The development of a three-component electron spin polarimeter

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THE DEVELOPMENT OF A THREE COMPONENT ELECTRON SPIN POLARIMETER

by

ANDREW E. R. MALINS

Department of Physics, Loughborough University
and
CLRC Daresbury Laboratory

A Doctoral Thesis
submitted in partial fulfilment of the requirements
for the award of
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June 2000

Supervisors: Dr. E. A. Seddon
Dr. M. D. Crapper
Dr. M. Petty
ABSTRACT

The thesis is primarily concerned with the design, construction and preliminary commissioning of a novel polarimeter for full three-dimensional analysis of electron spin polarisation. The polarimeter is described in detail, together with the theoretical basis for its operation. Studies of an amorphous ferromagnetic alloy, Co$_{68}$Fe$_4$Ni$_{18}$B$_{14}$Si$_{15}$, and its application as a secondary standard are presented. Finally, a design study of a GaAs polarised electron source, capable of providing both longitudinal and transverse polarisations, is detailed.

The three component polarimeter is a development of a retarding potential Mott polarimeter. It utilises spin dependent electron transmission, through an ultrathin ferromagnetic structure, for determination of longitudinal components of polarisation. The required ferromagnetic structure is a sandwich of a 10 Å thick layer of cobalt, supported and protected on both sides by layers of gold. Transverse polarisation measurements are obtained by conventional Mott scattering from the thick gold layer on the front face of the ferromagnetic structure. The electron optical design of the polarimeter is shown to be effective, when configured appropriately, for both the transmission and the Mott scattering modes of operation. The performance of the polarimeter is compared to an existing retarding potential type instrument.

The studies of Co$_{68}$Fe$_4$Ni$_{18}$B$_{14}$Si$_{15}$ amorphous ferromagnetic alloy demonstrate that melt-spun ribbon samples possess considerable lateral magnetic inhomogeneity, whether in their as-cast or field annealed state. This inhomogeneity is attributed to stress effects, caused either by the manufacturing process or the action of forming the ribbons into closed loops. The presence of such rich magnetic inhomogeneity precludes the use of these types of material as secondary polarisation standards.

The GaAs polarised electron source was designed to provide, in two separate modes of operation, both longitudinally and transversely polarised electron beams for the purpose of testing the new polarimeter. The operation of the source was modelled using electrostatic lens design software, the results of which clearly demonstrate its viability.
ACKNOWLEDGEMENTS

Upon completion of a project spanning four whole years, the finest accolade that I can afford my supervisors is the assertion that, given the chance to do it all again, I would choose the same project and the same supervisors. I am indebted to those supervisors; Elaine Seddon, Mike Crapper and Mike Petty. I am eternally grateful for their stalwart enthusiasm and unfaltering support, in the face of both the many successes and expensive blunders alike that have characterised my progress.

Special thanks are due to both Professor Tim Gay, at the University of Nebraska, USA, and Professor Georges Lampel, at the Ecole Polytechnique, France. Their collaboration, in the designs of the Hybrid Polarimeter and the GaAs source respectively, has been essential to the work detailed herein. Accordingly their coworkers must not be forgotten; Yves Lassailly, Cephise Cacho, Henri-Jean Drouhin and Adam Green.

Sincere thanks are also due to all those who have provided the vital technical support to the Hybrid Polarimeter and its associated projects. Accordingly I wish to thank the following: Ian Sumner, Ron Hearsey, Andrew Berry and Ian Sutton for their diligent and persistent efforts concerning noise reduction on the experimental apparatus; Rod Birchall, Ian Maxwell, and Arthur Rose for their assistance with design issues and their unsurpassed craftsmanship.
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Academic Journals

1) Experimental determination of the partial density of states for the binary alloys Pt$_3$V and Pt$_3$Mn.

2) Photoelectron spectroscopy of manganese-based Heusler alloys.

3) Amorphous alloys as secondary standards for electron spin polarimetry.

Other Publications

1) Experimental determination of the Pt 5d and V 3d partial density of states in the intermetallic compound Pt$_5$V.

2) Investigation of the band structure of Co$_2$MnSn.
3) Photoemission investigation of Pd$_2$MnSn.
M. D. Crapper, D. Brown, J. G. Smith, K. H. Bedwell, M. Petty,

4) Suitability of amorphous Co$_{50}$Fe$_4$Ni$_7$B$_{14}$Si$_{15}$ ribbon as a polarised electron standard.
P. K. Hucknall, K. Donovan, D. Greig, S. Clowes, E. McCash,
M. Hardiman, I. R. M. Wardell, D. Rubio-Temprano, A. E. R. Malins,

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1) Investigation of the electronic structure of intermetallic compounds using synchrotron radiation.
M. D. Crapper, D. Brown, M. Petty, K. H. Bedwell, S. J. Guilfoyle,
A. E. R. Malins, M. T. Butterfield; Conference Proceedings, I. Olejford,
L. Nyborg and D. Briggs, John Wiley and sons, ECASIA 97, Goteborg,
Sweden, June 1997, p891.

2) Experimental determination of the Pt 5$d$ and V 3$d$ partial density of states in the intermetallic compound Pt$_3$V.
D. Brown, M. D. Crapper, K. H. Bedwell, M. T. Butterfield, S. J.
Guilfoyle, A. E. R. Malins, M. Petty; Conference Proceedings, I. Olejford,
L. Nyborg and D. Briggs, John Wiley and sons, ECASIA 97, Goteborg,
Sweden, June 1997, p894.

3) The polarimeter development programme at CLRC Daresbury Laboratory.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ΔE</td>
<td>Inelastic Energy Window</td>
</tr>
<tr>
<td>Aₐ</td>
<td>Longitudinal component of Asymmetry</td>
</tr>
<tr>
<td>Aₜₜ</td>
<td>Transverse horizontal component of Asymmetry</td>
</tr>
<tr>
<td>Aₜᵥ</td>
<td>Transverse vertical component of Asymmetry</td>
</tr>
<tr>
<td>CHA</td>
<td>Concentric Hemispherical Analyser</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DL</td>
<td>Daresbury Laboratory</td>
</tr>
<tr>
<td>DTC</td>
<td>Differential Transmitted Current</td>
</tr>
<tr>
<td>FAT</td>
<td>Fixed Analyser Transmission</td>
</tr>
<tr>
<td>FOM</td>
<td>Figure-Of-Merit</td>
</tr>
<tr>
<td>FRR</td>
<td>Fixed Retardation Ratio</td>
</tr>
<tr>
<td>HT</td>
<td>High Tension</td>
</tr>
<tr>
<td>IMFP</td>
<td>Inelastic Mean Free Path</td>
</tr>
<tr>
<td>IRC</td>
<td>Interdisciplinary Research Council</td>
</tr>
<tr>
<td>KE</td>
<td>Kinetic Energy</td>
</tr>
<tr>
<td>MCP</td>
<td>MicroChannel Plate</td>
</tr>
<tr>
<td>MOKE</td>
<td>Magneto-Optical Kerr Effect</td>
</tr>
<tr>
<td>MXCD</td>
<td>Magnetic X-ray Circular Dichroism</td>
</tr>
<tr>
<td>MXLD</td>
<td>Magnetic X-ray Linear Dichroism</td>
</tr>
<tr>
<td>OFHC</td>
<td>Oxygen Free High Conductivity</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>Pₐ</td>
<td>Longitudinal component of Polarisation</td>
</tr>
<tr>
<td>Pₜₜ</td>
<td>Transverse horizontal component of Polarisation</td>
</tr>
<tr>
<td>Pₜᵥ</td>
<td>Transverse vertical component of Polarisation</td>
</tr>
<tr>
<td>RFA</td>
<td>Retarding Field Analyser</td>
</tr>
<tr>
<td>Sₑₑff</td>
<td>Effective Sherman function</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SEMPA</td>
<td>Scanning Electron Microscopy with Polarisation Analysis</td>
</tr>
<tr>
<td>SPS</td>
<td>Spin Polarised Spectroscopy</td>
</tr>
<tr>
<td>SRS</td>
<td>Synchrotron Radiation Source</td>
</tr>
<tr>
<td>Sₑₑ́</td>
<td>Theoretical Sherman function</td>
</tr>
<tr>
<td>UHV</td>
<td>Ultra High Vacuum</td>
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CHAPTER 1

INTRODUCTION

This thesis is a record of my work in the area of spin polarised electron beams, performed in the Spin Polarised Spectroscopy (SPS) group at the Daresbury Laboratory Synchrotron Radiation Source (SRS). A central theme is my progress in the design, build and commissioning of the world’s first single polarimeter sensitive to all three vector components of electron spin polarisation. Also detailed are studies of the amorphous ferromagnetic alloy Co_{66}Fe_{4}Ni_{4}B_{14}Si_{15}, and the design of a new GaAs based polarised electron source.

In this first chapter it is my intention to provide the background to the spin polarimeter development programme at the Daresbury Laboratory, both in terms of the physics involved, and the commercial and technological forces that motivate some aspects of this field of research.

1.1 BACKGROUND

The motivations for the above developments are manifold. The ability to analyse electron beams in spin, as well as energy, has bearing upon our knowledge and understanding of many areas of physics. Magnetism is a notable example; from the ubiquitous compass to the now indispensable commodities of power generation and data storage and retrieval, the technological application of magnetism is undoubtedly vital to twentieth century society. In particular, over the course of the last two decades, studies of magnetism have merged with the much younger science of the study of surfaces. The use of manufacturing techniques developed in the semiconductor industry has permitted the development of previously inconceivable magnetic nanostructures for study and technological application. These advances hold promise of an ever greater capacity for information
storage, combined with faster and more reliable access. At the present time phenomena of particular interest include the following.

- The perpendicular magnetic anisotropy that is exhibited by ultrathin ferromagnetic films, with the associated opportunity for increasing magnetic data storage density through the use of perpendicular encoding of information bits\(^1\,^2\).

- The nature of the magnetic coupling between neighbouring magnetic layers, interspaced by non-magnetic layers, in thin film structures. This coupling can be either ferromagnetic or antiferromagnetic. It can also exhibit an oscillatory behaviour with the thickness of the non-magnetic spacer layers\(^1\,^3\,^4\,^5\).

- The phenomenon of giant magnetoresistance, discovered in the late nineteen-eighties, which has already achieved application in commercial data storage systems\(^1\,^6\,^7\).

- The phenomenon of colossal magnetoresistance, analogous to giant magnetoresistance yet a much stronger effect, found in manganese perovskites\(^8\).

- The development of spin valves, and their application as spin transistors in a newly emerging field of spin electronics\(^9\,^10\).

Given the immense interest in these and other phenomena, it is understandable that the existing methods for the undertaking of such research should continue to be subject to the process of evolution, development and improvement.
1.2 MAGNETISM AND THE SPIN OF ELECTRONS

Magnetic effects in matter arise as a fundamental consequence of the electronic structure of the atom. Specifically they are due to the net angular momentum of the electrons in orbit around any particular atom, and the associated magnetic moment that arises as a consequence of this angular momentum. There is also a small magnetic effect that arises from the nature of the nucleus, but for our purposes this is considered to be negligible.

Three main types of bulk magnetic behaviour can be readily identified in matter. These are respectively diamagnetism, paramagnetism and ferromagnetism.

- Diamagnetism is an inherent property of all materials. The application of an external magnetic field to any sample will induce an electric current within the atomic electron orbitals of that sample, with an associated magnetic moment, according to Lenz's law. The induced moment acts to oppose the applied field, but for most materials it is very weak. The induced moment disappears upon removal of the applied field.

- Paramagnetic materials exhibit no net magnetic moment, since thermally induced crystal lattice vibrations cause the individual magnetic moments of their constituent atoms to be randomly aligned. However the application of a sufficiently large external magnetic field can bring about a partial orientation of the individual moments, to produce a small magnetisation in the same sense as that of the applied field. This magnetisation is proportional to the applied field; the constant of proportionality is known as the paramagnetic susceptibility.
• Ferromagnetic materials, the most widely known being the transition metals iron, nickel and cobalt, can develop a spontaneous magnetisation orders of magnitude stronger than a diamagnetic or paramagnetic magnetisation. This spontaneous magnetisation arises as a consequence of the possession by electrons of an intrinsic angular momentum, in addition to that associated with their orbital motion. This intrinsic angular momentum is known as spin, although this terminology is misleading from the quantum mechanical perspective. In ferromagnetic materials it becomes energetically favourable, through a coulombic effect known as the exchange interaction, for the spins of electrons to adopt a parallel alignment with each other. The magnetic moments of the individual atoms concerned then act to reinforce each other, resulting in a spontaneous bulk magnetisation.

In seeking to understand the origins of the ferromagnetism of elements and compounds, an ability to characterise their electronic structure, particularly in terms of electron spin, represents a powerful analytical tool. However, no meaningful measurement of electron spin can be made without first assigning a rigorous formalism to its theoretical description. And no such description may be achieved without recourse to quantum mechanics. Only the most basic issues are addressed here. The physics involved is discussed in detail in the texts of Kessler and Kirschner.

The spin of an electron is quantised and can have a value of ± 1/2. As such, electrons are fermions which obey the Pauli exclusion principle. The spin angular momentum components of fermions may be represented by a set of 2 x 2 matrices known as the Pauli spin matrices

\[
\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}
\]

The three components of observable spin are represented by the vector operators \( s_x, s_y, \) and \( s_z \) given by

\[
1.1a,b,c
\]
\[ s_x = (h / 4\pi) \sigma_x \quad \text{etc.} \quad (1.2) \]

The operator \( s \), representing the total spin, must obey the commutation relations of angular momentum. The practical result of this is that a simultaneous measurement of all three components of spin is impossible. Only one component, together with the total spin, may be experimentally determined.

