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The electron analogue to the Faraday rotation

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Abstract. We show experimentally that the Faraday rotation which is the rotation of the light polarization during transmission of linearly polarized light through a ferromagnet, has its analogue in experiments with spin-polarized electrons: the spin-polarization vector precesses around the direction of the magnetization. For low-energy electrons the precession angle per unit length is two orders of magnitude larger compared to the one observed with light. It is a direct measure of the elusive exchange energy as it depends on the energy of the electrons. We believe that applying this phenomenon will offer new prospects of studying magnetism.

Following the discovery of the wave-like nature of the electron in 1927 [1], it became obvious that it might be of interest to carry out experiments with a spin-polarized electron beam in analogy to experiments with polarized light. The vector of the electron spin polarization should appear as the analogue of the Stokes vector describing light polarization. However, apart from double scattering experiments [2], no such experiments have yet been carried out. So far, in most experiments where the interaction of spin-polarized electrons with ferromagnetic materials has been investigated, the spin polarization vector \vec{P}_0 of the incoming electron beam has been chosen parallel or antiparallel to the sample magnetization \vec{M} . In this way, the spin-selective scattering in ferromagnets has been investigated (see for example [3]). In particular, the spin filtering properties of ferromagnets have been established [4, 5]. It has been shown that an electron beam with \vec{P}_0 antiparallel to \vec{M} —where the direction of \vec{M} is defined by the direction of the majority spins—is more strongly attenuated than a beam with \vec{P}_0 parallel to \vec{M} . The different number of unoccupied majority- and minority-spin states generates the difference in the mean free path for majority- and minority-spin electrons [6, 7].

In order to fully describe the transmission of spin-polarized electrons through ferromagnets, it turns out that it is important to consider also the motion of the spin polarization vector. Experiments show that if there is a component of the spin polarization vector perpendicular to \vec{M} , then this component rotates into the direction of \vec{M} and simultaneously precesses around it. This is completely analogous to the absorptive dichroism and to the rotation of the plane of polarization in the Faraday effect, respectively, observed with polarized light.

It has long been known that there is an analogy between the mathematical description of a polarized light beam and that of a non-relativistic spin-polarized electron beam [8]. For simplicity, we consider in the following discussion a pure spin state, which is given by $\psi_0 = c_1\xi_1 + c_2\xi_2$. Here, $\xi_{1,2}$ represent a complete set of two orthonormal wavefunctions. In the case of light $\xi_{1,2}$ may be chosen to be right- and left-circularly polarized waves, while in the case of electrons, $\xi_{1,2}$ are wavefunctions with two opposite spin orientations. In the following these two spin orientations are chosen to be parallel and antiparallel to \vec{M} , respectively. The corresponding wavefunctions are called majority-spin (\vec{s} parallel \vec{M}) and minority-spin wavefunction (\vec{s} antiparallel \vec{M}). As we are interested in the motion of the spin polarization vector perpendicular to \vec{M} , we consider the wavefunction with equal amplitudes $\psi_0 = (\xi_1 + \xi_2)/\sqrt{2}$. The wavefunction after leaving the ferromagnet is then

$$\psi = \frac{1}{\sqrt{2}}(\sqrt{1+A} \cdot \xi_1 \cdot e^{-iE_1t/\hbar} + \sqrt{1-A} \cdot \xi_2 \cdot e^{-iE_2t/\hbar}) \quad (1)$$

with the energy eigenvalues E_1 and E_2 for the majority- and minority-spin wavefunction, respectively, t the time spent by the electrons within the ferromagnet, and A the transmission asymmetry. A is defined by $A = (I^+ - I^-)/(I^+ + I^-)$ with I^+ and I^- the transmitted current for spin \vec{s} parallel and antiparallel to \vec{M} , respectively. For a detailed discussion of A see [5].

Since the energy difference $\Delta E_{\text{ex}} = E_2 - E_1$ between majority and minority spins, the so-called exchange splitting, is non-zero in a ferromagnet, a phase shift, increasing with time, between the two spin states is introduced. In real space this increasing phase shift corresponds to a precession of the spin polarization vector around \vec{M} with the frequency $\omega = \Delta E_{\text{ex}}/\hbar$. The angle of precession is then $\epsilon = \omega t$. As $t = d/v$, with d the thickness of the ferromagnetic film and v the group velocity of the electrons, the precession angle is given by $\epsilon = \Delta E_{\text{ex}}d/\hbar v$, i.e. it depends linearly on the thickness of the ferromagnetic film. Such precession must occur whenever there is an energy difference between two orthogonal spin states, even in nonmagnetic materials. For example, the energy difference may be due to spin-orbit coupling in off-normal scattering.

