Multiple electron capture spectroscopy

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The experiments described in this thesis have been performed in the Atomic Physics research group (ATF), at the Kernfysisch Versneller Instituut in Groningen. Experimental set-ups in the Atomic Physics lab share an Electron Cyclotron Resonance Ion Source (ECRIS). The (highly charged) ions produced by the ECRIS are used to study interactions with various physical systems. The experiments on ion-surface interactions are done at the Surphyn’ set-up. Both the ECRIS and the Surphyn’ set-up will be described in detail in the following sections. Further, an overview will be given of the experimental techniques used to prepare and characterize the surfaces studied in this work.

### 3.1 ECRIS

In an ECRIS, highly charged ions are produced stepwise by electron impact ionization. In order to sequentially ionize the highly charged ions, electrons with a wide range of energies are needed. In the ECRIS, these electrons are produced inside a magnetic trap formed by a radial magnetic field from a hexapole permanent magnet and a longitudinal field from two magnetic coils. The electrons will gyrate inside the trap along the magnetic field lines with the cyclotron frequency \( \omega_c = \frac{2\pi e B}{m_e} \). Obtaining high energy electrons is achieved by applying a radiofrequency field (RF field) (14 GHz). When the RF frequency equals the revolution frequency \( \omega_c \), electron cyclotron resonance occurs: the electrons are accelerated by the RF field.
In the ATF ECRIS, the RF field is injected coaxially. The whole trap is put on high voltage (up to 25 kV), and the ions produced are extracted using a movable puller lens, which can be put on a negative voltage to improve the extraction of low energy or low charge state ion beams.

After extraction, the ions are charge-over-mass selected by an 110° bending magnet, and guided to the various experimental set-ups by means of a series of quadrupole magnets. The maximum charge state obtained with the current ECRIS is Xe$^{25+}$. The highest charge which can be obtained is limited by a number of factors, like recapture of electrons, the increasing amount of impact energy needed and the confinement time in the magnetic trap.

3.2 Surphyn

A sketch of the Surphyn’ set-up is shown in Fig. 3.2. The set-up consists of a cylindrical 300 mm diameter μ-metal UHV chamber, equipped with a sample manipulator$^1$, a deceleration lens system, a rotatable Electrostatic Analyzer (ESA), an ion gun$^2$ and a light polarization analysis system. There is also a sample transfer system attached, and an UHV evaporator system$^3$.

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$^1$Manufactured by Thermo Vacuum Generators, Hastings, UK
$^2$Manufactured by Specs GmbH., Berlin, Germany
$^3$Manufactured by Focus GmbH., Hünstetten-Kesselbach, Germany.
3.2 Surphyn’

The Surphyn’ chamber is connected to the ion beam line \( p \simeq 10^{-8} \text{ mbar} \) by a differentially pumping stage and a 45° bending magnet. The \( \mu \)-metal shielding of the set-up prevents for stray magnetic fields penetrating the chamber and disturbing the electron detection. Residual magnetic fields inside the chamber are of the order of a few \( \mu \)T. The chamber is kept at a pressure in the low \( 10^{-10} \text{ torr} \) by a 400 l/s ion getter pump. During sample preparation cycles, a differential pumping stage consisting of a combination of a rotary forepump and a turbo pump is also used.

The sample manipulator has three translational degrees of freedom, \( \Delta x = \Delta y = 25 \text{ mm} \) and \( \Delta z = 400 \text{ mm} \) (the coordinate system is indicated in Fig. 3.2), as well as two rotational degrees of freedom, the incidence and azimuth angle, \( \Delta \psi = 250^\circ \) and \( \Delta \phi = 100^\circ \). The manipulator has a non-magnetic sample holder, which allows for heating the sample either by electron bombardment up to 1200 °C or by radiative heating up to 530 °C. The temperature of the sample is measured by means of two non-magnetic N-type thermocouples. A soft iron yoke can be mounted on the sample holder, enabling the magnetization of the sample crystal, if desired.

The Specs ion gun is a fine focus and scannable ion source, with a tunable beam spot diameter from 125 \( \mu \)m to 1000 \( \mu \)m and a scanning area of \( 10 \times 10 \text{ mm}^2 \). It can be used for producing singly charged ions of noble gasses as well as of reactive gasses, like \( \text{O}_2 \) or \( \text{H}_2 \), in the 500 – 5000 eV energy range. The appli-
Cations of the ion gun range from sample cleaning and etching, to Low Energy Ion Spectroscopy (LEIS), depth profiling and Secondary Ion Mass Spectrometry (SIMS). In the experiments described in this thesis, the ion gun was mainly used for sputter-cleaning the sample and for LEIS.