The polarisation of a beam, or ensemble, of electrons may be represented simplistically as follows \(^{114},^{115}\). If the axis of quantisation is, for example, parallel to the x-axis then we have

\[ P = (\pm P, 0, 0) \quad (1.3) \]

where \( P \) is the absolute polarisation, given by

\[ P = (N_\uparrow - N_\downarrow) / (N_\uparrow + N_\downarrow) \quad (1.4) \]

where \( N_\uparrow(\downarrow) \) is the number of electrons with spin parallel (antiparallel) to the x-axis; in other words the number of cases for which the value \( + h/4\pi \) (\(- h/4\pi \)) is found.
1.3 THE STUDY OF MAGNETISM

The measurement of macroscopic magnetic properties is possible via a number of long-standing and well-understood techniques \(^{117}\). Such measurements may be subdivided into three types; force, induction and indirect techniques. The first two involve direct measurements of either the force on, or induction of, a magnetised sample respectively. These methods include the alternating gradient magnetometer and the superconducting quantum interference device. The third measurement type concerns the use of indirect techniques that take advantage of known relationships between detected phenomena and the magnetic properties of the sample, such as the Hall effect or AC susceptibility. All the above techniques permit characterisation of the magnetic behaviour of bulk samples.

An understanding of the precise origins of magnetic phenomena, however, requires knowledge of the electronic structure of the materials in question. The development of spectroscopic techniques for analysis of the electronic structure of magnetic materials has progressed concurrently with that of synchrotron radiation sources, of which the SRS at the Daresbury Laboratory is an example. Synchrotron radiation sources offer extremely intense monochromatic beams of radiation. These beams are ideal for use as probes of the properties of matter, since they permit measured signal intensities that are many orders of magnitude more powerful than those achievable with conventional X-ray sources.

As a probe of electronic structure X-rays are ideal since, through the mechanism of photoexcitation, they may induce the full range of possible atomic electron transitions for investigation by photoabsorption and photoemission techniques.

Three especially advanced X-ray spectroscopic techniques, in both absorption and scattering geometries, have been developed for use in conjunction with synchrotron radiation sources. These are magnetic X-ray dichroism, both
linear (MXLD) and circular (MXCD), and magnetic X-ray scattering. All three techniques are dependent upon the tunability and polarisation of synchrotron radiation X-ray beams, which permits the use of resonant techniques at absorption edges in order to increase otherwise extremely weak signals.

The technique of MXCD was first suggested in 1975 by Erskine and Stern, and verified experimentally by Schutz and coworkers in 1987. At the same time an experimentally more convenient spectroscopic technique, that of MXLD was proposed and demonstrated by Thole and coworkers. These techniques are both based on the differential absorption by the sample of left and right circularly polarised light, whilst the incident X-ray energy is scanned across an absorption edge. These two complementary techniques are particularly powerful. They offer submonolayer sensitive, element specific and quantitative analysis of both spin and orbital magnetic moments, combined with determination of the anisotropies involved.

The possibility of studying magnetic properties through X-ray scattering effects was inspired by the calculations of Platzman and Tsoar, and its feasibility demonstrated by the experimental work of de Bergevin and Brunel, in the early seventies. For an understanding of the physical basis of the technique, consider an X-ray incident upon an electron in an atomic orbital. The X-ray is scattered by both the charge and magnetic moment of that electron. The dominant mechanism is Thompson scattering by the electric charge; the effect exploited by established diffraction techniques for crystallographic structural investigations. The weaker magnetic interaction gives rise to magnetic scattering effects, superimposed upon those of diffraction; it is these effects that are exploited for magnetic studies.

Magnetic X-ray scattering offers a further means of magnetic investigation, capable of resolving the separate orbital and spin magnetisations in solids. In common with X-ray dichroism, magnetic X-ray scattering is element specific, and use can be made of resonant enhancement of the measured signal by tuning the incident X-ray energy to an absorption edge of the material under
investigation. However, this technique is seriously limited by the extremely weak nature of the magnetic interaction on which it is based. Signal intensities are therefore low, and as a result magnetic X-ray scattering experiments are very difficult to perform.

The processes of absorption and scattering of X-rays are not the only means of analysis of electronic transitions. Photoelectron spectroscopy \(^{122}\) offers a number of flexible, well established alternatives which although not fundamentally dependent upon synchrotron radiation, also benefit greatly from the intense photon flux that such sources offer. Thus spin resolved electron spectroscopy need not be confined to the relatively few synchrotron radiation based laboratories in existence throughout the world. Electron spectroscopy with energy analysis is inherently surface sensitive, the sampled depth being limited by the inelastic mean free path (IMFP) of electrons. This IMFP, according to the universal curve of Seah and Dench \(^{123}\), does not significantly exceed 100 Angstroms at energies of less than 2000 eV. Furthermore, electron spectroscopy also lends itself readily to species specificity.

In the realm of magnetic studies, the extension of electron spectroscopy to include spin resolution of sampled electrons has been revolutionary, offering as it does a direct window upon the spin resolved density of states of elements and compounds in both solid and gaseous form. Over the last two decades, spin polarised electron spectroscopy has developed into an extremely versatile tool for the study of surface and thin film magnetism \(^{124, 125, 126}\), enabling the study of both clean and adsorbate covered surfaces, thin films and multilayers.

Instruments incorporating spin analysis of electron beams are now highly advanced, a notable achievement being that of scanning electron microscopy with polarisation analysis (SEMPA). By taking advantage of the high lateral resolution of the scanning electron microscope, this technique permits imaging of the domain structure of magnetic surfaces \(^{127}\).
However, the standard method of achieving spin resolution in electron spectroscopy, that of Mott scattering, has a significant limitation. Whilst measurements of polarisation components transverse to the direction of propagation are straightforward, this method is inherently incapable of the measurement of longitudinal polarisation. Low energy spin dependent transmission of electrons through ultrathin ferromagnetic films offers a novel means of measurement of longitudinal electron beam polarisation. The creation of a polarimeter that is sensitive to all three components of electron spin polarisation will represent a significant technological advance in the field of electron spin polarimetry. Whilst the concept involved remains very much in its infancy, it is nonetheless hoped that this Hybrid Polarimeter, and developments of it, will enable significant advances in spin polarised electron spectroscopy, the study of magnetism at the atomic level, and many other areas of physics where spin analysis is of importance.
CHAPTER 2

POLARISATION ANALYSIS OF BEAMS OF ELECTRONS 1:
MOTT SCATTERING BASED METHODS

2.1 INTRODUCTION TO THE PHYSICS AND MEASUREMENT OF ELECTRON SPIN

In 1896 Zeeman first observed that the spectral lines of atoms were split in the presence of an externally applied magnetic field. This particular fine structure effect is now known as the Zeeman effect, an understanding of which requires that electrons be regarded as possessing their own intrinsic magnetic moment. This magnetic moment is itself due to the intrinsic angular momentum, or spin, of the electrons. The knowledge that electrons possess an intrinsic spin further enabled rationalisation of the Stern-Gerlach experiment of 1922. This experiment permitted the measurement of the magnetic moment of atoms, by the splitting of an atomic beam in an inhomogenous magnetic field.

However, such an approach to the measurement of the magnetic moment, or spin polarisation, of free electrons can never succeed. The neutral atoms of the Stern-Gerlach experiment do not experience the Lorentz force to which charged electrons are subject. The Lorentz force, together with the Heisenberg Uncertainty Principle, prevents unambiguous resolution of the two spin-split beams of electrons.

The problem of how to measure free electron spin polarisation was resolved in 1929 by Sir Nevill Mott. He proposed a double scattering experiment in which strong spin-orbit interaction permitted both the generation, and subsequent measurement, of the spin polarisation arising from the scattering of an initially unpolarised electron beam. Demonstration of this effect was not possible without advanced vacuum techniques, and so it was not until 1943 that corroborative experimental work was published.
Mott's research had, meanwhile, stimulated great interest in the possibility of generating, using and measuring polarised electron beams. In his 1956 review of electron spin polarisation, Tolhoek 27 considered electron polarisation as being analogous to the polarisation of electromagnetic radiation. From an in-depth quantum mechanical analysis, he went on to propose five methods for the generation of spin polarised electrons, and four methods for electron spin measurement. Kessler 23 discusses in detail various physical processes which may, in principle, be suitable for the measurement of electron polarisation. However, very few of these processes have been shown to be practical. The most widely practised technique remains that based on the spin-orbit induced asymmetry of Mott scattering, a technique that has since matured into a variety of modern spin polarisation detection systems 28, 29.

2.1.1 THEORY OF MOTT SCATTERING

The physical basis of Mott scattering is quantum-mechanical in nature: it manifests itself as a scattering asymmetry superimposed upon the otherwise symmetrical elastic scattering of electrons in the coulomb field of heavy nuclei.

![Diagram of symmetrical coulomb field about a nucleus](image)

Figure 2.1. Illustration of the symmetrical coulomb field about a nucleus (filled lines), and its modification due to spin-orbit coupling for spin-up (-down), ↑(↓), electrons (dashed lines) 23.
This asymmetry is illustrated graphically in Figure 2.1. This spin asymmetry is insignificant in purely forward scattering.

Mott scattering may be explained classically as follows. Consider the scattering of a high energy electron by a bare nucleus of charge Ze. In the rest frame of the electron, the nucleus represents a flow of charge with an associated magnetic field. The motion of the electron, in the electric field, \( E \), of the nucleus, therefore results in a magnetic field, \( B \), in the rest frame of the electron

\[
B = -\frac{1}{c} \mathbf{v} \times \mathbf{E} \tag{2.1}
\]

where \( \mathbf{v} \) is the velocity of the electron. Writing the electron-nucleus separation as \( \mathbf{r} \), the electric field of the nucleus may be written as

\[
\mathbf{E} = \frac{Ze}{r^3} \mathbf{r} \tag{2.2}
\]

and thus the magnetic field as

\[
\mathbf{B} = \frac{Ze}{cr^3} \mathbf{r} \times \mathbf{v} = \frac{Ze}{mc^3} \mathbf{L} \tag{2.3}
\]

where \( \mathbf{L} \) is the electron orbital angular momentum

\[
\mathbf{L} = m \mathbf{r} \times \mathbf{v} \tag{2.4}
\]

There is an interaction between the spin magnetic moment of the electron, \( \mu_s \), and the magnetic field, \( \mathbf{B} \). This results in the introduction of an additional term, \( V_{so} \), into the scattering potential, where \( V_{so} \) is given by

\[
V_{so} = -\mu_s \cdot \mathbf{B} \tag{2.5}
\]

Since the electron spin magnetic moment, \( \mu_s \), is related to the spin of the electron, \( \mathbf{S} \), we can write
\[
\mu_s = - (ge/2mc) S
\]  

(2.6)

where \( g \) is the spin \( g \) factor \((g \approx 2)\). The additional spin-orbit term, \( V_{so} \), then becomes

\[
V_{so} = (Ze^2/2m^2c^2r^3) \mathbf{L} \cdot \mathbf{S}
\]  

(2.7)

where an additional factor of \( 1/2 \) has been included to account for Thomas precession \(^{211}\). This additional spin-orbit term results in a spin dependency in the scattering cross section, \( \sigma(\theta) \), of electrons that are incident upon the nucleus

\[
\sigma(\theta) = I(\theta) \left[ 1 + S(\theta) \mathbf{P} \cdot \mathbf{n} \right]
\]  

(2.8)

Here \( I(\theta) \) denotes the spin averaged scattered electron intensity, and \( \mathbf{P} \) represents the incident electron Polarisation. \( S(\theta) \) is the asymmetry function; this represents the variation of the above spin dependency with scattering angle.

In the above description the angular momentum is defined to be along the normal to the scattering plane. The unit normal to this plane, \( \mathbf{n} \), is defined as follows

\[
\mathbf{n} = (\mathbf{k}_1 \times \mathbf{k}_2) / |\mathbf{k}_1 \times \mathbf{k}_2|
\]  

(2.9)

where \( \mathbf{k}_1 \) and \( \mathbf{k}_2 \) are respectively the electron wave vectors before and after scattering. The scattering plane, illustrated in Figure 2.2, contains the scattering nucleus and both the incident and outgoing electrons. Also illustrated is the precession of the polarisation vector, \( \mathbf{P} \), about the magnetic field, \( \mathbf{B} \), arising in consequence of the relative motion of the two charges.
2.1.2 PRACTICAL SPIN ANALYSIS

Mott scattering of a polarised electron beam results in a measurable asymmetry, $A(\theta)$, between left and right backscattered electron currents

$$A(\theta) = \frac{(N_L - N_R)}{(N_L + N_R)}$$  \hspace{1cm} (2.10)

Here $N_L$ and $N_R$ represent the number of electrons backscattered, in any given interval, to the left and right respectively, and $\pm \theta$ is the angle through which the beams have been backscattered. The geometry is illustrated in Figure 2.3.

The polarisation, $P$, of the beam, along the normal to the scattering plane, is related to the asymmetry, $A(\theta)$, by the expression
The asymmetry function, $S_{\text{eff}}(\theta)$, is referred to as the effective Sherman function \(^2\). The $S_{\text{eff}}$, sometimes also known as the analysing power, may be regarded as a measure of the spin sensitivity of the polarimeter in question; it must be determined by calibration \(^2\) and can have values in the range; \(1 \geq S_{\text{eff}}(\theta) \geq -1\). A theoretical 100 % efficient spin analyser would have an $S_{\text{eff}}(\theta)$ of ± 1. In practice, values of $S_{\text{eff}}(\theta)$ are very much lower than this; a Mott polarimeter operating at 100 kV might typically have an $S_{\text{eff}}(\theta)$ of 0.25.