The above discussion for a pure spin state ($|\vec{P}_0| = 1$) can be generalized to the case of an incompletely spin-polarized electron beam ($|\vec{P}_0| < 1$) [8]. If we choose, for example, \vec{P}_0 along the x -axis and \vec{M} along the z -axis, the spin polarization vector of the electron beam after leaving the ferromagnet is then

$$\vec{P} = \begin{pmatrix} P_0\sqrt{1-A^2}\cos(\epsilon) \\ P_0\sqrt{1-A^2}\sin(\epsilon) \\ A \end{pmatrix}. \quad (2)$$

and corresponds to two types of motion of the spin-polarization vector, namely, the precession by an angle of ϵ , discussed above, and a rotation into the direction of \vec{M} , which takes place in the plane spanned by \vec{P} and \vec{M} (see figure 1). The rotation into the direction of \vec{M} is caused by the spin filtering in the ferromagnet, which leads to the two different amplitudes shown in (1). This is analogous to the ellipticity that is observed when light passes through a medium with different absorption coefficients for two orthogonal polarization directions. The angle of rotation for a pure spin state is $\phi = \arctan(A/\sqrt{1-A^2})$.

In order to experimentally verify the spin motion discussed above, a ‘complete’ spin-polarized electron scattering experiment has been set up. It is schematically shown in figure 2. A spin-modulated electron source produces a transversely spin-polarized free electron beam

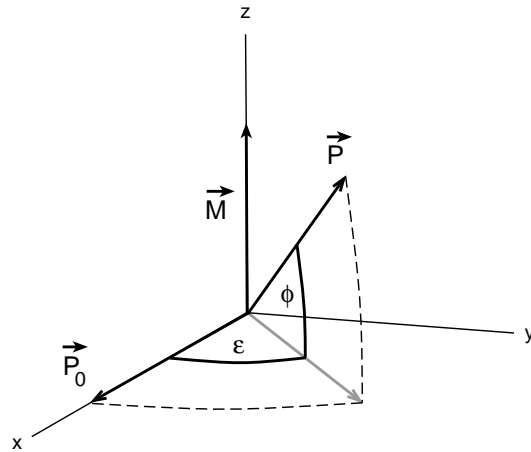


Figure 1. Schematic drawing of the two types of rotation of the spin polarization vector for $|\vec{P}_0| = 1$. Due to the different amplitudes for the two wavefunctions in (1) the spin polarization vector rotates by an angle of ϕ towards the sample magnetization \vec{M} . The different phase factors in (1), on the other hand, cause the spin-polarization vector to precess around \vec{M} by an angle of ϵ .

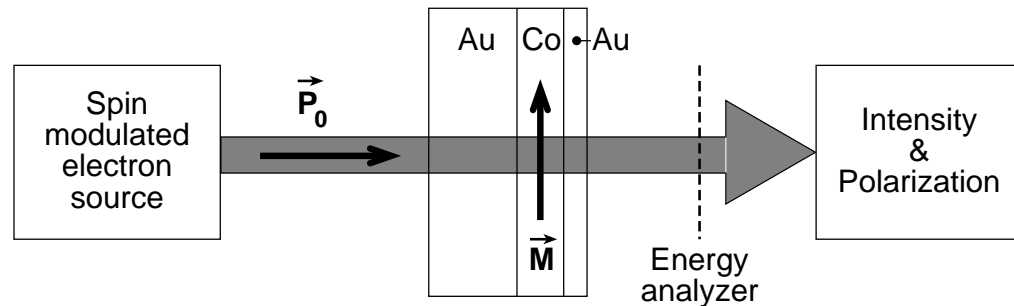


Figure 2. Schematics of the experiment. The experiment consists of a spin-modulated electron source of the GaAs-type [9] with variable spin polarization direction, a freestanding Au/Co/Au trilayer in which the ferromagnetic polycrystalline hcp Co film is magnetized remanently in-plane, a retarding field energy analyser, and a detection system in which the intensity and the degree of spin polarization is measured for the electrons transmitted by the trilayer.

