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New compact electron spin polarimeter with a high efficiency

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Abstract

We have developed a new compact retarding-potential Mott spin polarimeter and achieved an efficiency of 1.9×10^{-4} for gold target operating in 25 keV. A novel design of the retarding field electron optics with 0.59 sr collections solid angle for scattered electrons was adopted based on Monte Carlo calculations for the spin-dependent electron scattering process and electron beam ray-tracing calculations. Combined the new spin polarimeter with an angle-resolved photoelectron spectrometer, we have measured the spin- and angle-resolved photoelectron spectra and studied the spin-dependent electronic structure of Ni(110) along the Γ S line of its surface Brillouin zone.

Keywords: Mott polarimeter, electron optics, figure of merit, spin- and angle-resolved photoelectron spectroscopy

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I. Introduction

Spin- and angle-resolved photoelectron spectroscopy has been increasing its importance as one of the feasible experimental techniques to obtain direct information on the spin dependent electronic structures of magnetic and non-magnetic materials ¹. These experiments are achieved in combination with two measurements; an angle-resolved photoemission and an electron spin polarization. For the electron spin polarization measurements, many kinds of spin-polarimeters have been developed utilizing various spin-dependent scattering processes. Among them, the Mott scattering process is one of the most widely used methods to measure the electron spin polarization ^{2, 3, 4}. In this scattering process, transversely polarized electrons are scattered by a target with a large atomic number, which results in a left-right asymmetry of the scattering intensities due to the spin-orbit interaction. If we know the Sherman asymmetry function, S , of the target, we would obtain the transverse polarization component, P_t , of the incident electrons through the relation,

$$P_t = A/S,$$

where A is the left-right scattering asymmetry,

$$A = (N_L - N_R)/(N_L + N_R),$$

which is obtained by measuring the number of electrons scattered to the left, N_L , and right, N_R , respectively. The inverse square of the statistical error of the polarization measurement is proportional to

$$\epsilon = (I/I_0)S^2,$$

where I_0 is the number of electrons entering the polarimeter and I is the total number of the scattered electrons measured by the left and right electron detectors. ϵ is termed as a figure of merit and is defined as the efficiency of the Mott polarimeter.

In conventional type of Mott polarimeters, the electron detectors and the target are kept at a high voltage of about 100 kV in the vacuum to obtain a large value of the Sherman function and hence a large figure of merit. Since electronic equipments, e.g. amplifiers, discriminators, electron counters, etc., are preferable to be outside of the vacuum chamber and to be operated near the ground potential, the electric insulation is strenuous and this kind of polarimeters tend to be made with a large size. On the other hand, the diffuse scattering Mott polarimeters^{5,6} and the spin-polarized low energy electron diffraction type polarimeters would have a comparable efficiency with a smaller size⁷. However, being operated around 100 eV, their performances are influenced by the contamination of the target surfaces and the surfaces should be renewed or cleaned repeatedly. The very low energy electron diffraction type polarimeter developed recently has the same difficulty⁸. The efficiency of mercury vapor type of Mott scattering polarimeters is not so high and it is not so easy to make a reliable mercury vapor target². In the retarding-potential Mott polarimeter, the detectors for the scattered electrons could be operated near the ground potential and the whole system could be made with a very compact size. Because of its high efficiency, good stability, small size and possibility for the self calibration, the retarding-potential Mott polarimeter has become one of the most widely used electron spin polarimeters and the efficiency of 1.6×10^{-4} has been achieved with a size of about 10 cm^3 ^{9,10,11}.

In this paper, we present a new compact size retarding-potential Mott polarimeter with a high efficiency, which could be easily attached to an electron energy analyzer and be utilized to measure the spin- and angle-resolved photoemission spectra. In Sec. II, we will describe our design principles and in Sec. III, we will present the performance of the Mott polarimeter and an example of spin- and angle-resolved photoemission spectra obtained utilizing the new polarimeter.

II. Design considerations

So far, electron detectors of Mott polarimeters have been usually set at the direction of a 120° scattering angle, where the absolute value of the Sherman function of a gold atom takes its maximum for the incident electrons with energies between 50 and 120 keV¹².