2.1.2.1 The Sherman Function

The Sherman function has far-reaching implications for measurement of spin polarisation. The Sherman function of a particular scattering event is dependent upon three parameters: scattering energy; scattering angle; and the atomic number of the scattering nucleus. A number of groups have calculated the theoretical Sherman function, $S_{\text{th}}$, for the various experimental conditions available, most notably Sherman himself after whom the function is named \(^2\).

![Figure 2.4](image)

Figure 2.4. The energy and angle dependence of the Sherman function, according to Holzwarth and Meister.
Holzwarth and Meister, Bühning and more recently Ross and Fink have presented theoretical data on the Sherman function for scattering from nuclei at high energies. The data of Holzwarth and Meister, for a variety of scattering energies and angles, are illustrated in Figure 2.4.

Sherman functions pertaining to low energy scattering (below 1 keV) have been calculated by Massey and Mohr; spin dependent scattering effects from nuclei in this regime are almost negligible, but can be significant in scattering from atoms.

The value of the Sherman function is a linear function of the atomic number of the scattering nucleus involved. Therefore practical polarimeter systems utilise foil samples of heavy elements as their scattering centres; gold, thorium and uranium are used commonly as target materials. Gold is especially useful due to the ease with which its surface may be kept free of contamination in an ultra-high vacuum (UHV) environment.

In a practical measurement system, the issue is further complicated by the effects of the geometrical features of the polarimeter concerned; the $S_{\text{eff}}$ of an actual measurement will always be less than the calculated $S_{\text{th}}$. The $S_{\text{eff}}$ is influenced by the thickness of the scattering foil, inelastic scattering of electrons and the finite angular acceptance of the detector system.

Calculated values of the Sherman function are based upon the ideal situation of elastic point scattering. In reality the finite thickness of a scattering foil presents opportunities for electrons to undergo more than one elastic scattering event and still re-emerge at a viable angle for detection. Small angle scattering is subject to a significantly lower $S_{\text{th}}$. A sequence of a few small angle elastic scattering events, known as plural scattering, can occur more frequently with increasing foil thickness and acts to reduce the $S_{\text{eff}}$.

Elastic scattering events are always in a minority; the majority of electrons interacting with the foil are subject to inelastic scattering to at least some
degree. A sequence of many scattering events is known as multiple scattering. Such sequences are distinguished from plural scattering by the Gaussian distribution of energies that they present. In general, detector systems have poor energy discrimination and thus multiple inelastic scattering effects tend also to reduce the $S_{\text{eff}}$.

Detector systems furthermore have a finite angular acceptance; if the detector is centred upon an angle at which the $S_{\text{th}}$ is a maximum, a large angular acceptance will act to decrease the $S_{\text{eff}}$.

2.1.2.2 The Figure-of-Merit

A second parameter by which practical polarimeter systems may be characterised is known as the figure-of-merit (FOM), sometimes also termed the efficiency. The figure-of-merit is given by the formula

$$
\text{FOM} = S_{\text{eff}}^2 \cdot \frac{I}{I_0}
$$

(2.12)

where $I$ is the detected electron current and $I_0$ is the total incident current$^{23}$.

The relevance of the FOM can be seen by reference to Figure 2.5, which shows the variation with scattering angle, $\theta$, of the spin dependent scattering cross sections, $c(\theta)$, and the corresponding polarisation, $P$, for Mott scattering from a mercury vapour at 300 eV.

It is readily apparent that at angles where the total scattering cross section is highest the spin dependent scattering, and therefore also the measured asymmetry, demonstrates a minimum. Furthermore, in the high energy scattering regime, the cross section for Rutherford scattering decreases with increasing energy; an inverse square energy dependence is observed. In contrast the $S_{\text{th}}$, and thus the measured asymmetry, increases with increasing energy. Therefore, in any Mott scattering experiment, a compromise must always be made between high count rates and high measured asymmetry.
Figure 2.5. Illustration of the variation with scattering angle of the spin dependent scattering cross sections, and the corresponding behaviour of the polarisation, for Mott scattering from mercury vapour at 300 eV.$^{2,3}$

The FOM, as formulated in Equation 2.12, is inversely proportional to the statistical error in a measurement of the spin asymmetry due to an ensemble, or beam, of polarised electrons. The FOM should therefore be maximised in order to ensure that any given level of statistical error is achieved in the minimum possible measurement time.
2.2 MOTT SCATTERING BASED POLARIMETRY TECHNIQUES

A range of Mott scattering based polarimeter systems has evolved, with the different techniques utilising scattering energies of anywhere between 15 eV and 150 keV. The various polarimeter types vary tremendously in size, ease-of-use and reliability. Their respective performances, in terms of $S_{\text{eff}}$ and FOM are similarly varied. The most notable polarimeter systems that have evolved are described briefly below.\textsuperscript{2,8,10}

2.2.1 CONVENTIONAL HIGH ENERGY MOTT POLARIMETER

Conventional high energy Mott polarimeters achieve a high $S_{\text{eff}}$ through operation at scattering energies of 100 keV or greater. Such high scattering energies in turn result in diminished scattering intensities, but this can be offset, to a degree, by placing the individual detectors close to the scattering centre. In general such polarimeters offer very poor discrimination of electron kinetic energy, on account of the characteristics of the silicon surface barrier type detector systems normally employed, and the inability to bias the detector with a discriminating potential.

Figure 2.6. A schematic illustration of the Daresbury Laboratory conventional high energy Mott polarimeter.
A schematic diagram of the Daresbury Laboratory high energy Mott polarimeter \(^2\)\(^{18}\) is illustrated in Figure 2 6; this instrument illustrates the principal features of such systems. The backscattered electron detectors are centred at an angle of 120\(^\circ\), for which the \(S_{th}\) exhibits a broad maximum. Four azimuthally equispaced detectors are deployed on this instrument, enabling the measurement of both transverse components of the polarisation of the incident electron beam. Five further detectors are employed in this particular instrument. The straight through detector enables measurement of the incident electron current, less the absorbed and scattered components. The four forward scattering detectors, for which the spin dependent scattering asymmetry is negligibly small, permit monitoring of the instrumental asymmetry during the course of each experimental run \(^2\)\(^{19}\).

The application of a scattering potential of 100 kV, or greater, carries significant experimental difficulty. In consequence such polarimeter systems are generally physically large and unwieldy, and experimental configurations tend to be fixed and inflexible. Thin gold foils are used normally as the scattering centres for these instruments, in order to reduce the effects of plural and multiple scattering. These foils are prepared by evaporation of gold onto hydrocarbon carrier foils. The configuration of conventional high energy instruments can enable the application of a system of interchangeable foils, offering a range of thicknesses. This enables such polarimeters to be calibrated by a straightforward technique of extrapolating the measured asymmetry to one corresponding to a theoretical infinitely thin foil, at which all plural and multiple scattering is eliminated; this is discussed in Section 2.3.1.2.

Conventional high energy Mott polarimeters offer a competitive performance in terms of \(S_{\text{eff}}\) and FOM; a typical instrument \(^2\)\(^{20}\) might provide an \(S_{\text{eff}}\) of 0.16, and an FOM of \(2 \times 10^{-4}\). Such polarimeters are robust and reliable to operate, and have become established as the benchmark for electron spin analysis. They are, however, inflexible to operate; therefore they are not the preferred choice of the experimentalist.
2.2.2 RETARDING POTENTIAL MOTT POLARIMETER

Retarding potential Mott polarimeters, otherwise known as Micro-Mott polarimeters, are compact devices in which the backscattered electrons are decelerated by the same electric field used to accelerate the incident electron beam onto the scattering foil. A common design of such a polarimeter is illustrated in Figure 2.7.

![Figure 2.7](image_url) A sectional illustration of the conical geometry retarding potential Mott polarimeter of Burnett et al.

The outer casing of a retarding potential polarimeter is operated at, or close to, ground potential; this is therefore a safe and flexible polarimeter configuration. Backscattered electrons, that have retained sufficient energy, are able to overcome the retarding field due to the low potential of the casing, and thus reach the detectors. A particular advantage of this polarimeter design is the excellent discrimination against inelastically scattered electrons that is achieved by the use of a retarding field in front of the detectors.

These polarimeters employ a concentric electrode configuration, using either a hemispherical, conical or cylindrical geometry. The polarimeter illustrated in Figure 2.7 utilises conical geometry. As with high energy
polarimeters, the detectors are placed at 120° to the direction of propagation of the incident beam. Conical and spherical geometry based polarimeters may utilise four backscattered detectors for analysis of both transverse components of the incident electron beam polarisation.

The retarding potential polarimeter design is due to Farago \(^2\), and was first implemented in cylindrical geometry by Hodge et al. \(^2\). This particular configuration may be used for in-line polarisation analysis of electron beams. The use of an ultrathin gold foil as the scattering target results in minimal attenuation of the incident polarised beam. Electrons that pass undeflected through the foil are decelerated, and then leave through the rear of the polarimeter \(^2\). More usually the use of thick scattering foils \(^2\), in order to increase the backscattered signal intensity, precludes the use of forward scattering detection.

Potentials applied to the scattering foil range from 20 kV to 100 kV, although a potential of 20 kV is commonly employed. The FOMs, for such instruments, are in the region of \(1 \times 10^5\). Corresponding values of \(S_{\text{eff}}\) are in the range 0.15 - 0.25. Alternatives to gold (\(Z = 79\)) scattering foils can be used, and higher atomic number materials such as thorium \(^2\) (\(Z = 90\)) and uranium \(^2\) (\(Z = 92\)) have found advocates. The use of these materials increases both the \(S_{\text{eff}}\) and the backscattered signal intensity, since the spin-orbit interaction and the differential scattering cross section both increase with increasing atomic number. Although these materials are more reactive than gold, stable values of \(S_{\text{eff}}\) can be achieved through careful cleaning and passivation procedures. Operation at energies higher than 20 kV increases the \(S_{\text{eff}}\) and minimises both plural and multiple scattering, but results in a much reduced FOM due to reduction of the backscattered signal intensity.

As with conventional high energy Mott polarimeters, these instruments have found widespread application on account of their performance and their reliable nature. Their popularity is further enhanced by the compact configuration and experimental flexibility that they offer.
2.2.3 LOW ENERGY DIFFUSE SCATTERING MOTT POLARIMETER

Diffuse scattering polarimeters employ scattering at typically 150 eV from an amorphous gold surface. At such low energy the cross section for electron scattering is significantly improved over higher energy polarimeters. Furthermore these instruments are designed to collect backscattered electrons over a large solid angle. Thus this type of polarimeter can achieve an excellent $I/I_0$ ratio, and therefore also a high value of FOM. Furthermore, the low energy nature of these instruments enables them to be physically small and compact.

![Diagram of low energy diffuse scattering polarimeter](image)

Figure 2.8. A schematic illustration of the low energy diffuse scattering polarimeter of Scheinfein et al.\textsuperscript{2,30}

A schematic illustration of the operation of a diffuse scattering polarimeter\textsuperscript{2,30} is shown in Figure 2.8. The input optics is designed to focus the incident electron beam onto a freshly evaporated gold target film. The drift tube, target film and electrode E2 are all maintained at the same potential so that scattering occurs in an essentially field-free region. A suitable negative voltage applied to the electrode E1, together with a suitable positive voltage applied to the grid G1, aligns backscattered electron trajectories such that they are approximately
perpendicular to this grid. A negative bias is applied to the grid G2 in order to provide discrimination against secondary and inelastically scattered electrons. Elastically scattered electrons are able to pass through the grids, after which they are accelerated into, and detected by, a microchannel plate with a four quadrant anode system. These four quadrants provide the facility for measurement of both transverse components of the incident electron beam polarisation.

Under optimum operating conditions, diffuse scattering polarimeters can provide an $S_{\text{eff}}$ of 0.15 and an FOM of up to $2 \times 10^{-4}$. However, the low scattering energy necessitates regular renewal of the gold scattering target. Such polarimeters are also extremely difficult to set up and operate correctly. A final significant drawback of the technique is the lack of any means of self calibration. This type of polarimeter is not in widespread use.

2.2.4 SPIN POLARISED LOW ENERGY ELECTRON DIFFRACTION

A left/right asymmetry arises in the diffracted beams that follow the scattering, at low energy, of electrons from a single crystal metal surface of high atomic number $^{231}$. This is the foundation of the Spin Polarsed Low Energy Electron Diffraction polarimeter. This technique permits the construction of a compact polarimeter instrument exhibiting a good $S_{\text{eff}}$ and FOM $^{232}$. Instrumental asymmetries may be eliminated either by reversal of the incident beam polarisation, or rotation of the crystal. Tungsten is the preferred target material as it can be rapidly and reproducibly cleaned with relative ease.

An $S_{\text{eff}}$ of 0.27 has been achieved $^{233}$ for the (2,0) family of Bragg peaks, diffracted at 104.5 eV from a tungsten (001) surface. A corresponding FOM of $1.6 \times 10^{-4}$ suggests that a carefully designed SPLEED polarimeter can compete with the best of alternative polarimeter designs. However, these devices are highly sensitive both to the quality of the incident beam and the adsorption of residual gas molecules upon the crystal. Large diameter electron beams may
not be coupled easily into a SPLEED polarimeter, and variation of the angle of incidence at the crystal, by greater than $\pm 2^\circ$, can introduce serious instrumental asymmetries. Even when the instrument is maintained at $1 \times 10^{10}$ torr, contamination of the crystal surface can reduce the $S_{\text{eff}}$ by 10% over the course of just one hour. These factors make the SPLEED polarimeter a difficult instrument to operate; the results are critically dependent upon the care with which such an instrument is set up.

2.2.5 MERCURY VAPOUR MOTT POLARIMETER

Mott scattering may also be achieved from a low vapour pressure of mercury atoms. Consider a low energy electron incident upon a mercury atom. If the electron penetrates the electronic orbitals of the atom, it effectively sees a retarding potential due to these orbitals, as well as the positive charge of the ($Z = 80$) nucleus. This situation is analogous to the configuration of the retarding potential Mott polarimeter.