having a spin polarization \vec{P}_0 . By applying a combination of electric and magnetic fields to the electron beam, \vec{P}_0 can be rotated into any desired direction in space. The electron beam impinges perpendicular onto a ferromagnetic polycrystalline hcp Co layer of varying thickness sandwiched between Au layers, which serve both as support and protection layers. It is important that spin-orbit coupling cannot produce any spin polarization in this geometry. The total thickness of the freestanding structure is around 25 nm. The Co film is remanently magnetized in-plane. The transmitted electrons are energy analysed by a retarding field and their spin polarization is detected by Mott scattering. Besides the elastic electrons, there is also a broad distribution of inelastically scattered electrons. However, the elastic electrons can be separated by applying a retarding field [5]. In the following, we discuss the elastic electrons only.

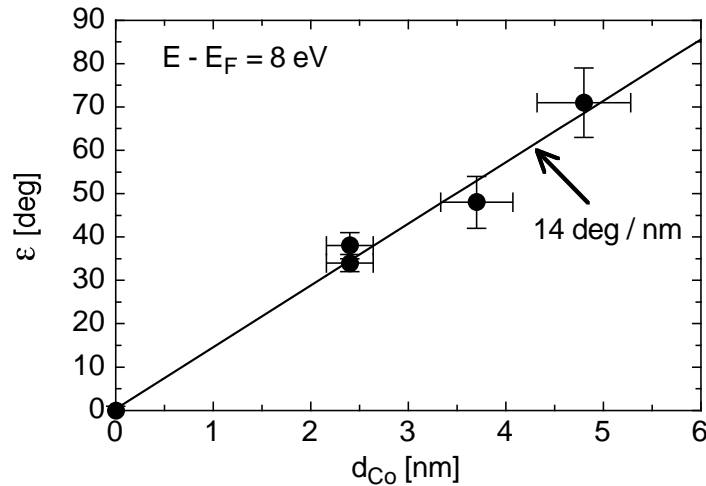


Figure 3. The precession angle ϵ as a function of the Co thickness d_{Co} , measured with elastic electrons of energy $(E - E_{\text{F}}) = 8$ eV. The point at zero Co thickness was measured with a pure Au film of 20 nm thickness. A linear fit to the data yields a slope of $14 \pm 1.5^\circ/\text{nm}$. This confirms the linear thickness dependence of the precession angle ϵ , equation (3).

Figure 3 shows the experimental precession angle ϵ for different Co thicknesses at a primary energy $E - E_{\text{F}} = 8$ eV where E_{F} is the Fermi energy. A linear relationship between ϵ and thickness d is apparent, as expected. The slope is $14 \pm 1.5^\circ/\text{nm}$. We can estimate ϵ by assuming a free electron behaviour, which is reasonable for electrons in the energy range of interest. Then, the group velocity is simply $v = \sqrt{2E/m_e}$, with m_e the free electron mass and E the energy of the primary electron beam measured with respect to the inner potential of Co (~ 16 eV [10]). One obtains:

$$\epsilon = \sqrt{\frac{m_e}{2\hbar^2}} \frac{\Delta E_{\text{ex}}}{\sqrt{E}} \cdot d . \quad (3)$$

Assuming $\Delta E_{\text{ex}} = 0.2$ eV for the Co sp-bands [11], one obtains $\epsilon \sim 7^\circ$ per 1 nm Co film thickness. Considering the approximate nature of the theoretical estimates for ΔE_{ex} , this is a reasonable result. It demonstrates the interest that fundamental research will take in this clear-cut experiment to measure ΔE_{ex} .

We note that the precession around \vec{M} can also be viewed as the Larmor precession of the electron spin around a hypothetical magnetic field, the Weiss field [12]. Such a point of view is justified by the fact that the exchange interaction between the spins in a ferromagnet acts in a way as if there were a magnetic field acting on each spin. In fact, the magnetic field producing the observed precession angle is ~ 4000 Tesla, which is of the same order of magnitude as the Weiss field within the classical molecular field theory. The contribution to the precession angle by the dipole field of the ferromagnetic layer is negligible, producing $0.01^\circ/\text{nm}$ or less.

