Electron polarimetry with bremsstrahlung

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Abstract. Due to the spin-orbit interaction, the electron scattering from the nucleus is sensitive to the spin orientation of that electron. This is used for polarimetry of electron beams in the Mott method. The spin-orbit interaction was also observed in bremsstrahlung. In this article we analyze its potential for polarimetry as an alternative to the Mott method. It can simultaneously measure all three electron polarization components. It should work in the energy range of 50 keV up to several MeV and can be applied at beam intensities higher than 100 nA. It needs a thin heavy element target, two or four x-ray detectors and one x-ray linear polarimeter.

Polarized electron beams are frequently used in solid state, atomic, nuclear and particle physics. Their typical applications are studies of the spin-effects in atomic collisions, parity violation effects in electron scattering and precision nucleon structure, see [1] and references therein. Photo-ionized polarized electrons can yield information on the magnetic properties of surfaces [2]. Polarization of the Compton-scattered electrons contains information on the circular polarization of the incoming gamma-rays; this can be used for gamma-ray polarimetry [3].

In the energy region of 50 keV up to several MeV electron polarization is typically measured with the Mott technique. It uses the influence of the spin-orbit interaction on the Coulomb collision with an atomic nucleus. More specifically it uses the part that affects the electrons spin-oriented perpendicular to their momentum. The spin-orbit component of the scattering potential is $V_{SO} \propto \mathbf{L \cdot S}$, where $\mathbf{L}$ is the orbital momentum which is perpendicular to the scattering plane, see figure 1. The spin-up electrons predominantly scatter to the right of the plane defined by the momentum and the spin; the spin-down electrons predominantly scatter to the left: $\sigma(\theta) \propto (1 + S(\theta)\mathbf{S} \cdot \mathbf{L}/L)$. Here $S(\theta)$ is the Sherman function [4], see figure 2. This asymmetry depends on the electron energy, the charge of the nucleus and the polar scattering angle θ. At its maximum, which is tens of percents, it is easily observed. By now Mott polarimeters achieved a high level of maturity. Most of their implementations use a thin gold scattering foil and several detectors which sample the azimuthal angular distribution of the scattered electrons. Excellent reviews are available in [1, 5] and particularly in the book *Polarized Electrons* by J. Kessler [6].

The energy range where Mott polarimetry can be used is defined by the following factors.
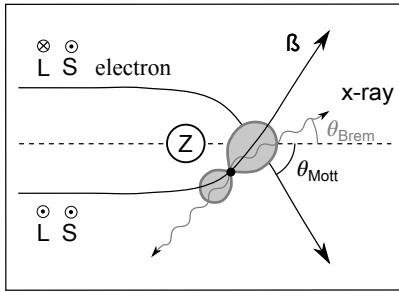
Figure 1. Classical description of Coulomb scattering and bremsstrahlung. Due to the spin-orbit interaction the transversely polarized electrons move in different potentials when they scatter to the left and to the right of the plane defined their spin **S** and the incoming momentum direction (dashed line). In relativistic collisions the bremsstrahlug x-rays are emitted predominantly along the electron scattering direction. Therefore they too have a similar asymmetry. However the x-rays are distributed around the propagation direction of the scattering electron. Because of this the x-ray correlation is more complex.

At energies lower than 50 keV the spin asymmetry is already significantly reduced. It is further reduced due to multiple scattering in the foil. The latter effect can be taken into account by several measurements with foils of different thickness and an extrapolation to the zero thickness. Here foils thinner than 50 nm are required for a reliable measurement. Those are not self-supporting and need a substrate. At higher energies thicker self-supporting targets are used. Gas vapors or jets are also used. They produce very thin targets but they significantly complicate the setup. At energies of several MeV and higher the large Mott scattering asymmetry appears only at the very backward scattering angles, see figure 2. At these angles a reliable asymmetry measurement is complicated. In addition the scattering cross section is small.

At energies of several electron-volts scattering off magnetic surfaces is used [7]. The backscattering cross section in this case is much higher than that of Mott scattering. As a result this technique is significantly more efficient. At the other end of the spectrum, at the energies of hundreds of MeV, one applies Møller electron-electron scattering [8]. It too uses polarized targets. In this paper, however, we are interested in the energy range of the Mott technique.