Figure 2.9. An illustration of the mercury vapour Mott polarimeter developed by Jost et al.$^{234}$.
A schematic illustration of a mercury vapour Mott polarimeter is shown in Figure 2.9. In this instrument the incident electron beam is scattered, at an energy of 15 - 300 eV, by a cloud of mercury vapour. Electrons that are scattered through ± 90° are focused, by two symmetrically placed electrostatic energy analysers, onto two channeltron detectors. This instrument has achieved an FOM of 4 x 10⁻⁵.

The low voltage design of this type of instrument again permits a compact instrument to be constructed, subject to the constraints imposed by the source of mercury vapour. However, polarimeters of this type are difficult to set up and operate; they are also not readily adaptable for use in UHV experimental systems.
2.3 PRACTICAL CONSIDERATIONS IN MOTT SCATTERING EXPERIMENTS

2.3.1 CALIBRATION OF POLARIMETERS

An accurate determination of polarisation, from an experimental measurement of spin asymmetry, requires detailed knowledge of the $S_{\text{eff}}$ for the polarimeter. The $S_{\text{eff}}$ is frequently quite different from the theoretical value, and thus a variety of techniques have evolved for its determination.

It should be noted that, due to the uncertainties surrounding the effects of multiple and plural scattering, asymmetry measurements using Mott scattering should be regarded as being subject fundamentally to an absolute uncertainty of ±5%\(^2\).\(^35\).

2.3.1.1 The Double Scattering Method

This is the most accurate method available for the determination of $S_{\text{eff}}$, with reports of the reduction of experimental uncertainties to below 0.3%\(^2\).\(^36\). A double scattering experiment is, however, very difficult to perform rigorously on account of the strict requirements for symmetrical geometry of the apparatus.

Figure 2.10. Illustration of a double scattering experiment for the determination of effective Sherman function\(^28\).
Consider the double scattering experiment illustrated in Figure 2.10. An unpolarised incident beam scatters from a target. Electrons scattered through an angle $\theta_1$ are subject to scattering at a second, identical target, where they are detected if scattered through an angle of $\pm \theta_2$. The scattering plane is defined by these trajectories, with a corresponding normal $n$ to the scattering plane as shown. The unpolarised incident beam may be considered as having equal numbers of electrons with spins parallel and antiparallel to $n$. From Equation 2.8 it follows that the number, $N_\uparrow$, of spin parallel electrons scattered through angle $\theta_1$ is proportional to $1 + S(\theta_1)$. The number, $N_\downarrow$, of spin antiparallel electrons scattered through $\theta_1$ is proportional to $1 - S(\theta_1)$. This is illustrated in Figure 2.11.

![Figure 2.11. The scattering of an unpolarised beam.](image)

Thus the electrons scattered through $\theta_1$ acquire a net polarisation, $P(\theta_1)$, given by

$$P(\theta_1) = \frac{(N_\uparrow - N_\downarrow)}{(N_\uparrow + N_\downarrow)} = S(\theta_1) n$$

(2.13)

The subsequent scattering of the polarised beam from the second target results in left hand, $N_L$, and right hand, $N_R$, scattered beams with a corresponding asymmetry, $A(\theta_2)$, where

$$A(\theta_2) = \frac{(N_L - N_R)}{(N_L + N_R)}$$

(2.14)
Since the first and second scattering events are coplanar, $N_L$ is proportional to $N_\uparrow [1 + S(\theta_2)] + N_\downarrow [1 - S(\theta_2)]$, while $N_R$ is proportional to $N_\uparrow [1 - S(\theta_2)] + N_\downarrow [1 + S(\theta_2)]$. Substitution into Equation 2.14 yields the result

$$A(\theta_2) = P(\theta_1) S(\theta_2)$$

(2.15)

If the experiment is performed such that $\theta_1 = \theta_2 = \theta$, with identical target materials and thicknesses at both scattering centres, and electron energy held constant, then Equation 2.15 becomes

$$A = S_{\text{eff}}^2$$

(2.16)

Equation 2.16 thus provides a direct measurement of effective Sherman function from a measurement of asymmetry.

Although the double scattering technique has been used for purposes of polarimeter calibration \(^2\)\(^3\)\(^7\), it has been far more commonly used in tests of theoretical calculations of the Sherman function \(^2\)\(^3\)\(^6\). In this latter context it should be noted that the technique does not remove uncertainties due to multiple and plural scattering at the target foils. More recently the accuracy of the double scattering calibration technique has been improved by the use of an initially polarised electron beam \(^2\)\(^3\)\(^8\).

2.3.1.2 Extrapolation To Elastic Point Scattering

Plural and multiple scattering of electrons within target foils has already been discussed as a mechanism for the reduction of the effective Sherman function. These processes become less and less pronounced with decreasing target foil thickness, suggesting a possible means of calibration. Measurements of asymmetry from target foils of varying thickness may be extrapolated to an asymmetry for a hypothetical infinitesimally thin foil; plural and multiple scattering would not occur within such a foil. This approach to calibration is most commonly used in conjunction with conventional high energy Mott
polarimeters, in which a range of target foil thicknesses may be positioned at the scattering centre without significant experimental difficulty.

A major difficulty with this approach, however, is the lack of consensus concerning the precise dependence of the asymmetry upon target thickness. The standard approach is to measure the asymmetry for target foils of sufficient thinness that a linear fit to the data can be justified on statistical grounds. Various fitting parameters have been applied: $1/A$, $1/\sqrt{A}$, $\ln A$ and $A$ have been plotted against foil thickness by several experimental groups. Experimentally, the use of count rate in place of foil thickness eliminates errors in measurements of the latter; the count rate is found to be approximately proportional to the foil thickness. For these fitting procedures to be valid, linear scattering conditions must prevail. Higher order scattering effects can be decreased by increasing the electron energy, reducing the minimum foil thickness and, if possible, reducing the inelastic energy loss window. However, the most carefully undertaken experiments will still be subject to higher order effects to some degree. Therefore the technique of extrapolation to elastic point scattering, for determination of the effective Sherman function, is subject to an error of a few percent.

2.3.1.3 Extrapolation to Zero Inelastic Energy Loss

An alternative means of calibration, again by extrapolation to a hypothetical state of purely elastic scattering, is available through the use of retarding potential Mott polarimeters. The configuration of these instruments permits variation of the maximum inelastic energy loss to which the electrons may be subjected without preventing their detection.

The inelastic energy loss that an electron undergoes on transmission through a material is proportional to the distance travelled within the medium. The mean rate of energy loss with distance travelled by electrons in a gold medium is approximately $1.2 - 0.5 \text{ eV} \text{ Å}^{-1}$ for energies in the range 20 - 100 keV. Thus application of, for example, an inelastic energy loss window, $\Delta E$, of 1000 eV
restricts detection to only those electrons that have travelled less than $2 \times 10^3 \text{Å}$ into the scattering foil. Further reduction of the energy window progressively restricts scattering to thinner regions of the target foil. An extrapolation to an energy window of zero eV energy loss may therefore be regarded as analogous to an extrapolation to zero foil thickness.

This technique is particularly straightforward to perform experimentally. However, it suffers from a serious drawback in that it fails to eliminate the effects of plural scattering. This results in a systematic error in deduced values of $S_{\text{eff}}$; for high energy polarimeters this error is limited to less than 3%, but for low energy polarimeters it can amount to as much as 20%. The result is the attribution of too high an $S_{\text{eff}}$ to the polarimeter concerned, with deduced polarisations correspondingly too low. This effect is illustrated in Figure 2.12 below, where results taken at high energy can be seen to agree closely with predicted values of the theoretical Sherman function; at lower energies an increasing discrepancy emerges.

![Figure 2.12](image)

**Figure 2.12.** The energy dependence of the Sherman function for gold at a scattering angle of 120°, compiled by Gay and Dunning (28). The solid and dashed lines represent calculations of $S_{\text{th}}$ by Ross and Fink (216), and Holzwarth and Meister (214), respectively. The data points are due to a number of experimental groups and correspond to foil thicknesses of 100 - 1250 Å, and inelastic energy loss windows of either 0 or 25 eV.
2.3.1.4 Calibration with a Polarised Electron Beam Source

Calibration of polarimeters may also be achieved by the use of a source of electrons of known polarisation. This enables a direct measurement of $S_{\text{eff}}$. Various such sources exist, the use of a gallium arsenide based source being the most popular in this application\textsuperscript{23}. This technique is discussed in detail in Chapter 7. Briefly, a polarised beam of electrons may be created through photoemission from a gallium arsenide crystal surface; the photoemitted beam can be highly polarised when the crystal is illuminated with circularly polarised radiation of a suitable wavelength. A calibrated determination of the source polarisation may be achieved by measurement with a calibrated conventional high energy Mott polarimeter. Alternatively the source polarisation may be accurately determined through an optical measurement\textsuperscript{240}. If the polarised electron beam is incident upon a suitable gaseous atomic target, such as a vapour of zinc, spin angular momentum is transferred to these atoms through inelastic exchange collisions. The resultant polarised atoms then emit circularly polarised radiation in the direction of the spin transfer. The measurement of $S_{\text{eff}}$, with a source calibrated in this manner, has been achieved with an accuracy of approximately 0.8 % for a retarding potential Mott polarimeter\textsuperscript{241}.

A second method for the generation of electron beams of known polarisation is through chemi-ionisation reactions\textsuperscript{242}. A beam of metastable helium($2^3S$) atoms is pumped optically with circularly polarised light. When this beam is crossed with a gas of spin singlet atoms, such as carbon dioxide or nitrogen, the resultant collisions release electrons with a polarisation equal to that of the metastable atoms. The polarisation of the helium atoms is determined with a Stern-Gerlach analyser. This method has been employed in the calibration of a retarding potential Mott polarimeter, with an experimental uncertainty of ± 5 % in the measured $S_{\text{eff}}$\textsuperscript{243}. 

32
Finally, the $\beta$-decay of the radioisotope $^{60}\text{Co}$ has also been used successfully for this purpose $^{244}$, with an absolute accuracy of approximately 1.5 %. This technique, whilst attractive in the field of $\beta$-decay polarisation measurements, is not as useful in other applications because of the poor intensity of these sources and the handling difficulties involved.

### 2.3.2 ELIMINATION OF INSTRUMENTAL ASYMMETRIES

An ideal polarimeter would have identical detectors and perfect alignment of its electron optics. In this case a single measurement of left and right backscattered count rates would enable determination of the incident electron beam spin polarisation. In reality detectors are not subject to identical efficiencies. Furthermore the electron optical alignment is always affected by a degree of asymmetry, through both the engineered geometry of the apparatus and inhomogeneity of the scattering foil. A detailed discussion of instrumental asymmetries, the effects of beam misalignments and the means for their elimination is given by Kessler $^{23}$.

Polarimeters with the facility for monitoring of forward scattering provide a direct means of monitoring and eliminating instrumental asymmetries $^{219}$. However, if the means exists for accurate reversal of the incident beam polarisation without affecting the beam trajectory, then the elimination of instrumental asymmetries can also be achieved by straightforward algebraic manipulation of asymmetry data $^{218}$. Consider the rearrangement of Equation 2.10 to give the ratio of count rates in the left and right backscattering detectors

$$\frac{N_L}{N_R} = \frac{1 + A}{1 - A}$$  \hspace{1cm} (2.16)

Representing the false instrumental asymmetry by $A_F$, and denoting the relative detector efficiencies by a coefficient $\delta$, we have

$$\frac{N_L}{N_R} = \delta \cdot \left[ \frac{1 + A}{1 - A} \right] \cdot \left[ \frac{1 + A_F}{1 - A_F} \right]$$ \hspace{1cm} (2.17)
If the count rates for forward and reversed magnetisation are denoted by the subscripts $\uparrow$ and $\downarrow$ respectively, we obtain

\[
\frac{N_L \uparrow}{N_R \uparrow} = \delta \cdot \frac{(1 + A) / (1 - A)}{1 - A / (1 + A)} 
\]

(2.18a)

\[
\frac{N_L \downarrow}{N_R \downarrow} = \delta \cdot \frac{(1 - A) / (1 + A)}{1 + A / (1 - A)} 
\]

(2.18b)

Equations 2.18a,b may be combined to eliminate $\delta$ and $A_F$, thus giving the true spin asymmetry

\[
A = \frac{(X - 1)}{(X + 1)} 
\]

(2.19)

where

\[
X = \sqrt{\frac{N_L \uparrow N_R \downarrow}{(N_L \downarrow N_R \uparrow)}} 
\]

(2.20)

This approach makes the assumption that when the polarisation is reversed all other beam parameters remain constant, including the instrumental asymmetry. The procedure further assumes that the instrumental asymmetries are constant over the duration of any particular experiment. Clearly, if the instrumental asymmetry does deviate during an experiment the measured asymmetry will not be accurate. If the quantity $\sqrt{\frac{N_L \uparrow N_R \downarrow}{N_R \uparrow N_R \downarrow}}$ remains constant during the course of a measurement, instrumental asymmetries can be considered to have been eliminated.
2.3.3 ANALYSIS OF ERRORS IN MEASUREMENTS OF ASYMMETRY

The following discussion of errors concerns only the uncertainty that arises as a consequence of the counting statistics involved in measurements of asymmetry. The effects of inaccuracies in $S_{\text{eff}}$ and instrumental asymmetry, discussed earlier, must be assessed separately.