### 3.2.1 Ion deceleration and collimation

The ions are extracted from the ECRIS with energies in the keV range, and are decelerated by floating the whole set-up on the ion source potential. In this way, the ions can be decelerated in principle to zero energy. The actual deceleration takes place in a four element electrostatic lens system placed at the beam line entrance in the chamber (Fig. 3.3). The desired energy of the ions entering the set-up is determined by applying an offset potential $V_{\text{bias}}$ in series with the source potential. The final energy of an ion with charge $q$ is given by the sum of the $V_{\text{bias}}$ and a small contribution due to the plasma potential in the ion source, $V_p \simeq 10$ V [45]:

$$E_i = q \cdot (V_{\text{bias}} + V_p)$$

The overall transmission of the ions from the analysis magnet of the ECRIS to the sample is of the order of 1%, depending somewhat on the mass-over-charge ratio of the ions (the higher the charge, the lower is the transmission). The ion current can be monitored either by a movable Faraday cup placed in front of the deceleration stage, or by measuring the sample current. The latter method is used during data collection in order to be able to correct for beam fluctuations.
3.2 Surphyn’

Figure 3.4: Lens system, sample and ESA. The observation angle $\theta$ of the ESA can be varied between $0^\circ$ and $140^\circ$.

Typical sample currents range from a few tens nA to a few hundred nA, but values of up to a few $\mu$A can be reached for He$^+$ ions. The electrostatic lens system induces no extra beam intensity loss for deceleration factors up to 100, while the beam spot size is only slightly larger than for the direct beam. For deceleration factors higher than 100, the beam tends to diverge more strongly, therefore the diaphragm D$_4$ (cf. Fig. 3.3) was installed for additional collimation of slow ions. A detailed description of the deceleration stage can be found in ref. [45].

3.2.2 Electrostatic analyzer

All ion and electron spectra presented in this thesis were taken using the hemispherical electrostatic analyzer (ESA) sketched in Fig. 3.4. Since the ESA has been thoroughly described in previous works ([45, 46]), only the main features of the spectrometer will be presented here.

In a hemispherical ESA, voltages are applied on the inner and outer hemispheres to set the pass energy for the charged particles. The voltages $V_i$ and $V_o$ on the inner and outer hemispheres are varied in such a manner that the potential $V(r)$ on the central trajectory is zero. The electric field between two concentric...
spheres is given by:

\[ E(r) = \frac{(V_0 - V_i) r_o r_i}{r^2 (r_o - r_i)} \]  

(3.2)

with \( r \) the trajectory radius between \( r_o \) and \( r_i \). Integration of \( E(r) \) yields the potential \( V(r) \), using the boundary conditions \( V(r_o) = V_o \) and \( V(r_i) = V_i \):

\[ V(r) = \frac{V_o r_o - V_i r_i}{r_o - r_i} - \frac{(V_o - V_i) r_o r_i}{r (r_o - r_i)} \]  

(3.3)

By setting \( V(r) = 0 \) on the central trajectory \( r = (r_o + r_i)/2 \), the ratio of the voltages to be applied on the plates is obtained:

\[ \frac{V_o}{V_i} = -\frac{r_i}{r_o} \]  

(3.4)

The pass energy of a particle of charge \( q \) on the central trajectory is:

\[ E(q) = q \frac{V_o - V_i}{r_o r_i^{-1} - r_i r_o^{-1}} \]  

(3.5)

The ratio between the applied voltage and the energy of the detected particle, called the spectrometer proportionality factor \( F \), is:

\[ F = \frac{1}{r_o r_i^{-1} - r_i r_o^{-1}} \]  

(3.6)

The radii of the ESA are \( r_o = 52 \text{ mm} \) and \( r_i = 48 \text{ mm} \), yielding a voltage ratio of \( V_o/V_i = -0.923 \) and a proportionality factor \( F = 6.24 \). As the ESA is hemispherical, the real \( V_o/V_i \) and \( F \) deviate slightly from the ideal values. Calibration of the ESA gave \( V_o/V_i = -0.935 \) and \( F = 6.42 \) [47].