One limitation of the Mott technique comes from its sensitivity only to the transverse spin components. To measure longitudinal polarization one uses a spin rotation. This is done with a Wien filter. Such a filter generates perpendicularly oriented magnetic and electric fields, see figure 3. Their relative strengths are selected such that only electrons of a given velocity would pass it straight: $\mathbf{F} = e\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) = 0$. Such electrons must propagate perpendicular to both **E** and **B**. Because of this Wien filters are commonly used as filters of the velocity. At the same time the electron spin precesses in the magnetic field: $d\mathbf{S}/dt \propto \mathbf{B} \times \mathbf{S}$. By adjusting the strength of this field the longitudinal polarization may be turned into the transverse one. The transverse polarization is then measured with the Mott polarimeter.

The polarized electron beams that are nowadays available at accelerators have typical intensities of the order of 10 μA. This corresponds to 6×10^{13} electrons per second, which is more than enough for Mott polarimetry — it may even saturate the detectors. Often polarimetry is
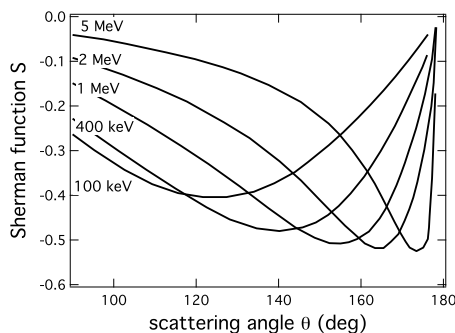
Figure 2. The left-right asymmetry of Coulomb scattering of transversely polarized electrons as a function of the scattering angle θ and the electron's kinetic energy [9].
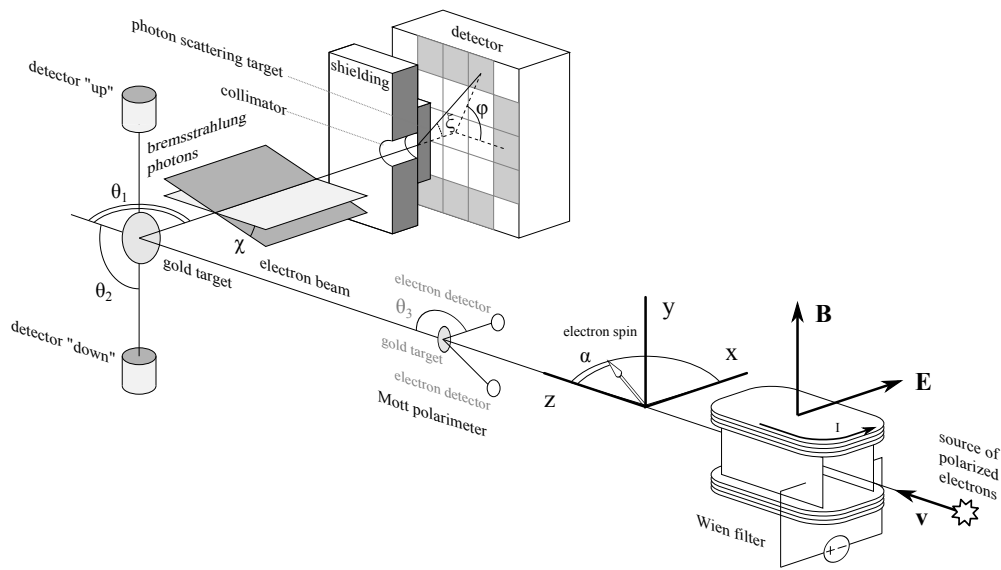
Figure 3. The experimental setup. The source produces longitudinally polarized electrons. Their spins are rotated within the horizontal plane to an angle α by the Wien filter. The degree of the beam polarization is monitored by the Mott polarimeter. The second electron polarimeter, based on bremsstrahlung, consists of a gold target and three detectors. The ratio of the x-ray intensities emitted up and down are monitored by a couple of scintillator detectors. Linear polarization of x-rays emitted in the horizontal plane is measured with the Compton polarimeter. It consists of an aluminum scatterer and a segmented germanium planar detector.

done with the intensity reduced by three or four orders of magnitude. The other alternative is to use the full intensity but to collimate the scattered electrons. This may give a more reliable result, as it is often important to monitor polarization with the same beam intensity that is used for the experiments.