Though there is a complete analogy to the Faraday rotation observed with light, the strength of this effect with electrons is two orders of magnitude larger. While a precession of the order of $10^\circ/\text{nm}$ is found for electrons, only $0.1^\circ/\text{nm}$ is found for photons [13]. This difference in the strength of the ‘magneto-optic’ phenomena arises because the electron spin couples directly

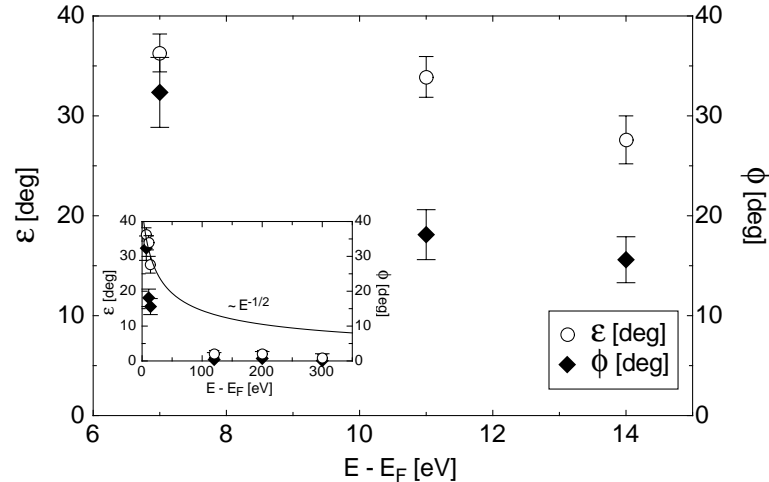


Figure 4. The angles ϵ and ϕ versus the energy $E - E_F$. We note that the values of the angle ϕ are normalized to $|\vec{P}_0| = 1$ (pure spin state). The Co thickness of the trilayer is 2.4 nm. The inset shows both angles over a larger energy range. The solid line is the prediction of equation (3) with $\Delta E_{\text{ex}} = \text{constant}$.

to the sample magnetization whereas the coupling of the photons to the magnetization must be mediated by the spin-orbit interaction.

The energy dependence of both ϵ and ϕ is shown in figure 4. While large values for both types of rotation are found at low energies, vanishingly small values are obtained at high energies (see inset). We note that for energies $E - E_F$ between 15 and 120 eV the transmitted current was too small to be detected because of the mean free path minimum in this energy range [14]. The drop in ϕ with increasing energy is due to the decreasing matrix element for spin-dependent scattering into the Co 3d shell [5]. In other words, the spin filtering of the ferromagnetic Co film is strongly reduced at higher energies, resulting in equal amplitudes in (1) and hence a vanishing rotation angle ϕ . It is, however, possible that some exchange potential may still be recovered at special electron energies, for instance at 50 and 750 eV, where holes in the 3p or 2p shells can resonantly be excited. The angle ϵ , on the other hand, is solely caused by the phase difference that develops between the majority- and minority-spin wavefunction (see equation (1)). According to equation (3) ϵ decreases with $E^{-1/2}$, but the observed much steeper decrease of ϵ proves that ΔE_{ex} is also reduced when E increases. This is in accordance with theory: the higher the energy, the weaker the exchange interaction between the impinging hot electrons and the electrons below E_F [15].

The Faraday rotation with electrons offers new prospects of studying magnetism, because it opens up the possibility to measure the exchange splitting ΔE_{ex} with great sensitivity for energies above the vacuum level, an energy range which is inaccessible to other experimental methods including spin-resolved inverse photoemission spectroscopy [16].

Very interestingly, the Faraday precession might serve as an ‘internal clock’. It is, for instance, known that the existence of potential wells in well-defined multilayer systems leads to a resonant behaviour of electrons at certain energies [17]. As a consequence, electrons with energy on-resonance spend a longer time within the ferromagnet as compared to electrons with energy off-resonance. Thus, an enhancement of the lifetime within the well should show up in

the precession angle upon variation of the primary electron energy. Furthermore, the experiment described here may be viewed as an interference experiment with electrons for the detection of quantum mechanical phases. So far, phase sensitive experiments have only been done by using two different geometrical pathways for the electrons. In the present experiment, the phase is probed by the spin part of the wavefunction using only one single geometrical pathway.

Experiments of the kind presented here can be modified in different ways. The most obvious modification can be done by changing from transmission to reflection geometry, which is the electron analogue to the magneto-optic Kerr effect. In view of the wealth of information gained by the magneto-optic effects with light, their electron analogues promise to become powerful tools to study magnetism.

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