The energy resolution of the ESA is 0.5% FWHM, with a total acceptance of \( 1.12 \times 10^{-7} E \) (sr eV). Electrons which have energies higher than 20 eV can be measured with nearly 100% efficiency. For electrons with energies lower than 20 eV, the transmission is distorted due to the residual magnetic field, leading to a loss in detection efficiency.

For the conversion of the raw counts detected by the ESA to absolute number of emitted particles, one has to take into account different correction factors [47]. One factor is the proportionality of the spectrometer acceptance to the energy of the detected particle, therefore the number of counts has to be divided by energy. Other correction factors are the angular emission probability, which is not necessarily isotropic, and a geometry correction, which compensates for the overlap between the ion beam spot and the spectrometer spot on the surface.
3.2.3 Light polarization analysis

In the following, a description of the method used in Chapter 4 to measure the degree of polarization of light will be given. While strictly monochromatic light must be in some state of polarization, light that contains a band of wavelengths can be unpolarized or partially polarized. For our discussion, we will consider quasi-monochromatic light propagating in the \( z \) direction, having the orthogonal components at a point in space given by [48]:

\[
E_x(t) = a_x(t)e^{-i[\omega_m t - \phi_x(t)]}, \quad E_y(t) = a_y(t)e^{-i[\omega_m t - \phi_y(t)]}
\]

(3.7)

where \( a_x \) and \( a_y \) are the electric field amplitudes along the \( x \) and \( y \) axes, respectively, and \( \omega_m \) is the mean frequency of an electric field with bandwidth \( \Delta \omega \ll \omega_m \). The field amplitudes \( a_l(t) \) and phases \( \phi_l(t) \) are constant for monochromatic light, whereas for quasi-monochromatic light, these quantities fluctuate irregularly and are statistically correlated. The timescale on which the pair \( a_l(t) \) and \( \phi_l(t) \) show a similar time response is given by the coherence time \( \tau \sim 2\pi/\Delta \omega \). We say that the light is unpolarized, or natural, if the time evolution of the pair of functions \( a_l(t) \) and \( \phi_l(t) \) is completely uncorrelated within the detection time.

Several methods have been developed to describe the polarization of light and the evolution of the polarization state as light passes through optical components. Making use of the quasi-monochromatic fields, Jones calculus uses a \( 2 \times 2 \) coherency matrix to represent polarizations. In this work, the Stokes vector representation will be used, as it contains readily measurable quantities, and it can be related to the coherency matrix. For a quantitative description of the evolution of the polarization states of the light upon passage through various optical components, real Mueller \( 4 \times 4 \) matrices can be combined with Stokes vectors.

The coherency matrix \( J \) can be written as:

\[
J = \begin{pmatrix}
\langle E_x(t)E_x(t)^* \rangle & \langle E_x(t)E_y(t)^* \rangle \\
\langle E_y(t)E_x(t)^* \rangle & \langle E_y(t)E_y(t)^* \rangle 
\end{pmatrix} = \begin{pmatrix}
J_{xx} & J_{xy} \\
J_{yx} & J_{yy}
\end{pmatrix}
\]

(3.8)

where the angle brackets denote the time average and the asterisk denotes the complex conjugate. The four elements of the Stokes vector are related to the Jones matrix as:

\[
I = J_{xx} + J_{yy} = \langle a_x(t)^2 \rangle + \langle a_y(t)^2 \rangle \\
M = J_{xx} - J_{yy} = \langle a_x(t)^2 \rangle - \langle a_y(t)^2 \rangle \\
C = i(J_{xy} + J_{yx}) = 2\langle a_x(t)a_y(t) \cos(\Delta \phi) \rangle \\
S = i(J_{yx} - J_{yy}) = 2\langle a_x(t)a_y(t) \sin(\Delta \phi) \rangle
\]

(3.9)

Each of the four Stokes parameters is related to the difference between light
intensities of specified orthogonal pairs of polarization states:

\[
A = \begin{pmatrix} I \\ M \\ C \\ S \end{pmatrix} = \begin{pmatrix} P_{0^\circ} + P_{90^\circ} \\ P_{0^\circ} - P_{90^\circ} \\ P_{45^\circ} - P_{-45^\circ} \\ P_{rcp} - P_{lcp} \end{pmatrix}
\]  