However, in practice, the electron detectors of the spin polarimeter should not be simply set at the scattering angle of 120° to obtain a high efficiency. Although the scattering intensity is higher for a large collection angle, the Sherman function is smaller for a larger collection angle, so we have to choose an appropriate collection angle and balance the intensity and the Sherman function to achieve a high efficiency. In addition, in constructing a Mott polarimeter, only a solid state target instead of an atomic one can be used and we have to consider the effective Sherman function in which the multiple and plural scattering are included. It is known that the effective Sherman function considerably depends on the target thickness¹³. Therefore, when we design a Mott polarimeter with a high efficiency, we have to know how the effective Sherman function and the scattering intensity depend on the target thickness and the scattering angle. For the retarding-potential Mott polarimeters, the dependence of the effective Sherman function and the scattering intensity on the energy loss windows has also to be considered. The energy loss window is the inelastic energy loss that an electron can suffer and still reach to the electron detector.

We have carried out the Monte Carlo calculations on the spin-dependent scattering process for 50 keV electrons incident on a gold target, and obtained the dependence of the effective Sherman function and the scattering intensity on the target thickness and inelastic energy loss windows for the scattering angles from 90° to 180° ¹⁴. Figure 1 and Fig. 2 show the effective Sherman function and the scattering intensity for different inelastic energy loss windows. We can see from these figures, the scattering intensity takes its maximum at the scattering angle of about 120° , and when the inelastic energy loss window is larger than 1200 eV the effective Sherman function is almost constant over a wide range of scattering angles. This enables us to design a Mott scattering spin polarimeter setting the electron detectors at the position of 120° and the larger the collection angle for scattered electrons, the higher the efficiency of the Mott polarimeter.

The new Mott polarimeter has been intended to be connected with a hemispherical electron energy analyzer to measure the spin- and angle-resolved photoemission spectra and the polarimeter consists of three parts of electron optics, which is shown in Fig. 3; a transport lens, a focus lens and the retarding optics. The transport lens consists of three

elements and its main purpose is to transfer the electron beam from the hemispherical electron energy analyzer to the electron spin polarimeter. The focus lens is a two elements lens and is used to focus the beam on the target as small as possible. The types and the sizes of the elements of both lenses were chosen to minimize the spherical aberration within the given geometrical restriction of our measurement system. For the transport lens, the magnification was set to be one and for the focus lens, magnification was set to be zero which results in an infinitesimal image on the target. The geometrical and electrical parameters of the lens system were chosen after referring to the data tables in ref. 15. The applying voltages of the 2nd and the 3rd elements of the transport lens were iterated using a commercial electron optics program to achieve the best focus ¹⁶. The schematics of the transport and focus lens system with typical applying voltages and the results of the ray tracing calculations are shown in Fig. 4. We could obtain the radius of the image on the target smaller than 0.3 mm for an incident electron beam with radius of 2 mm and the angle of divergence of 12°. The transmittance of the lens system is estimated by the calculation to be nearly one.

The most crucial thing in designing a retarding-potential Mott polarimeter is the retarding optics for the scattered electron beam. For the retarding-potential Mott polarimeters, the width of the energy loss window is usually set to be a few hundred eV to 1 keV and we have to collect the scattered electrons with different energies within the energy loss windows. Since we adopt a large collection angle to obtain a high scattering intensity, a special care should be taken to design the geometry and the applying voltages to the electrodes of the retarding optics to minimize the aberrations of the electron beam ¹⁷. Utilizing the electron optics program, the most reliable design of the retarding optics was determined. The schematics of the Mott polarimeter is shown in Fig. 5. To avoid the defocusing of the electron beam, a nearly radial retardong electric field was achieved for the scattered electrons. The inner and outer spherical electrodes are shaped a little larger than a hemisphere, actually 7/12 of a whole sphere, to minimize the effects of the flinging field and spherical grids are fixed at the apertures in the inner sphere. The aperture of the outer sphere tends to focus the electron beam. The cylindrical lens close to the outer sphere and the plane

grid in front of the multichannel plate (MCP) are used to lead the electron beam to the MCP with an almost perpendicular direction, which results in the increase of the electron counting efficiency of the detectors for low kinetic energy electrons, i.e. for electrons with large energy loss. Some of the calculated traces of the scattered electron beam in the retarding optics are shown in Fig. 6. In this figure, we can see only the electron beam with a 1500 eV energy loss and a 25° of divergence will fail to reach the MCP. This leads to a 50° of collection opening angle and a solid angle of 0.59 sr, which is much larger than those in the retarding-potential Mott polarimeters reported.