2.3.3.1 Measurements of Spin Asymmetry

Measurements of the electron count rates at every detector are subject to an error. Consider Equation 2.20

$$X = \sqrt{\frac{(N_L \uparrow N_R \downarrow)}{(N_L \uparrow N_R \downarrow)}}$$

(2.20)

Partial differential error equations may be derived, for the error in $X$ that arises from the individual errors in each detector channel

$$\frac{\partial X}{\partial N_L \uparrow} = 0.5 \cdot \sqrt{\frac{N_R \downarrow}{(N_L \uparrow N_L \downarrow N_R \uparrow)}}$$

(2.21a)

$$\frac{\partial X}{\partial N_L \downarrow} = 0.5 \cdot \sqrt{\frac{(N_L \uparrow N_R \downarrow)}{(N_R \uparrow N_L \uparrow)}}$$

(2.21b)

$$\frac{\partial X}{\partial N_R \uparrow} = 0.5 \cdot \sqrt{\frac{(N_L \uparrow N_R \downarrow)}{(N_R \uparrow^3 N_L \downarrow)}}$$

(2.21c)

$$\frac{\partial X}{\partial N_R \downarrow} = 0.5 \cdot \sqrt{\frac{N_L \uparrow}{(N_R \downarrow N_L \downarrow N_R \uparrow)}}$$

(2.21d)

The actual error in the quantity $X$ arising from, for example, the error in $N_L \uparrow$ is therefore given by

$$\Delta X (N_L \uparrow) = \Delta N_L \uparrow \cdot 0.5 \cdot \sqrt{\frac{N_R \downarrow}{(N_L \uparrow N_L \downarrow N_R \uparrow)}}$$

(2.22)

and similarly for the other count rates.
If the errors in $N_L\uparrow$, $N_L\downarrow$, $N_R\uparrow$, and $N_R\downarrow$ are assumed to be independent of each other, and further that these count rates are large enough that Poissonian statistics may be assumed, then these errors combine in quadrature. Thus

$$\Delta X = 0.5 \sqrt{\left[(N_R\uparrow N_L\downarrow + N_L\uparrow N_R\downarrow + N_L\uparrow N_R\downarrow + N_L\uparrow N_L\downarrow) / (N_R\uparrow N_L\downarrow)^2\right]}$$  \hspace{1cm} (2.23)$$

where the error in $N_L\uparrow$ is given by $\sqrt{N_L\uparrow}$, and likewise for the other count rates.

Returning now to Equation 2.19, the differential error equation for the error in the measured asymmetry may be derived

$$A = \frac{X - 1}{X + 1}$$  \hspace{1cm} (2.19)$$

$$\frac{\partial A}{\partial X} = 2 \frac{(X + 1)^2}{(X + 1)^2}$$  \hspace{1cm} (2.24)$$

If we combine Equations 2.23 and 2.24, then an expression for the statistical error, $\Delta A$, in the measured asymmetry can be derived

$$\Delta A = 2 \cdot \Delta X / (X + 1)^2$$ \hspace{1cm} (2.25)$$

2.3.3.2 Hysteresis Loops

The measurement of a hysteresis loop does not eliminate instrumental asymmetry. Rather, the instrumental asymmetry appears as an offset upon which the spin asymmetry is superimposed. A different treatment is required for the estimation of statistical errors in such a measurement. Consider Equation 2.10

$$A = (N_L - N_R) / (N_L + N_R)$$  \hspace{1cm} (2.10)$$
The partial differential error equations, for the error in asymmetry, can be derived

\[ \frac{\partial A}{\partial N_L} = 2 \frac{N_R}{(N_L + N_R)^2} \]  
(2.26a)

\[ \frac{\partial A}{\partial N_R} = -2 \frac{N_L}{(N_L + N_R)^2} \]  
(2.26b)

If Poissonian statistics are assumed, this leads to the statistical error in the measured asymmetry \( \Delta A \)

\[ \Delta A = \sqrt{N_R \cdot [2N_L/(N_L + N_R)^2] + \sqrt{N_L \cdot [2N_R/(N_L + N_R)^2]}} \]  
(2.27)
The physics of spin-orbit coupling induced asymmetry, in the scattering of electrons from heavy nuclei, has been introduced through a classical model. This is known as Mott scattering, an effect that has been shown to enable the measurement of the electron spin polarisation of beams of electrons. This effect is very small, but is nonetheless measurable. Typically, for a conventional high energy Mott detector \(^{245}\), the resulting ratio of the detected electron current to the incident beam current, \(I / I_0\), will be less than \(10^{-2}\). This means that for every thousand polarised electrons incident at the scattering foil, less than ten will be detected. In contrast, the equivalent analysis of polarised light may be performed with almost negligible loss. The efficiency, \(S_{\text{eff}}^2 (1 / I_0)\), of such a Mott detector will be of the order of \(10^{-4}\). This compares with an efficiency of close to unity for a polarised light analyser \(^{23}\).

Mott scattering analysis may be performed through a variety of experimental configurations. These configurations, and their respective advantages and disadvantages, have been discussed. The most common instruments worldwide are the conventional high energy Mott polarimeter and the retarding potential Mott polarimeter. These polarimeter configurations have been thoroughly characterised, and are well established on account of their robust and reliable nature.

Practical considerations in the measurement of Mott scattering have been discussed in some detail. These include the requirements and various methods available for calibration, and an analysis of the errors and instrumental asymmetries involved.
CHAPTER 3

THE DESIGN AND COMMISSIONING OF THE "MICRO-MOTT 2" RETARDING POTENTIAL MOTT POLARIMETER

3.1 INTRODUCTION

The Spin Polarised Spectroscopy (SPS) group has two instruments for measurement of the spin polarisation of electron beams; a high energy (100 kV) Mott polarimeter \(^{31,32,33}\) and a low energy (20 kV) retarding potential Mott polarimeter \(^{32,33,34}\).

The high energy polarimeter is a permanent fixture on the end-station of Beamline 1.2 of the Synchrotron Radiation Source (SRS). This beamline supplies radiation from a dipole bending magnet and provides a photon energy range of 5 - 85 eV. The end-station, containing the polarimeter, is an ultra high vacuum (UHV) experimental chamber for condensed matter studies.

The retarding potential Mott polarimeter, known as “Micro-Mott 1”, was developed to complement the high energy instrument: it is a more flexible instrument that may be used in conjunction with a number of beamlines at the SRS, thus enabling a variety of experimental configurations. Operating at a much lower energy than the Mott polarimeter on Beamline 1.2, and with its outer casing maintained at close to earth potential, Micro-Mott 1 is a far more compact instrument than the high energy polarimeter.

In 1995 the SPS group began the design and construction of a second Micro-Mott polarimeter, for use on one of the Liverpool University Interdisciplinary Research Centre (IRC) beamlines at the SRS. However, insurmountable problems were encountered with its use on the IRC beamline. Therefore, in 1997 this second polarimeter, known as “Micro-Mott 2”, was reallocated to the SPS group before it could be commissioned.
Designed for use in an experimental chamber with a 19 inch diameter baseflange, Micro-Mott 2 required conversion to the 17 inch diameter of the SPS group experimental chambers. This conversion required a new baseflange and minor modifications to the magnetic shield, the electrostatic shield and the polarimeter support bracket. Rebuilt, the instrument nonetheless required characterisation and benchmarking.
3.2 OVERVIEW OF THE MICRO-MOTT 2 INSTRUMENT

Micro-Mott 2 is a retarding potential type Mott polarimeter, based on spherical geometry. The instrument configuration is illustrated schematically in Figure 3.1. This diagram also details the measurable components of electron spin. The instrument is configured such that a horizontally propagating electron beam is first energy analysed by a 180° concentric hemispherical analyser (CHA). Polarisation analysis is then achieved by scattering the energy analysed beam from a gold foil held at a potential of around 20 kV. Backscattered electrons are retarded by the low potential of the outer casing of the instrument, and are then collected by four detectors maintained at near ground potential. The detectors are deployed so as to enable measurement of two orthogonal components of electron spin polarisation, \( P \). The polarimeter is capable of resolving only components of spin that are transverse to the original direction of propagation of the incident electron beam, \( P_{TH} \) and \( P_{TV} \); the subscripts denote "transverse horizontal" and "transverse vertical" respectively.

![Image of Micro-Mott 2 instrument configuration](image)

**Figure 3.1.** The configuration of Micro-Mott 2 and the measured components of electron spin polarisation, \( P_{TH} \) and \( P_{TV} \).
3.3 CONSTRUCTION OF THE MICRO-MOTT 2 INSTRUMENT

A photograph of the Micro-Mott 2 polarimeter is shown in Figure 3.2, with a portion of the electrostatic shield removed to reveal the detector system.

Figure 3.2. The Micro-Mott 2 instrument; part of the electrostatic shield has been removed to reveal the polarimeter detector system.

The instrument is mounted upon a main support bracket that sits on the inner flange of a two-stage differentially pumped rotary feedthrough. This enables full 360° azimuthal rotation of the instrument; no polar adjustment is possible. The CHA is mounted, electrically isolated, on this support bracket. A commercial CHA analyser is employed; specifically an HA50 analyser, manufactured by VSW Ltd, with a mean radius of 50 mm. The underlying principles of the design and operation of a CHA are discussed in Appendix A. The transport electron optics and the polarimeter itself are mounted, such that electrical isolation is again ensured, on the exit aperture of the CHA. All
electrical connections to the instrument are made via suitable feedthrough sockets mounted on the rotary feedthrough, thus eliminating motion of any wiring with respect to the instrument.

A sectional assembly drawing of the Micro-Mott 2 polarimeter, and associated transport optics, is illustrated in Figure 3.3.

![Figure 3.3. A sectional assembly drawing of Micro-Mott 2](image)

The polarimeter is constructed entirely out of materials that are both non-magnetic and compatible with UHV; predominantly aluminium (the casing), non-magnetic stainless steel (inner hemisphere and transport optics), oxygen free copper and macor machineable ceramic. Trapped volumes were carefully avoided in the construction. The polarimeter optics were designed and built to avoid sharp edges and rough surfaces that might cause arcing of the high tension (HT) applied to the inner hemisphere. The spacing of the hemispheres was chosen to enable the instrument to support an applied HT of 20 kV.
The inner hemisphere is mounted, isolated from the outer hemisphere, by a macor plate. The HT is applied to the inner hemisphere, via a mounting bolt, through this plate. A gold scattering foil, 0.02 mm thick, sits at the centre of the inner hemisphere and is held in place by a locking ring.

Structurally, the polarimeter depends on the outer hemisphere to act as a chassis, or casing, for its associated electron optics and detectors. The input optics of the polarimeter consists of a four lens element system designed to collect and focus energy analysed beams onto the Mott scattering foil. The third lens of this system has been converted to enable x/y deflection of the electron beam.

The four detector apertures, in both the inner and outer hemispheres, are equispaced azimuthally about the polarimeter axis. These apertures are further aligned with the centre point of the gold foil, at an angle of 60 degrees to its surface normal. The apertures in the inner hemisphere are designed to accommodate reentrant cones, the purpose of which is to minimise the collection by the detectors of electrons that have been scattered from surfaces other that of the gold foil. However, these reentrant cones have yet to be fitted.

The detectors deployed on the polarimeter are microchannel plate (MCP) devices manufactured by Hamamatsu, model number F1551 - 21S. The design and operation of MCP detectors are discussed in Appendix B. Micro-Mott 2 was constructed with an electron optical lens element situated immediately in front of each detector; this enables application of an energy window, ΔE, for discrimination against inelastically scattered electrons. The polarimeter casing itself may further be biased electrically, thus providing additional focusing for improved collection of backscattered electrons. The polarimeter design is such that the four detectors each subtend a solid angle of approximately 0.10 sr at the gold foil.

An electrostatic shield is necessary to screen the interaction region of the experimental chamber from the many separate potentials applied to the
polanmeter. A part of this shield is visible in Figure 3.2. Magnetic shielding of
the polarimeter, principally from the magnetic field of the Earth, is also
necessary. This is achieved through the use of mu-metal high permeability
alloy, either as the material of the experimental chamber, or in the form of a
liner within the chamber. A mu-metal disc, that lies just above the baseflange,
was used to screen the underside of Micro-Mott 2. This screening reduces the
magnetic field of the Earth, within the experimental chamber, to the milligauss
level.
3.4 CONTROL INSTRUMENTATION

All ancillary equipment for the operation of Micro-Mott 2, with the exception of the personal computer (PC), are mounted and earthed in a dedicated control rack. This equipment includes a CHA controller, power supplies for the electron optical elements, electronic signal processing equipment and a Microlink computer interface. Operation of the CHA controller and the acquisition of data is achieved, via the Microlink unit, with an IBM PC. The control and data acquisition system is described in more detail in a CLRC Daresbury Laboratory technical report \(^3\) \(^2\).

3.4.1 POWER SUPPLIES

A schematic of the power distribution system is illustrated in Figure 3.4.

![Schematic diagram of the Micro-Mott 2 power distribution system.](image)

Figure 3.4. Schematic diagram of the Micro-Mott 2 power distribution system.
The various electron optical elements, including the MCP detectors, are powered by nine 0 - 5000 V DC switch-mode type power supplies manufactured by Applied Kilovolts. These supplies, powered by a single mains transformer, are housed in a dedicated unit constructed at the University of Sussex. This unit, known as the Sussex supply, also contains a 0 - 30 kV switch-mode HT supply for bias of the Mott scattering foil.

All power supplies within the Sussex unit float on the kinetic energy rail potential that is set by the PC. The kinetic energy rail is maintained at a potential equivalent to the selected transmission energy of the CHA. The floating of all electron optical supplies upon the kinetic energy rail ensures that the trajectories of electrons passing through the instrument are not affected by the magnitude of their kinetic energy; the transmission of the instrument is constant for all electron kinetic energies.

The CHA controller is a dedicated commercial unit manufactured by VSW. Normally the HAC300 model is used (0 - 300 eV). However, this model is interchangeable, when required, with other models that provide a greater range of kinetic energy analysis.