(3.10)

therefore \( I \) represents the total intensity of the light, \( M \) is the intensity difference between horizontal (along \( x \) axis) and vertical (along \( y \) axis) linearly polarized light, \( C \) is the intensity difference between \( 45^\circ \) and \(-45^\circ \) linearly polarized light and finally, \( S \) is the intensity difference between right- and left-handed circularly polarized light. The Stokes parameters are related by:

\[
I^2 \geq M^2 + C^2 + S^2
\]  

(3.11)

The degree of polarization of the light can be written as:

\[
P = \sqrt{\frac{M^2 + C^2 + S^2}{I^2}}
\]  

(3.12)

If one replaces the numerator in Eq. 3.12 with \( M^2 + C^2 \), the degree of linear polarization is obtained, while if the numerator is replaced by \( S^2 \), the degree of circular polarization is obtained. If a light beam characterized by the Stokes vector \( A \) passes through an optical component, the output state \( A' \) can be determined by using the transformation \( A' = MA \), where \( M \) is the \( 4 \times 4 \) Mueller matrix describing the respective optical component. Of course, \( M \) can be a product of \( n \) cascaded components \( M_i \):

\[
M = \prod_{i}^{n} M_i
\]  

(3.13)

The order in which the matrix product is written has to follow the sequence in which the optical components are reached by the light. For example, if the light is incident on component 1 and exits component 2, the Stokes vector \( A' \) is obtained as \( A' = M_2M_1A \).

In order to measure the polarization properties of an optical beam, a polarization analyzer is needed [49]. For example, a circular polarizer, made by combining a rotatable quarter-wave retarder and a linear polarizer, can be used as a polarization analyzer. The optical system used for the detection and polarization analysis of the light (see Fig. 3.2) is made of a solid Al mirror, a bi-convex quartz lens (\( f = 100 \) mm), and the actual polarization analyzer, made of a rotatable quarter-wave retarder, a linear polarizer, an interference filter for selecting the appropriate wavelength and finally, a photomultiplier tube (PMT) for detecting the intensity of the output light. In our experiment, the part of the optical system following the quartz lens is outside the vacuum chamber, a fused silica port
being in between the lens and the quarter-wave plate. The components which affect the polarization state of the light are the mirror, the quarter-wave retarder and the linear polarizer. The corresponding Mueller matrices are [49]:

\[
M_m = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]

\[
M_r(\delta, \beta) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos 4\beta \sin \frac{\delta^2}{2} & \sin 4\beta \sin \frac{\delta^2}{2} & -\sin 2\beta \sin \delta \\
0 & \sin 4\beta \sin \frac{\delta^2}{2} & -\cos 4\beta \sin \frac{\delta^2}{2} + \cos \frac{\delta^2}{2} & \cos 2\beta \sin \delta \\
0 & \sin 2\beta \sin \delta & -\cos 2\beta \sin \delta & \cos \delta
\end{pmatrix}
\]

\[
M_{pol}(\theta) = \frac{1}{2} \begin{pmatrix}
1 & \cos 2\theta & \sin 2\theta & 0 \\
\cos 2\theta & \cos 2\theta^2 & \cos 2\theta \sin 2\theta & 0 \\
\sin 2\theta & \cos 2\theta \sin 2\theta & \sin 2\theta^2 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}
\]  

(3.14)

where \(M_m\) is the Mueller matrix for a mirror, \(M_r(\delta, \beta)\) is written for a retarder of retardance \(\delta\) rotated at an angle \(\beta\) from the \(x\) axis and \(M_{pol}(\theta)\) is the matrix of a linear polarizer at angle \(\theta\). The Stokes vector \(A'\) of the light detected in the PMT is then:

\[
A' = M_{pol}(\theta) M_r(\delta, \beta) M_m A
\]  

(3.15)

The resulting intensity \(I'\) detected by the PMT depends on the four initial Stokes parameters as follows:

\[
I' = \frac{1}{2} \left[ I + M (\cos 2\theta \cos 2\beta - \cos \delta \sin 2\theta \sin 2\beta) + 
          + C (\cos \delta \sin 2\theta \cos 2\beta + \cos 2\theta \sin 2\beta) + S \sin \delta \sin 2\theta \right]
\]  

(3.16)

By fitting the above expression to the measured intensity, one can determine the four initial Stokes parameters of the light, \(I, M, C\) and \(S\), and therefore obtain the degree of linear and circular polarization.