In the design of Mott polarimeters, another important thing is to avoid the accidental electric breakdown of the high voltage, which will cause a serious damage to the whole measurement system. In fact this limits the minimum size of the polarimeter. It is known the breakdown voltage is independent on temperature and vacuum when temperature and pressure are below 500 °C and 10⁻⁶ Torr, respectively. The smoother surface of the electrodes, the higher the breakdown voltage and the contamination will reduce the breakdown voltage. Among many factors which affect the electric breakdown, the most important one is the distance between the electrodes. The breakdown voltage is higher for longer distance between electrodes. Other important factors are the area and the configuration of the electrodes. Increasing the electrode area makes the breakdown voltage decrease. Convex electrodes have higher breakdown voltage than plane ones, even though for the same voltage, a higher electric field is expected at their smaller radius surface for convex ones ¹⁸. One empirical design criterion for the breakdown voltage of a distance between electrodes was given by the equation ¹⁹,

$$WE_c^2 \exp(-K_1/E_c) = K_2, \quad (1)$$

where W (eV) is the maximum possible energy of a particle at the electrode surface, E_c (V/cm) is the electrical field intensity at the cathode surface, K_1 is 1.7×10^{-5} , and K_2 is 1.8×10^{14} . Equation (1) determines a threshold below which no breakdown should occur even before conditioning. It is calculated from eq. (1), the electric field intensity at the cathode

surface should be below 130 kV/cm if we would work our polarimeter up to 40 kV. It is also reported that it is not so difficult to maintain a 100 kV/cm field strength between electrodes²⁰. In our design, 130 kV/cm was chosen as the limit of the electric field strength on the cathode surface. We use a special configuration to increase the breakdown voltage. The last element of the focus lens is inserted into the preceding lens element. By using this configuration, we could increase the insulating length between these two lens elements with the performance unchanged. We could also change a plane gap to a convex one and decrease the electric field intensity at the surface of the last lens element, i.e. the cathode of the focus lens. The surface of the last element of the focus lens and the inner and outer sphere of the retarding optics are polished to mirror to increase the breakdown voltage.

III. Performance of new Mott polarimeter

It is known that the secondary electron from Ni(110) surface irradiated by unpolarized electron beam are polarized^{21, 22}. These secondary electrons were used as the source of polarized electrons to calibrate our polarimeter. The energy of the primary electrons is set at 400 eV and the angle of incidence of the primary electrons is set at 30° with respect to the Ni surface normal. The measurement is done in normal emission manner and the sample is -30 V biased to depress the background. To eliminate the instrumental asymmetry, we measured the scattering asymmetry of the secondary electrons by two successive measurements with opposite magnetization direction.

All the performance was checked by using gold target. The measured scattering asymmetries of secondary electrons of 2 eV kinetic energy for different energy loss windows for 25 kV operating voltage are shown in Fig. 7. In the figure, the asymmetry does not simply decrease with the increase of the energy loss window due to the increasing contribution of inelastically scattered electrons, but has a peak at about 200 eV. This is related to the large collection angle of the retarding optics. When the kinetic energy of electrons entering MCP tends to zero, the motion direction of electrons can easily be deflected by the electrode in front of the MCP and only the electrons whose motion direction are perpendicular to the MCP plane can arrive MCP. For the electrons with sufficiently large

energy loss, we can see from the electron ray tracing calculations in Fig. 6, only the electrons with the angle of divergence of about 20° and 0° can arrive MCP. The electrons with angles of divergence around 20° tend to arrive in the region out of center of MCP, which forms a shape of a doughnut. On the other hand, the electrons with smaller angle of divergence near zero distribute around the center of MCP and forms a disk in the MCP plane.

As the energy loss window increases, the contribution of the doughnut to the scattered electron intensity decreases and for the energy loss window larger than 200 eV it is almost negligible. Hence, for the energy loss window larger than 200 eV, the asymmetry is determined by the electrons scattered with smaller angle of divergence, which will decrease as the energy loss window increases. When the energy loss window is smaller than 200 eV, the contribution of the doughnut to the scattered electron intensity is comparable with that of the disc and the contribution of the electrons of the doughnut area will increase as the energy loss window decreases, which results in the decrease of the effective Sherman function. As the energy loss window tends to zero, the contribution of the disc becomes so small that it does not contribute to the measured asymmetry.

Extrapolating the energy loss window to zero, the effective Sherman function of electrons of this disk is 0.317 corresponding to the value of gold atom at the scattering angle of 120°¹², and the effective Sherman function of the doughnut tends to 0.252 which is the average of $S(\theta)\sin\phi$ for electrons with 25° of divergence. Because of the above described complex behavior of the scattering asymmetry with the energy loss window, the calibration of the effective Sherman function could not be done by a simple extrapolation to the zero energy loss window. We adopted the average of measured spin polarization of the secondary electrons with 2 eV kinetic energy to calibrate the polarimeter^{23, 24}. The measured asymmetry of the secondary electrons from Ni(110) for different kinetic energy is shown in Fig. 8. Comparing this result with those in ref. 23 and ref. 24, the effective Sherman function of the polarimeter can be calibrated, which is shown in Fig. 9 (b).