The Mott scattering foil is usually biased by a dedicated commercial 0 - 30 kV supply manufactured by Wallis. This supply is used on account of concerns over the stability of the Sussex 30 kV supply. The Wallis supply has the disadvantage of not floating on the kinetic energy rail. However, when operated in conjunction with the HAC300 hemispherical analyser controller, this corresponds at most to an error of 300 V in an applied potential of 20 kV.

In order to measure an electron spin asymmetry, an axis of quantisation must be established at the sample under investigation. This is achieved experimentally by energising a solenoid to magnetise the sample. Micro-Mott 2 utilises a programmable Thurlby-Thandar TSX3510P (35 V, 10 A) supply for this purpose. Reversal of polansation is achieved by reversal of the supply polarity via the Microlink unit. A Solartron 7150 programmable digital
multimeter is used to provide an accurate measurement of the applied magnetising current.

3.4.2 SIGNAL PROCESSING

3.4.2.1 Standard System

The signal processing system is module based, utilising a Nimbin rack and appropriate amplification and filter modules manufactured by EG&G Ortec. The system is illustrated in the flow diagram of Figure 3.5, along with the shaping effects of the processing units on a typical charge pulse.

![Flow diagram of signal processing units](image)

Figure 3.5. Flow diagram of the signal processing units and their shaping effects on the electron signal.

The standard detector chain is configured as follows, with each detector assigned its own discrete channel of signal processing. The electron cascade pulses generated at an anode are fed directly to an Ortec 142 charge preamplifier; this same preamplifier connection is also used to supply the
anode HT potential. The 142 unit amplifies the signal, which is then fed to an Ortec 850 shaping amplifier. This module shapes the charge pulse such that its rise and fall time correspond to a standard pulse width of 2.0 μs. The shaped signal then passes to an Ortec 855 discriminator unit. Here the pulse height is referenced to externally adjustable upper and lower levels. Pulse heights falling outside these set limits are rejected, and the remaining pulses are amplified to a pulse height of 4.0 V before passing to the Microlink crate for counting. The adjustment of these discrimination limits, for optimum performance, is illustrated in Figure 3.6.

![Figure 3.6. Schematic diagram of the pulse height distribution, illustrating the set-up of upper and lower discrimination limits.](image)

This system enables noise induced pulses to be eliminated almost completely by careful optimisation of the discriminator levels of the Ortec 855 unit. These levels are set by careful monitoring of the dark count rate - the detector output with no electron beam signal present - on an oscilloscope.

The output of this signal processing system has been shown to be linear with the input signal for count rates of up to 30 kHz. \(^3\)\(^5\).
3.4.2.2 Fast System

The standard system is more than adequate for photoemission studies. However, electron beam initiated secondary electron spectroscopy studies routinely involve significantly greater count rates. The standard signal processing system becomes saturated when count rates exceed 30 kHz. The finite rise and fall times of the individual charge pulses, arising from electrons striking the detectors, result in piling up of the pulses. The practical consequence of this is that when analysing low energy secondary electrons, of typically 1 - 10 eV kinetic energy, the count rates must be deliberately reduced. If this wasted signal could be harnessed then the data collection times, to achieve a given statistical accuracy, could be reduced dramatically.

A fast signal processing system was therefore developed \(^3\)\(^6\), \(^3\)\(^7\). The fast system, like the standard system described above, is based on EG&G Ortec amplification and filter modules mounted in a Nimbin rack. Specifically, the fast system utilises an Ortec 474 timing filter amplifier, in place of the Ortec 850 shaping amplifier, on each channel of the original processing system. The Ortec 474 enables the rise and fall times of charge pulses to be reduced to a combined total of 50 ns or better. This reduces the pile-up of charge pulses, thereby increasing the maximum count rate for which the processing system can maintain a linear output. The fast processing system has been shown to provide a linear output for count rates up to 100 kHz per channel \(^3\)\(^5\).

3.4.3 COMPUTER CONTROL

Computer control of the HAC300, the kinetic energy rail and pulse magnetisation circuitry is provided through a Microlink crate, manufactured by Biodata Ltd., and appropriate electronic modules. Microlink modules are further responsible for collection of the processed MCP detector signals and, when used in conjunction with an SRS beamline, measurement of the beam intensity for normalisation of detected signals. A schematic of the computer
control and data acquisition system is illustrated in Figure 3.7. The system configuration is described in detail in a CLRC Daresbury Laboratory technical memorandum 38.

Figure 3.7. Schematic of the Micro-Matt 2 computer control and data acquisition system.

The Microlink is interfaced to a PC via a general purpose interface bus. The PC operates a Fortran based routine for control of the Micro-Mott 2, programmed by the Daresbury Laboratory data acquisition group.

3.4.4 NOISE REDUCTION MEASURES

A UHV experimental chamber, without viewports or feedthroughs, is a perfect Faraday cage. Therefore, its interior can be considered to be perfectly screened from all external sources of electrical noise. However, this Faraday cage is compromised by the presence of viewports or feedthroughs in the chamber walls. In the case of feedthroughs, whether for application of electron...
optical potentials or for extraction of high frequency detector signals, the cables involved act as antennae. This antenna action severely compromises the screening of the chamber.

This problem is minimised by application of suitable screening to all plugs that connect to feedthroughs. Where possible power cables terminate in metal cases on which the feedthrough plug is mounted, earthing airborne noise. The cases contain low pass filtering to decouple cables from noise borne by the chamber earth. In particular, the power connections for the MCP detectors are made through an input box that contains a Zener diode chain circuit, in order to maintain a constant potential difference across the plates. Cables that carry high frequency output signals are connected to the chamber by screened SHV type connections. These connections, between the preamplifiers and the chamber, should also be as short as possible to minimise pick-up of ambient noise.

A careful programme of noise reduction, for the SPS Micro-Mott polarimeters, was begun in 1995. This work was initiated by the desire to operate the polarimeters with high count rates; the required fast detector channels are sensitive to high frequency noise such as that generated by turbo pumps\textsuperscript{39}.

A systematic approach was taken to the location and elimination of every possible source of noise. Where possible, digital systems were removed and replaced with analogue equivalents. Mains borne noise was eliminated by powering the polarimeter data acquisition and control rack via an isolation transformer. The careful layout of all cables and earth straps on the apparatus prevents pick up of ambient noise through antenna action of earth loops. This, together with screening of all cables and earthing of all equipment, resulted in a reduction of ambient noise levels, for Micro-Motts 1 and 2, to less than 5 counts per channel per second with the fast signal processing system. The noise level for the standard processing system is essentially zero.
3.5 OPERATION OF MICRO-MOTT 2

Micro-Mott 2 is normally operated with a pass energy of 15 or 25 eV applied to the CHA, in order to provide satisfactory count rates. Upon exit from the fringing field of the CHA, the electron beam is subject to lens potentials of 800, 600 and 2000 volts respectively in the three remaining elements of the transport optics. These potentials are designed to provide both focusing of the beam onto the gold foil in the inner hemisphere, and to prevent any low energy electrons generated by scattering from the CHA exit aperture from progressing further.

The deflector plate power supply, designed principally for use in conjunction with the Hybrid Polarimeter (see Chapter 5), enables ± 4.5 volts to be superimposed upon the 600 volt potential of the deflector elements. This provides a limited means of converging the count rates of the four detector channels.

The options available for the potentials applied to the outer hemisphere, detector lens elements and MCPs are discussed in detail in Section 3.7.2.1. However, the Sussex power supply unit restricts operation of all electron optical elements to an upper limit of 5 kV. Normally the instrument would operate with the MCP front faces and detector lens elements at 200 V, corresponding to an energy window of 200 eV, and the outer hemisphere at 1000 V. The applied energy window may be varied in 10 equal steps from 100 to 1000 eV.

The MCP detectors are operated normally with a potential difference of 1500 V applied across their front and rear faces. As the plates age, this potential difference may be increased to maintain detection efficiencies. The anodes immediately behind the channel plates are maintained a further 100 - 150 V above that of the detector rear faces.
Micro-Mott 2 was originally designed for operation with the scattering foil maintained at an HT potential of 20 kV. However, operation is currently limited to an HT of 17 kV since, beyond this level, the HT is prone to breakdown. This risks damaging the MCP detectors and is therefore not advisable. This is discussed further in Section 3.7.2.1.
3.6 COMPARISON OF MICRO-MOTT 1 WITH MICRO-MOTT 2

The Micro-Mott 1 instrument, with almost identical energy analysis, transport optics, path lengths and detection systems provides a benchmark for the performance of Micro-Mott 2. Operationally, the two instruments are almost identical. The only exceptions are that for Micro-Mott 1 there is no x/y deflection facility on the transport optics, and the outer hemisphere is held at the potential of the kinetic energy rail. The construction of Micro-Mott 1 is, however, somewhat different in several respects.

Micro-Mott 1 was engineered to a standard design, developed by Dunning and coworkers at Rice University in the USA. The instrument is a retarding potential polarimeter of comparable size to Micro-Mott 2. However, the underlying geometry is conical, whereas that of Micro-Mott 2 is spherical. The spherical geometry of Micro-Mott 2, and its improved electron collection at the detectors, should confer a small improvement in performance upon this instrument.

Being of a standard design, the issues of calibration and characterisation of Micro-Mott 1 are much simplified; an extensive investigation into the polarimeter performance has been undertaken by Dunning and coworkers. When operated with an HT of 20 kV applied to a gold scattering foil, and an inelastic energy window of 1.3 keV, the polarimeter design is reported to give an effective Sherman function, $S_{\text{eff}}$, of 0.11. The corresponding figure-of-merit (FOM) is $2.7 \times 10^{-5}$.

Also, Micro-Mott 1 is mounted upon a two circle goniometer, enabling both polar and azimuthal adjustment of its alignment. Furthermore, the HT reaches the instrument via a static feedthrough on the baseflange, and therefore any alignment of the instrument within the chamber results in relative motion of the HT cable; this has been the cause of significant problems in the stability of the applied HT.
Finally, the use of reentrant cones, in the inner hemisphere detector apertures, potentially has implications for both the $S_{\text{eff}}$ and FOM of a polarimeter. The reentrant cones of Micro-Mott 2 have yet to be fitted, in order to investigate the polarimeter performance without them.
3.7 INVESTIGATION OF POLARIMETER PERFORMANCES

Experimental work was undertaken for the purpose of commissioning and characterising the Micro-Mott 2 facility, and to enable its comparison with the performance of the original Micro-Mott 1 instrument.

3.7.1 EXPERIMENTAL DETAILS

3.7.1.1 Source of Polarised Electrons

Amorphous ferromagnetic glass ribbons have been suggested as potential standard sources of polarised electrons \(^3\text{12}\). Their use as standards is discussed in detail in Chapter 6. While there are reservations about the reliability of the absolute polarisation of the secondary electron cascade, such ribbons can nonetheless be relied upon for the generation of a polarised electron beam. Furthermore, this method of polarised electron beam generation is simple and straightforward to implement experimentally.

Briefly, a suitable ribbon sample, in our case an as-cast sample of the alloy Fe\(_{80}\)B\(_{20}\) \(^3\text{13}\), is formed into a closed loop that passes through a small solenoid. This sample is then bombarded with an unpolarised, energetic electron beam. The experimental configuration is illustrated in Figure 3.8, along with the two spin asymmetry components transverse to the emitted beam direction; \(A_{TH}\) and \(A_{TV}\), where the subscripts denote "Transverse Horizontal" and "Transverse Vertical" respectively.

It is important that the loop possesses a gentle radius in order to prevent stress induced magnetic effects. Furthermore, the ends of the ribbon must overlap and be clamped firmly together, to reduce the influence of stray magnetic fields. When the ribbon is in a saturated, remanent magnetisation state, achieved by pulsing a current through the solenoid, the emitted cascade of secondary electrons exhibits a pronounced transverse polarisation. Reversal
of the ribbon magnetisation reverses the spin polarisation of the secondary electron cascade. The Fe\textsubscript{80}B\textsubscript{20} ribbon used for these studies has been demonstrated to routinely produce electron beam polarisations as high as 0.20.

Figure 3.8. Schematic illustration of the use of an amorphous ferromagnetic ribbon for the generation of a polarised beam of electrons, and the two spin asymmetry components analysed by Micro-Motts 1 and 2.

In practice, to achieve a satisfactory polarisation, the ribbon sample must be thoroughly cleaned prior to use; this is achieved by bombardment of the sample with 1.6 keV argon ions, with a drain current of 10 - 15 \( \mu \text{A} \).

Electron bombardment of the ribbon sample is achieved with an EG5 electron gun, a commercial instrument manufactured by VSW Ltd. The EG5 uses a hot filament and anode arrangement to generate an electron beam. In the
following experimental work, on account of noise problems associated with the fast signal processing system, the filament current was set so as to limit count rates to below 30 kHz; all data were collected using the standard signal processing system. A filament current of between 2.0 and 2.1 A was typical; the maximum current for sustained reliable operation is 2.6 A. The beam energy was set to 1.6 keV. Higher beam energies were avoided to prevent damage to the ribbon sample.

The sample manipulator provided micrometer adjustment of lateral and vertical sample position, and azimuthal adjustment of sample angle. The sample was positioned for grazing incidence, $\sim 10^\circ$, of the primary electron beam, and normal emission with respect to the input optics of the CHA.

In the following experimental work, once a region of the sample had been identified as providing a strong measurable asymmetry, the sample position was held constant. However, it was not possible to be certain that the same area of the sample was analysed from one experiment to another. The EG5 electron gun proved very unstable during an initial warm-up period of approximately one hour, after which it would behave consistently. A standardised procedure for optimisation of count rate was adopted, and applied to each experimental run. Instrument settings and results were self-consistent throughout all experimental work, leading to a degree of confidence that all experiments involved essentially the same area of the sample ribbon surface.