### 3.3 Experimental techniques

In this section, an overview will be given of the two techniques used in this work to probe surface magnetism, as well as of other experimental techniques used presently to characterize magnetic surfaces and to explore surface spin polarization. Also, the main ideas behind Low Energy Ion Spectroscopy (LEIS), used for determining the chemical composition of surfaces, will be given. The first technique that we have used for probing magnetism is Electron Capture
Experiment Spectroscopy (ECS), which exploits the fact that the spin of the captured surface electron couples to the orbital angular momentum of the ion, leading to changes in the degree of circular polarization of the light emitted by the excited projectile [1, 25–28]. This technique is suitable to study the long-range magnetization of the surface. In order to have access to the short-range spin ordering at the scale of the electron exchange length, we have developed a new method for probing surface spin polarization, called Multiple Electron Capture Spectroscopy (MECS) [9]. MECS is based on the Auger electron emission from excited atoms formed upon interaction of slow, multiply charged ions with surfaces [16–20]. The relative intensity of the spectral peaks can be related to the local degree of surface spin polarization.

3.3.1 Electron capture spectroscopy

The method of Electron Capture Spectroscopy (ECS) was first developed by Rau et al. [24, 50]. In their experiment, the spin polarization of electrons captured into fast (150 keV) deuterons was detected via a nuclear reaction. After scattering off a ferromagnetic surface, the neutralized deuterons collide with a solid target, creating alpha particles. A part of the spin polarization of the electron shell of the neutralized deuterons is transformed via the hyperfine interaction into nuclear polarization of the alpha particles. The quantity measured is the angular anisotropy of the emitted alpha’s. This is a rather complex method and the analysis of the obtained results is by no means straightforward due to the intermediate steps involved.

Later, ECS was applied to electron capture into excited atomic terms. The electron spin polarization is then probed via the analysis of the circular polarization of fluorescence light. This branch of ECS matured and has been applied to study a whole variety of magnetic surfaces ranging from pure crystals to thin films [1, 25–28, 51]. Singly charged ion beams of 5 – 100 keV are scattered grazingly off ferromagnetic surfaces, the spin of the captured electrons couples to the orbital angular momentum via spin-orbit coupling, leading to a shift in the population distribution over magnetic sub-states. This in turn causes changes in the degree of polarization of the light emitted by the neutralized projectiles. Ion beams in grazing incidence interact only with the top-most surface layer, making ECS a suitable method for probing long-range magnetization of ferromagnetic surfaces. This method and the results that we have obtained using it will be discussed in more detail in Chapter 4.

3.3.2 Multiple electron capture spectroscopy

Multiple Electron Capture Spectroscopy (MECS) exploits the changes observed in the characteristic Auger spectra from slow, multiply charged ions, as a func-
tion of the spin polarization of a surface [9]. As the spin of the electrons is conserved during the capture process, there is a different capture probability into different spin states depending on the surface’s polarization. If the surface has a high degree of spin polarization, on average, high spin states will be more likely to be populated, while for a surface of low or no polarization, electron capture into low spin states becomes more likely. Then by varying the spin polarization of a surface (for example, by changing the temperature of a ferromagnet), changes occur in the relative peak intensities in the Auger spectra. Having in mind that slow, multiply charged ions capture electrons from an area of a few Å² up to a few tens of Å² (depending on the scattering conditions), MECS has the potential of becoming a tool for probing surface magnetism on a length scale below the electron exchange length.

3.3.3 Other techniques

There is a number of established techniques to investigate surface magnetism, each with its respective strengths and weaknesses. For example, the techniques based on Magneto-Optical Kerr effect (MOKE) [52] or magnetic second harmonic generation [53] have the advantage of allowing for magnetic field dependent measurements, a possibility owed to the fact that photons are used as probe. In addition, X-ray magnetic circular dichroism offers elemental sensitivity [54]. However, the probing depth is in the order of a few atomic layers, and the surface area probed is in the order of a few μm². The surface sensitivity can be enhanced by using soft-X-rays, the Auger electrons produced in the sample having lower energies and therefore shorter escape lengths [55, 56].