In this article we present a different approach for the electron beam polarimetry. It uses bremsstrahlung emitted in electron collisions with heavy nuclei. As bremsstrahlung is the process secondary to Mott scattering it takes its spin properties. Namely bremsstrahlung has the left-right asymmetry in the number of the emitted x-rays. It appears due to a correlation between the direction of the emitted x-ray and the direction of the scattered electron in the moment of the x-ray emission, see figure 1. This correlation is a results of the Lorentz angle transformation and thus it is noticeable at relativistic velocities. Similarly to Mott scattering, the x-ray emission asymmetry reaches tens of percents and it can be easily observed.

In addition to the left-right emission asymmetry, we propose to measure bremsstrahlung linear polarization. The angle of polarization is sensitive to the precession of the electron's spin induced by the spin-orbit interaction: $d\mathbf{S}/dt \propto \mathbf{L} \times \mathbf{S}$. As a result the angle of polarization χ is correlated with the spin components within the scattering plane. Recently this correlation was observed in two experiments [10, 11, 12].

Below we outline the principles of such a technique. The electron polarization components along the axes x, y and z are S_x, S_y and S_z such that $S_x^2 + S_y^2 + S_z^2 \le 1$. Linear polarization is described by the Stokes parameters P_1 and P_2 such that the degree of polarization P and the angle χ are:

$$P = \sqrt{P_1^2 + P_2^2}, \ \ \cos 2\chi = \frac{P_1}{P}, \ \ \sin 2\chi = \frac{P_2}{P} . \tag{1}$$

The Stokes parameters are functions of the energy of both the electron and the x-ray and the spin orientation. Here we use the notation $P_{1,2}(S_x, S_y, S_z)$ which depicts only the spin dependence.
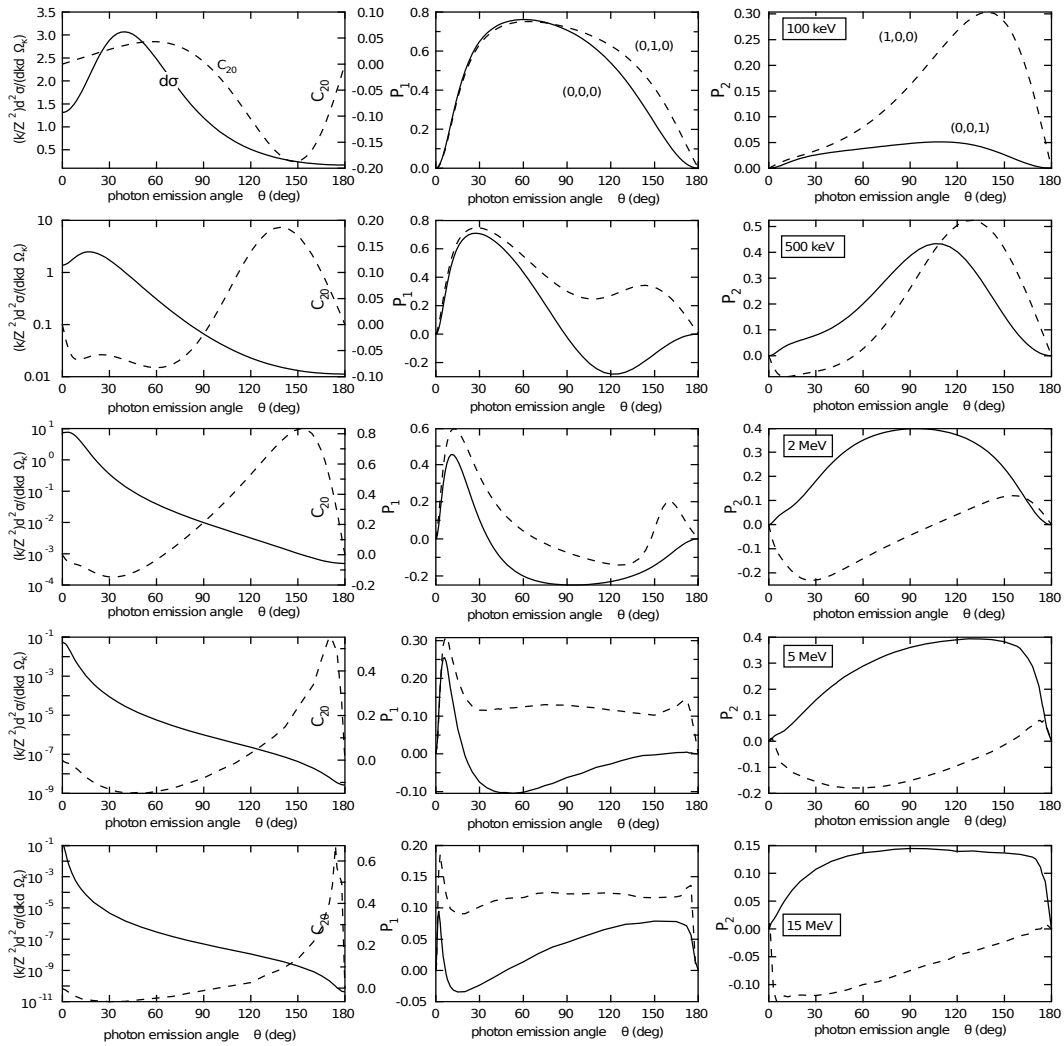
Figure 4. Theoretical predictions for bremsstrahlung polarization correlations in electron collisions with gold nuclei at the hard-photon limit [11]. The angular-differential cross section is shown in the units of $(k/Z^2)d^2\sigma/(dkd\Omega_k)$, where $-eZ$ is the nuclear charge and k is the photon energy. The parameter C_{20} describes the left-right asymmetry of the emitted photons and the Stokes parameters P_1 and P_2 describe their linear polarization.