3.7.1.2 Sample Bias

Stray electrons originating other than from the sample are the cause of an undesirable non-polarised background signal. Such stray electrons are few in number above kinetic energies of a few eV, and are therefore easily eliminated by the application of a bias potential of $-20$ V to the sample. True secondary electrons from the sample are shifted to higher energy by 20 eV, while stray
electrons remain as a small signal at low energy. The situation is illustrated in Figure 3.9.

**Figure 3.9.** The use of a sample bias to eliminate detection of stray electrons.

It should be noted that the characteristic secondary electron peak, as illustrated in Figure 3.9, only arises when the analyser input aperture is aligned normal to the sample. Away from normal incidence this peak becomes smeared out towards higher energy, dramatically reducing its intensity.

### 3.7.1.3 Experimental Chambers

All experimental work was undertaken using the two dedicated SPS group UHV chambers, known as Surf 0 and SPS 1. There are no major differences between the two; each routinely achieves a base pressure of $2 \times 10^{-10}$ mbar or better. When operating with the EG5 electron gun, a pressure of $2 \times 10^{-9}$ mbar was routinely recorded for both chambers.
Each chamber is pumped by an ion pump, a rotary backed turbomolecular pump and a titanium sublimation pump. Standard surface science equipment is available on each chamber, including RF quadrupole residual gas analysis and ion gauges for pressure measurement, and an argon ion gun for sample cleaning.

3.7.2 CHARACTERISATION AND COMMISSIONING OF MICRO-MOTT 2

3.7.2.1 Investigation of Polarimeter Optics

The first step was to test the application of HT to the inner hemisphere. The applied HT was found to be limited to 17 kV. This was carefully investigated with a series of tests at atmospheric pressure, at various stages of assembly of the polarimeter. Breakdown of the HT was identified as occurring between the baseplate of the outer hemisphere and the base of the inner hemisphere. It is believed that sharp edges on the counterbores of the inner hemisphere base are the cause of this breakdown.

Next it was necessary to verify that the polarimeter optics were functioning correctly. The behaviour of count rates, with both the applied HT and the applied inelastic energy window (ΔE), represents two basic tests of instrument function. The results of these tests on Micro-Mott 2 are illustrated in Figures 3.10 and 3.11 respectively.

In both cases the instrument behaved exactly as expected. At higher values of applied HT, progressively fewer backscattered electrons were detected. Similarly, the inelastic energy window controls the range of energy loss within which inelastically backscattered electrons may still reach the detectors; as this window is increased, so too do the count rates.
Figure 3.10. Count rate versus applied HT for Micro-Mott 2.

Figure 3.11. Count rates versus inelastic energy window for Micro-Mott 2.

The focusing effects of the detector optics were also investigated. The ability to bias separately the casing of the polarimeter was implemented specifically to improve focusing at the detectors. This was modelled using SIMION v4.0 electrostatic lens design software\textsuperscript{3,15}, the results of which suggested that count rates should improve with increasing casing potential. The model is shown in Figure 3.12, which compares two configurations. The upper configuration of 1000 V casing potential focuses all but the outermost electron paths through to the detector. The lower configuration, with only 100 V applied to the casing, loses two outer electron paths of the same set of modelled trajectories, these electrons being attracted back to the inner hemisphere.
Figure 3.12. SIMION v4.0 models of the detector optics on Micro-Mott 2; the upper model demonstrates improved focusing due to the higher potential applied to the casing.

This focusing effect was demonstrated experimentally by measuring the count rate against increasing casing potential. The results are shown in Figures 3.13 and 3.14. Figure 3.13 concerns a focus potential applied to the casing, with the energy window applied to the detector lens elements and MCP front faces.
Figure 3.14 illustrates the converse configuration; the focus potential is applied to the detector lens elements, with the energy window applied to the casing and MCP front faces.

Figure 3.13. Count rates versus the focus potential applied to the casing; an energy window of 200 eV is applied to the detector lens elements.

Figure 3.14. Count rates versus the focus potential applied to the detector lens elements; an energy window of 200 eV is applied to the casing.

The former configuration results in the highest count rates, and was therefore chosen for implementation as standard operational procedure. Concerns over
the ability of the casing to support reliably a high potential restricted the experimental set-up to a focus potential of 1000 V.

Investigations into the linearity of the response of the detectors, with increasing count rate, proved impossible with the EG5 electron gun; accurate control of the incident electron current could not be achieved. However, Micro-Mott 2 uses the same MCP detectors and signal processing hardware as Micro-Mott 1, so the detectors should behave similarly \(^{3,5}\).

### 3.7.2.2 Measurements of Electron Beam Polarisation

Initial verification of electron beam polarisation can be made by a relatively quick measurement of spin asymmetry with the sample remanently magnetised in opposite directions. Figure 3.15 illustrates a time scan of count rates taken with magnetisation pulses of 2.00 A reversed every fifth point; the inelastic energy window is 200 eV. The corresponding asymmetries, \(A_{TH}\) and \(A_{TV}\), are shown in Figure 3.16.

![Graph](image.png)

**Figure 3.15.** Count rates for an asymmetry test at 1 eV secondary electron kinetic energy, with \(\Delta E = 200\) eV.

The count rates of Figure 3.15 illustrate clearly the small but distinct increase and reduction in opposing detector signals that results, due to Mott scattering, when the magnetisation of the ribbon is reversed. It should be noted that the
asymmetry illustrated in Figure 3.16 includes the instrumental asymmetry of the polarimeter, which appears as an offset about the x-axis.

Figure 3.16. Measured asymmetries, $A_{TH}$ and $A_{TV}$, for an asymmetry test at 1 eV secondary electron kinetic energy, with $\Delta E = 200$ eV.

The experimental arrangement enables the measurement of hysteresis loops. Two examples are shown in Figures 3.17 and 3.18, the data being taken shortly after that of Figures 3.15 and 3.16 above, and with the experimental arrangement unchanged.

Figure 3.17. 1 eV energy resolved hysteresis loop for Fe$_{80}$B$_{20}$; 2.5 hours post sputter clean.
Figure 3.18. 1 eV energy resolved hysteresis loop for Fe$_{80}$B$_{20}$; 4.0 hours post sputter clean.

The difference in the remanent magnetisation of these two loops is explained by the progressive accumulation of a layer of contamination at the sample surface. The loop of Figure 3.17 was obtained 2.5 hours after the sample had been sputter cleaned. That of Figure 3.18 corresponds to a period of 4.0 hours after cleaning; by this time the secondary electron signal can be considered to be generated to a large extent by contamination on the sample surface.

The strong vertical component of spin asymmetry, $A_{TV}$, indicates that the predominantly imaged magnetic domain is pinned by some mechanism, and is therefore unable to orientate itself along the axis of magnetisation. It should be reiterated that the Fe$_{80}$B$_{20}$ sample demonstrates significant magnetic inhomogeneity. The probing of a different area of the sample failed to produce any measurable asymmetry, parallel or transverse to the axis of magnetisation.

The influence of the detector focus potential, on the measured asymmetry, was investigated. The asymmetry obtained, for remanent saturation magnetisation, was measured across a range of focus potentials from 0 - 1200 V applied to the casing; the inelastic energy window was maintained at 200 eV. The results are illustrated in Figure 3.19, where the asymmetry can be seen to remain
constant over this range. The count rates increased, from approximately 15 kHz per detector at 0 V, to almost 29 kHz at 1200 V.

![Graph showing Asymmetry versus Casing Potential](image1)

Figure 3.19. Asymmetry versus focus potential applied to the casing.

Calibration of Micro-Mott 2 was performed through the energy window extrapolation technique described in Chapter 2, Section 2.3.1.3. The asymmetry of 1 eV secondary electrons was measured for the whole range of available energy window settings; the results are shown in Figure 3.20. The

![Graph showing Asymmetry versus Inelastic Energy Window](image2)

Figure 3.20. Asymmetry versus inelastic energy window; the results extrapolate to asymmetries of theoretically pure elastic scattering $A_{TH} = -0.020$ and $A_{TV} = 0.018$. 

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illustrated data were collected with the energy window applied to both the detector lens elements and the casing.

The results of Figure 3.20 extrapolate to asymmetries of theoretically pure elastic scattering $A_{TH} = -0.020$ and $A_{TV} = 0.018$. The applied HT at the Mott scattering foil was 17 kV, which corresponds to a theoretical Sherman function, $S_{th}$, of $0.29^{316}$. The relation

$$P = A / S_{th} \quad (3.1)$$

where $A$ is the measured asymmetry, enables calculation of the corresponding beam polarisation, $P$. Thus, from Figure 3.20, we have $P_{TH} = 0.069$ and $P_{TV} = -0.062$. Now Equation 3.1 can be rearranged to enable calculation of the $S_{eff}$

$$S_{eff} = A / P \quad (3.2)$$

The above asymmetries, measured with $\Delta E = 200$ eV, and polarisation values may be substituted into Equation 3.2 to determine the $S_{eff}$ at this particular energy window. Therefore we obtain

$$S_{eff}(TH) = -0.22 = S_{eff}(TV) \quad (3.3)$$

This calibration procedure was repeated four further times in order to investigate the effects of different applied lens potentials, and energy window configurations, upon the measured value of $S_{eff}$. Two analyses investigated the effects of application of the energy window on the detector lens elements, with firstly 200 V, and secondly 1000 V, applied to the casing. The remaining two analyses corresponded to the energy window applied on the casing, with the detector lens elements held firstly at 200 V, and then at 1000 V. The results of all five calibration runs are given in Table 3.1.
Table 3.1. Calculated effective Sherman functions, $S_{\text{eff}}(\text{TH})$ and $S_{\text{eff}}(\text{TV})$, for different electron optical configurations of Micro-Mott 2; extrapolations of both longitudinal and transverse asymmetries have been utilised.

The tabulated values of effective Sherman function are in close agreement, indicating that the precise configuration of the instrument has no significant effect upon the $S_{\text{eff}}$.

As discussed in Chapter 2, Section 2.3.1.3, it is important to note that whilst these results eliminate the effect of inelastic scattering from the analysis, the more important effect of multiple elastic scattering is not accounted for; the actual effective Sherman function is expected to be significantly lower than the value quoted above.

3.7.3 CHARACTERISATION OF MICRO-MOTT 1

The Micro-Mott 1 instrument does not offer the flexibility that is available on Micro-Mott 2, in terms of focusing and energy window application at the detectors. It is therefore a more simple instrument to characterise. The characterisation utilised a similar experimental set-up to that for Micro-Mott 2. A sample of Fe$_8$B$_{20}$ ribbon, from the same production batch as that used with Micro-Mott 2, provided the source of polarised electrons. The polarimeter was mounted within the SPS 1 experimental chamber and, most importantly, was operated with an applied HT of 20 kV.

<table>
<thead>
<tr>
<th>Casing /V</th>
<th>Detector lens /V</th>
<th>$S_{\text{eff}}(l)$</th>
<th>$S_{\text{eff}}(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$</td>
<td>$\Delta E$</td>
<td>-0.22</td>
<td>-0.22</td>
</tr>
<tr>
<td>800</td>
<td>$\Delta E$</td>
<td>-0.22</td>
<td>-0.22</td>
</tr>
<tr>
<td>200</td>
<td>$\Delta E$</td>
<td>-0.23</td>
<td>-0.22</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>800</td>
<td>-0.23</td>
<td>-0.23</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>200</td>
<td>-0.23</td>
<td>-0.22</td>
</tr>
</tbody>
</table>
Hysteresis loops were obtained readily with the polarimeter. A sample area that provided a good spin asymmetry was again chosen, and maintained for the acquisition of all data. A hysteresis loop taken at this point, with an energy window of 400 eV, is illustrated in Figure 3.21. The cause of the offset about the y-axis is not known. The higher coercive field revealed by these results, as compared with the data taken by Micro-Mott 2, is believed to be due to the magnetic inhomogeneity of the sample.

Figure 3.21. 1 eV energy resolved hysteresis loop for Fe₈₀B₂₀.

Figure 3.22. Asymmetry versus inelastic energy window; the results extrapolate to an asymmetry of theoretically pure elastic scattering $A_{TH} = -0.038$. 
As with Micro-Mott 2 above, an energy window extrapolation procedure was performed in order to calibrate Micro-Mott 1. The asymmetry of 1 eV secondary electrons was measured for the whole range of available energy window settings; the results are shown in Figure 3.22.

Since the Mott scattering foil was maintained at 20 kV, an $S_{th}$ of -0.30 is assumed. This leads, through Equations 3.1 and 3.2, to an $S_{eff}$ value of -0.20 at an energy window of 400 eV. The value of $S_{eff}$, for an energy window of 200 eV, is found to be -0.24.
3.8 CONCLUSIONS

The Micro-Mott 2 polarimeter has been demonstrated to function correctly. The optimum values of applied potential, on the various electron optical elements of the instrument, have been determined. The polarimeter remains limited at present to operation with an applied HT of 17 kV, resulting in a small but significant reduction in the $S_{\text{eff}}$. It is believed that only minor modifications are necessary, to achieve operation at the designed HT level of 20 kV.

The values of $S_{\text{eff}}$, for both Micro-Motts 1 and 2, have been measured by extrapolation of the inelastic energy window. The results, for an inelastic energy window of 200 eV, are given in Table 3.2.

<table>
<thead>
<tr>
<th>Polarimeter</th>
<th>Applied HT</th>
<th>$S_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-Mott 1</td>
<td>20 kV</td>
<td>-0.24</td>
</tr>
<tr>
<td>Micro-Mott 2</td>
<td>17 kV</td>
<td>-0.22</td>
</tr>
</tbody>
</table>

Table 3.2. The measured values of $S_{\text{eff}}$ for Micro-Motts 1 and 2, for an inelastic energy window of 200 eV.