We have measured the scattering intensity of our polarimeter as a ratio of the incident electron intensity to the scattered electrons intensity counted by the detectors. The scattering

intensities of different energy loss windows at 20, 25 and 30 keV operating voltages are shown in Fig. 9(a). The efficiency of the polarimeter obtained is shown in Fig. 9(c). The maximum efficiency of $(1.9 \pm 0.2) \times 10^{-4}$ is obtained for a 25 keV operating voltage and a 800 eV energy loss window. The corresponding scattering intensity and the Sherman function are $(9.7 \pm 0.2) \times 10^{-3}$ and 0.14 ± 0.01 , respectively. Our result of the efficiency is slightly larger than the largest efficiency reported by using a thorium target. Since the atomic weight of thorium is larger than that of gold, by replacing the target from gold to thorium the effective Sherman function and the scattering intensity will increase by 10 - 20 % and 15 %, respectively⁴. Hence, the efficiency of our polarimeter will increase to 2.9×10^{-4} by using a thorium target, which will be 1.8 times larger than those reported, so far.

There have been many studies to investigate the spin-dependent electronic study of solids, solid surfaces and atoms and molecules on solid surfaces. However, most of the spin- and angle-resolved photoemission measurements have been achieved in normal emission, which provides information on the electronic structure in a restricted symmetry of the bulk Brillouin zone^{24, 25, 26}. This is mainly due to the experimental difficulties accompanying to the rotation of the electron energy analyzer and/or the spin polarimeter, e.g. a large size Mott spin polarimeter was difficult to be rotated and a very small mis-alignment in the transport lens system during the rotation of the electron energy analyzer might make it troublesome to re-adjust the applying voltage to the lens elements. The spin polarimeter in this study was designed especially to avoid those difficulties. By connecting the Mott polarimeter to the end of an angle-resolved photoemission spectrometer, we have measured spin- and angle-resolved photoemission spectra out of normal emission direction. Figure 10 shows the spin- and angle-resolved photoemission spectra of clean Ni(110) along the Γ S line of its surface Brillouin zone. The spectral feature at 1.3 eV binding energy emerges near S point, corresponding to an emission angle near 50°, and show a large negative spin polarization.

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Figure Captions

- Figure 1. The calculated effective Sherman functions for different scattering angles for 300, 600, 900, 1200, 1800 and 2700 eV of inelastic energy loss windows.
- Figure 2. The calculated scattering intensities for different scattering angles for 300, 600, 900, 1200, 1800 and 2700 eV of inelastic energy loss windows.
- Figure 3. Schematics of the spin polarimeter and the transport lens system.
- Figure 4. Schematics of the transport and focusing lens systems with a result of the ray tracing calculation. Note that the trace of electron is expanded along vertical direction.
- Figure 5. Schematic diagram of the retarding-potential Mott polarimeter.
- Figure 6. Results of ray tracing calculations for the scattered electron beams in the retarding optics for the electrons with 0, 500, 800 and 1500 eV of energy loss and 0° , 5° , 10° , 15° , 17.5° , 22.5° and 25° of divergence.
- Figure 7. Scattering asymmetry of secondary electrons from Ni(110) with 2 eV kinetic energy for different energy loss windows. The polarimeter is working at 25 kV. Bar in every measured point represents the statistical error.
- Figure 8. Scattering asymmetry of secondary electrons for different kinetic energies from Ni(110) excited by unpolarized electron beam. The polarimeter is working at 25 kV and the energy loss window is set at 800 eV. Bars show the statistical errors of the measurement.
- Figure 9. Measured scattering intensity (a), effective Sherman function (b) and efficiency (c) of the Mott polarimeter for different energy loss windows working at 20, 25 and 30 keV. The lines in every panel show the polynomial function fitting to the experimental results. Bars show the statistical errors of the measurements.
- Figure 10. Spin- and angle-resolved photoelectron spectra of clean Ni(110) surface measured along the GS line excited by He I radiation. θ is the photoelectron emission angle of every spectrum.

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Figure 7 S. Qiao et al. Rev. Sci. Instr.

Figure 8 S. Qiao et al. Rev. Sci. Instr.

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Figure 10 S. Qiao et al. Rev. Sci. Instr.