Similarly the differential cross section is a function of the spin: $d\sigma(S_x, S_y, S_z)$. Figure 4 shows the theoretical predictions for the energies of 100 keV up to 15 MeV at the hard-photon limit. Only the independent components are displayed. The others can be obtained from the following equations. The bremsstrahlung cross section and polarization produced by a partially polarized electron beam are [11]:

$$d\sigma = d\sigma(0,0,0)(1 - S_y C_{20}), \tag{2}$$

$$P_1 = \frac{P_1(0,0,0)(1 - S_y) + S_y P_1(0,1,0)(1 - C_{20})}{1 - S_y C_{20}}, \tag{3}$$

$$P_2 = \frac{S_x P_2(1,0,0) + S_z P_2(0,0,1)}{1 - S_y C_{20}}. \tag{4}$$

Here C_{20} represents the x-ray left–right emission asymmetry from the transverse polarized
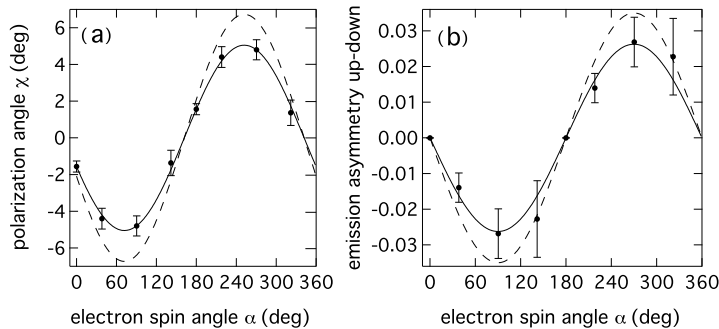
Figure 5. **a)** The angle χ of x-ray polarization as a function of the spin angle α. **b)** The x-ray emission asymmetry up–down as a function of the spin angle α. The data points are the results of the experiment discussed in the text [11]. The dashed lines are the predictions for the 100% polarized electrons and the solid lines are for 75% polarized ones which were used in the experiment.

electrons. It is the bremsstrahlung analogue of the Sherman function S. By measuring the up–down x-ray emission asymmetry one can determine S_x and in addition to that by measuring linear polarization of the x-rays emitted in the horizontal plane one can determine S_y and S_z. For a more reliable determination of S_y one can also measure the left–right emission asymmetry.

