integration over the angle of 5° to have a reasonable statistics. The lower value of the experimental asymmetry than the theoretical one might be due to the misalignment of magnetic domains in the cobalt film.

4. Conclusions
A simple model is proposed to describe a spin asymmetry of the binding energy spectrum measured using spin-resolved (e,2e) spectroscopy on a ferromagnetic surface. We model our experiment by scattering of the primary electron with the spin projection \( <s_1> \) by the valence electron with the spin projection \( <s_2> \). One can assume that valence electrons within binding energy range \( \varepsilon \) to \( \varepsilon + d\varepsilon \) have an average spin projection \( \zeta(\varepsilon) = <s_2> \) defined by spin-asymmetry of the density of states within this energy range. The incident electron beam with spin polarization \( P \) is characterized by an average spin \( \zeta_1 = <s_1> = \frac{1}{2} P \). This model is applied to analyze the asymmetry of the measured binding energy spectrum of the cobalt film. The comparison of the measured and calculated spectra shows a qualitative agreement.

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References
[1] Samarin SN, Berakdar J, Artamonov O and Kirschner J 2000 Phys. Rev. Lett. 85 1746.
[2] Landau LD and Lifshitz EM 2003 Quantum Mechanics (Non-relativistic Theory) Volume 3 Third Edition. Course of Theoretical Physics (Butterworth Heinemann) p 574.
[3] Berakdar J 1999 Phys. Rev. Lett. 83 5150.
[4] Morozov A, Berakdar J, Samarin SN, Hillebrecht FU, Kirschner J 2002 Phys. Rev. B 65 104425.
[5] Spišác D and Hafner J 2004 Phys. Rev. B 70 014430.