Spin-resolved electron spectroscopies can either probe the spin-dependent density of states, like spin-polarized electron emission (SPEE) and spin-resolved appearance potential spectroscopy, or can probe spin-specific electron states as function of the wavevector, like the technique of spin-resolved inverse photoemission [57,58]. The surface sensitivity of techniques using low-energy electrons is limited by the inelastic mean free path of electrons in a solid, which is of ~ 5 Å at its lowest, meaning that the information depth is still of the order of a few atomic layers. Also, the measured samples are required to be in a remanent state of magnetization, and to have shapes which minimize stray magnetic fields that otherwise can easily disturb the low-energy electrons.

Experimental methods with nanometer resolution are, for example, magnetic force microscopy (MFM) or scanning electron microscopy with polarization analysis (SEMPA) [59, 60]. Spin-polarized scanning tunnelling microscopy (SP-STM) combines excellent surface sensitivity with unprecedented spatial resolution at the scale of the electron exchange length [61]. However, a ferromagnetic tip can have a disturbing influence when investigating magnetically soft materials [62].
3.3.4 LEIS

Low energy ion scattering (LEIS) can be used for determining the chemical composition of surfaces, as well as for estimating the surface roughness [2]. In LEIS, ions of known species and energy (in the keV range) impinge on a surface, and the energy distribution of the scattered projectiles is measured under a fixed scattering angle. The major scattering contribution comes from elastic scattering, and the collision process can be described by one or a sequence of two-body collisions. The investigation of the chemical composition requires only elementary physics (conservation of momentum and energy), while effects due to shadowing of the surface atoms give indications on the surface roughness [1, 2]. For the analysis of the LEIS spectra from this work, a model where the scattering is described as a sequence of two-body elastic collisions will be used. This approximation works well for keV ion energies because the collision time of a few fs is much shorter than the period of crystal phonons. The energy transferred in a collision for a given scattering angle determines the elastic scattering event. If we consider a hard-sphere collision between an ion and a surface atom at rest, the final energy of the scattered projectile can be obtained from conservation laws of energy and momentum [2]:

\[
\begin{align*}
M_p v_{i,p}^2 &= M_p v_{f,p}^2 + M_a v_a^2 \\
M_p v_{i,p} &= M_p v_{f,p} \cos \theta + M_a v_a \cos \phi \\
0 &= M_p v_{f,p} \sin \theta - M_a v_a \sin \phi
\end{align*}
\]  

(3.17)

where \( M_p, M_a \) are the projectile and the surface atom mass, respectively, \( v_{i,p}, v_{f,p}, v_a \) are the initial and final velocity of the projectile, \( v_a \) is the recoil velocity of the atom and finally, \( \theta \) and \( \phi \) are the scattering and the recoil angle, respectively. The energy ratio of the primary and scattered ions, \( E_{f,p}/E_{i,p} \), which is the measured

![Figure 3.5: Hard-sphere elastic scattering.](image-url)
3.3 Experimental techniques

Figure 3.6: LEIS spectra from an oxidized (solid line) and clean (dotted line) Fe(110) surface.

quantity in LEIS, can be extracted from Eq. 3.17:

\[
\frac{E_{f,p}}{E_{i,p}} = \left( \frac{\cos \theta \pm \sqrt{\mu^2 - \sin^2 \theta}}{1 + \mu^2} \right)^2
\]

(3.18)

where \( \mu = \frac{M_a}{M_p} \). In Eq. 3.18 only the plus sign applies if \( \mu > 1 \), otherwise both plus and minus signs are valid. By using noble-gas ions and detecting only the scattered ions, practically only projectiles that have suffered single collisions are detected, as the probability of a noble-gas ion surviving a multiple collision series as ion is very small, due to its high ionization potential.

As an illustration of the technique, Fig. 3.6 shows two LEIS spectra taken with 2 keV He\(^+\) ions scattered over 60° from an oxidized (solid curve) and a clean Fe(110) surface. Using the scattering cross-sections determined by Wheeler [63] for a series of oxides surfaces, the analysis of the LEIS spectrum of the oxidized Fe shows that the oxide is Fe\(_3\)O\(_4\). In order to obtain a clean Fe surface, long cycles of Ar\(^+\) sputtering and annealing to elevated temperatures were required. After approximately two months of preparation, a clean Fe(110) surface was obtained, as seen in the dotted LEIS spectrum.