The experimental demonstration of this technique is published in [11]. Here we repeat some details of the experiment that are relevant for electron polarimetry. The experimental setup is shown in figure 3. The beam of polarized electrons passed through the Wien filter. It rotates the spins in the horizontal plane by an angle α. With this arrangement the transverse spin component S_y is zero. The degree of polarization was measured with the Mott polarimeter to be 75%. The beam passed the 200 nm thick gold foil and emitted bremsstrahlung in collisions with the gold nuclei. The transverse spin component S_x is detected by a combination of two scintillating detectors "up" and "down" mounted in the vertical plane at the scattering angle $\theta_2 = 120°$. The Compton polarimeter observed x-rays emitted in the horizontal plane. The angle of linear polarization is sensitive to S_x and S_z. The polarimeter consists of an aluminum scatterer and a segmented germanium detector to sample the azimuthal angular distribution of the scattered x-rays. The detector's active area of 5x5 cm is segmented with the 5x5 pixel matrix. The outer segments that are marked gray were used for the polarization measurement. The detector was shielded against the ambient x-rays from nearly all angles except for the collimator opening. The technique of Compton polarimetry is described in [10, 11].

In the experiment we used a 100 keV electron beam with an intensity of 0.1 μA up to 1 μA. Linear polarization for each spin orientation was measured for 4 hours. The total count rate of up to a few kHz was registered in the outer segments of the detector. This detector can accept up to 100 times higher rates. Therefore much quicker measurements with higher beam intensities are possible. The measurements of the up–down x-ray emission asymmetry with scintillators were done with the beam intensity of a few nA to reduce the count rate. Each measurement took half an hour. Due to the temperature variations the scintillator output drifted in time. As a result the count rate in any selected energy interval also drifted. This introduced systematic effects. To reduce those we split the data into one-minute intervals and analyzed them individually.

Only the hard end of the x-ray spectrum was analyzed. The reason for this is a high radiation background that appears at lower energies. It originates from the electrons that scatter in the target, impact the thick walls of the chamber and emit intense bremsstrahlung in collisions with the nuclei of the wall. The accelerator room itself has an intense background. It is produced by the electrons that are lost to the walls of the beam line. To reduce this background one can collimate the x-rays and shield the detector. The germanium polarimeter was properly shielded. The scintillator detectors, on the other hand, were not shielded, and as a result the measured up–down intensity ratio was reduced.

We have varied the spin angle α in steps of 45° and did measurements for each of these settings. Figure 5a shows the observed angle of x-ray polarization χ as a function of the spin
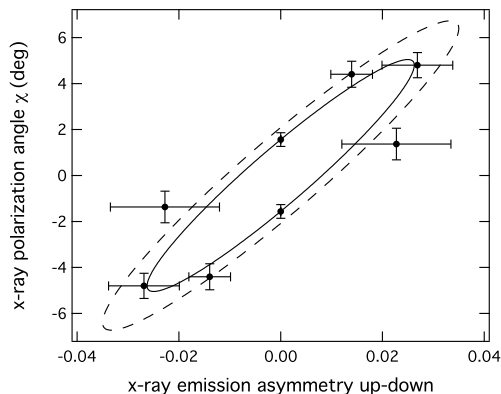
Figure 6. The x-ray polarization angle χ as a function of the x-ray emission asymmetry up–down. The data points are the results of the experiment discussed in the text [11]. The dashed line is the prediction for the 100% polarized electrons and the solid line is for 75% polarized electrons.

angle α. From this we extracted the degree of the electron beam polarization of $75 \pm 4\%$, which agrees with the Mott result and has a comparable uncertainty. This result is obtained with the assumption that the electrons are polarized horizontally ($S_y = 0$). This was the case in our experiment. In the general case one can determine it by measuring the left–right x-ray emission asymmetry, see Eq. (2). To extract the angle of polarization we measured the up–down x-ray emission asymmetry, see figure 5b. Both of the measurements are then combined into a single figure 6. The dashed curve outlines the allowed parameter space. Within this region each parameter combination corresponds to a specific angle of electron polarization α and a specific degree of electron beam polarization.

In summary we state that the angle and the degree of electron beam polarization can be measured with the bremsstrahlung technique. It requires two or four detectors for measuring the x-ray emission asymmetries and one x-ray polarimeter. With this technique all three electron polarization components can be simultaneously determined. This is an advantage as compared to the Mott technique. If the Compton polarimetry is used, the measurement can be done within a few hours with the electron beam intensity higher than 100 nA. For a faster measurement a higher beam intensity is needed. This is a disadvantage as compared to the Mott technique, which requires much smaller intensities. However, sufficiently intense beams are available at accelerators. In addition the bremsstrahlung measurement requires detectors that are more sophisticated as compared to the electron detectors.

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