These values of $S_{\text{eff}}$ are believed to be too high. In particular, the $S_{\text{eff}}$ for the Micro-Mott 1 polarimeter has previously been determined by Dowling, through inelastic energy window extrapolation, to be -0.18 for an energy window of 400 eV \(^{34}\). This value is lower than that obtained in this work. The difference is believed to be due to the use, by Dowling, of values of $S_{\text{th}}$ as determined by Holzwarth and Meister \(^{3,17}\).

It is apparent that the omission of the reentrant cones, from the inner hemisphere of Micro-Mott 2, has not impaired the performance of this instrument. The absence of the cones might in fact confer an improved FOM upon Micro-Mott 2. This should be investigated further.
For efficient operation of Micro-Mott 2, the following set-up of the electron optical potentials is recommended:

- The lowest possible value of inelastic energy window should be applied, without causing a reduction of count rates.

- If count rates are low, for example when analysing Auger electrons, a higher energy window should be selected.

- The energy window should be applied on both the MCP front faces and the detector lens elements.

- The casing should be maintained at a potential of 1000 V to optimise count rates.

The application of a focusing potential upon the casing has been shown to improve count rates without any effect upon the $S_{\text{eff}}$ of the instrument.
CHAPTER 4

POLARISATION ANALYSIS OF BEAMS OF ELECTRONS 2: SPIN DEPENDENT TRANSMISSION BASED METHODS

4.1 INTRODUCTION

Experiments reported over the last decade have laid the foundation for the separate polarisation analysis, based upon the exchange interaction, of both longitudinal and transverse electron spin components. In particular the transmission of electrons, at low energy, through an ultrathin ferromagnetic film exhibits spin dependence as a consequence of the exchange interaction.

This new approach has evolved from advances made in the theory of electron transport in condensed matter, and the realisation that a spin dependency exists in the inelastic mean free path (IMFP) of electrons traversing a solid ferromagnetic matrix. However, research in this field remains in its infancy. Over the last few years a number of preliminary spin filter devices have been proposed and investigated $^{41, 42, 43, 44}$. However, the results to date have increased rather than resolved the confusion and disagreement that exists concerning the precise nature of the spin dependency of the IMFP in low energy transport through ferromagnetic transition metals.

This chapter presents a review of spin filter research. The issues involved in understanding the physics of the transport of electrons through condensed matter are discussed, particularly in the context of the most successful model to date for low energy transport through ferromagnetic transition metals $^{45}$. Finally, the various efforts to harness the spin dependency in transmission are described and a critique is presented of the conflicting data that these have produced.
4.2 ELECTRON TRANSPORT

Consider excitation of an electron within a solid surface, by some external means, to an energy above the Fermi level. This electron will be subjected to some combination of elastic and inelastic collisions, until it either breaks free of the surface altogether or is scattered back into the Fermi sea of conduction electrons.

In the case of high energy excitation, applicable in Auger electron spectroscopy and X-ray photoelectron spectroscopy techniques for example, the resulting cascade of emitted secondary electrons is always of the same profile. This is illustrated by a plot of the distribution of the cascade electrons with kinetic energy, as shown schematically in Figure 4.1.

Figure 4.1 A schematic illustration of a typical secondary electron cascade distribution with kinetic energy, for electrons emitted from a surface under illumination by a high energy source, \( E = E_{\text{in}} \), of either photons or electrons. Contributions that are due to elastic, inelastic and Auger scattering processes are labelled \(^4\,^6\).
The large peak at the incident energy is due to electrons that have undergone purely elastic scattering, either in single or multiple events, within the surface. The remaining background signal sweeps up from just below the elastic peak to a large secondary peak at very low electron energy. This background is made up of two types of electrons, primary and secondary. Primary electrons are those that have lost energy in a single well defined inelastic scattering event, such as the excitation of a core level electron or the production of a plasmon. They are found at energies of a few eV all the way up to immediately below the elastic peak. The almost featureless background of secondary electrons is created by a variety of processes of varying importance. These include inelastic scattering and the creation of Auger electrons, magnons, phonons and electron-hole pairs. The primary electrons may be readily distinguished against this background by inspection of the derivative with energy of the cascade signal. Some secondary electrons, such as those created in Auger processes, are also revealed by characteristic features in the differential energy distribution spectrum. However the majority of secondary electrons undergo multiple inelastic collisions, losing much of their energy, until they are emitted at low energy. There they form a definitive maximum in the cascade distribution. The underlying theory of this secondary electron cascade has been studied in detail by Wolff.
4.3 THE INELASTIC MEAN FREE PATH AND THE UNIVERSAL CURVE

When describing the transport of electrons through a solid, it is usual for elastic scattering to be neglected; for an isotropic source in an amorphous solid as many electrons will be scattered into a given direction as will be scattered out of it\(^4\). The transport of electrons may then be quantified through the inelastic mean free path (IMFP), denoted by the symbol \(\lambda\). The IMFP is formally defined as the average distance travelled, by an electron with a given energy, between successive inelastic collisions\(^4\). IMFPs cannot be measured directly. In practice IMFPs are found by the measurement of attenuation lengths; if a beam of electrons traverses a thickness \(x\) of material, its incident intensity \(I_0\) will be attenuated such that

\[
I = I_0 \exp \left( -\frac{x}{L} \right)
\]

where \(I\) is the measured intensity and \(L\) is the attenuation length. Although an attenuation length is not strictly the same as an IMFP, it is common practice for these two terms, and the symbol \(\lambda\), to be used interchangeably.

The electron IMFP is a quantity of vital importance in electron spectroscopy. It is inversely related to the total inelastic scattering cross section, denoted by the symbol \(\sigma\). The high inelastic scattering cross section, of electrons in the energy range 10 - 1000 eV, restricts escape into vacuum to only those electrons in the topmost layers of a surface. The surface sensitivity of electron spectroscopic techniques therefore arises directly from the universally low values of IMFP that are exhibited by materials in this energy range.

Measurements of IMFP can be found in the literature for many materials, and for various energies. For most materials, in the energy range 10 - 2000 eV, the IMFP has a value between 2 and 50 Å; a broad minimum exists in the energy range 50 - 100 eV. A compilation of these measurements resulted in the establishment of the “Universal Curve’’\(^4\), illustrated in Figure 4.2. Among photoemission practitioners the Universal Curve is commonly believed to
enable prediction of the IMFP, for any given material, in the energy range $10^{-1000}$ eV.

Figure 4.2. The Universal Curve of inelastic mean free path versus electron kinetic energy, due to Somorjai $^{14}$.

The data from which the Universal Curve was drawn were mostly obtained through overlayer photoemission experiments. In an overlayer experiment the intensity of a well defined substrate peak is plotted against increasing overlayer thickness. In this way an attenuation length may be obtained. Such overlayer experiments are usually performed by monitoring either core levels, in X-ray photoelectron spectroscopy, or Auger electron peaks. The intensity contributions from substrate and overlayer must be separated accurately, and therefore good energy resolution is a prerequisite for successful application of this method. The description of the attenuation of intensity by Equation 4.1 is an approximation that is acceptable in most cases: it breaks down, for example, in the case of a thin overlayer that has formed islands, with uncovered substrate areas remaining $^{47}$. 

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The earliest measurements of attenuation lengths by the overlayer technique were reported by Crowell et al.\textsuperscript{4,15}. This group investigated photoemission at very low energy from metal films evaporated onto freshly cleaved surfaces of silicon. They deduced IMFP values of approximately 740 Å, 440 Å and 170 Å for gold, silver and palladium respectively at an energy of 1.1 eV. For copper they quote an IMFP in the range 50 - 100 Å.

This was followed by the work of Siegbahn et al. who investigated Langmuir-Blodgett films of α-iodostearic acid\textsuperscript{4,16}.

The overlayer technique was extended by, amongst others, Norman and Woodruff\textsuperscript{4,17} who used it to test the energy dependence of the IMFP in gold, silver and magnesium up to electron energies of 150 eV.

However the overlayer method suffers from a fundamental drawback where low energy measurements are concerned. A lack of distinguishing substrate features, in the region below 10 eV, prevents the identification of anything other than the drop in intensity that occurs as the Fermi level is approached.

The low energy measurements of the IMFPs of gold, silver and aluminium made by Kanter in 1970, by investigation of electron transmission through free standing polycrystalline films of various thickness, therefore represented an extremely important extension to the energy range of IMFP data\textsuperscript{4,18}.

Kanter’s measurements, and those of Crowell above, remained the only determinations of IMFP below 10 eV until Pierce and Siegmann pioneered a novel application of spin polarised spectroscopy\textsuperscript{4,19}. They measured attenuation lengths in thin film overlayers of nickel on copper and vice-versa, the substrate in each case providing a dissimilar spin polarisation to that of the overlayer. In this way substrate electrons could be marked definitively. Subsequent analysis of the effects of the overlayers upon transmission of marked electrons enabled determination of the IMFPs at an energy of approximately 5 eV above the Fermi level.
Various attempts to model quantitatively the behaviour of IMFP with energy and material have been reviewed by Powell. To date the most accurate model of the variation of IMFP with material and energy is due to Penn. However this model is appropriate only in the energy regime of 200 - 2000 eV.

The general applicability of the Universal Curve came into question, however, with the publication of the first reviews of the field. The data showed large scale scatter about the proposed curve, the origin of which could be ascribed to both errors of measurement and possible material dependency of the IMFP.

Importantly, the work of Abraham and Hopster cast significant doubt upon the applicability of the Universal Curve to ferromagnetic transition metals at low energy. They investigated the attenuation lengths of both 0 and 10 eV spin polarised secondary electrons, originating from the nickel (110) surface, with overlayers of adsorbed oxygen. The Universal Curve predicted an attenuation length of 30 - 50 Å for 0 eV electrons, with that at 10 eV being approximately a factor of five shorter than this. In practice no significant difference was observed between the two; both energies demonstrated an attenuation length of only 3 - 4 atomic layers.

These findings have been supported by the more recent work of Donath et al. This group established an attenuation length of approximately two atomic layers for spin polarised electrons, with energies below 10 eV, emitted from overlayers of tantalum on magnetic substrates of Ni₈₀Fe₂₀. This generalises the results of Abraham and Hopster to non ferromagnetic transition metals. They further proposed that spin flip scattering plays a dominant role in the origin of the short probing depths in transition metals.

Siegmann has written a number of review papers on this topic, in which he describes in detail the application of the spin polarised overlayer method for the determination of IMFPs, whether for a non-magnetic overlayer deposited upon a magnetic substrate or vice-versa. Siegmann has also
proposed the following simple rule for the behaviour of low energy IMFP in transition metals.

A good example is the overlayer experiment of Donath et al. 4,24, where tantalum was sputter deposited onto a polycrystalline iron substrate. Cascade electrons were excited by an unpolarised primary electron beam with an energy of 2 - 3 keV. The polarisation of electrons emitted in the energy range 5 - 10 eV above the Fermi level was measured, with an accuracy of better than ± 5 %. Coverage of the substrate, with an increasing thickness of tantalum, reduced the polarisation of the cascade electrons. This occurs as a consequence of increased scattering of polarised electrons within the tantalum, resulting in their removal from the cascade, and the generation of increased numbers of unpolarised electrons. Denoting electrons originating in the substrate and overlayer by the subscripts s and o respectively, and writing x for the overlayer thickness, the emitted polarisation is given by

\[ P = \left[ \frac{1}{1 - \exp \left( -\frac{x}{\lambda} \right)} \right] / I \]

(4.2)

The total intensity of the cascade, I, is given by

\[ I = (I_s^+ + I_s^-) \exp \left( -\frac{x}{\lambda} \right) + (I_o^+ + I_o^-) \left[ 1 - \exp \left( -\frac{x}{\lambda} \right) \right] \]

(4.3)

Here the superscripts + and - denote majority and minority spins respectively, where the axis of quantisation is determined by the magnetisation direction of the substrate. The IMFP so determined is related to the total scattering cross section, \( \sigma \), through the relation

\[ \sigma = 1 / \lambda \]

(4.4)

The available data for \( \sigma \), determined through overlayer experiments on transition metals, has been fitted by Siegmann 4,5 to yield a simple empirical rule.
\[ \sigma = \sigma_0 + \sigma_d (5 - n) \]  

(4.5)

The total scattering cross section, \( \sigma \), is composed of two distinct parts; a constant part, \( \sigma_0 \), equating to scattering from non-\( d \)-band atomic energy levels, and a part, \( \sigma_d (5 - n) \), that is proportional to the number of unoccupied states in the \( d \)-band of the element in question. Within the parentheses, 5 corresponds to the total number of states available for a single spin state, and \( n \) denotes the number of states that are actually occupied. This is illustrated in Figure 4.3, due to Siegmann \(^{45}\) and references therein, which shows determinations of \( \sigma \) for a number of magnetic and non-magnetic overlayers. Application of this model to ferromagnetic metals requires that the spin averaged number of available states, \( n = (n^+ + n^-) / 2 \), be inserted into the above equation, thus yielding \( \sigma = (\sigma^+ + \sigma^-) / 2 \) for the spin averaged total cross section. Figure 4.3 clearly indicates a trend that is independent of ferromagnetic behaviour.

![Figure 4.3](image-url)

Figure 4.3. The total scattering cross section \( \sigma \) in nm\(^{-1} \) versus number of unoccupied \( d \) orbitals for the transition metals indicated, in the secondary electron kinetic energy range 5 - 10 eV \(^{45}\). Open circles indicate average values from different laboratories, while individual results are denoted by crosses.
The linearity of this relation indicates that electron-electron scattering is the dominant energy loss mechanism in this energy regime; $\sigma_0$ then accounts for all scattering events other than into unoccupied $d$-band states, where as $\sigma_d$ denotes scattering into a single unoccupied $d$-band state. These results suggest that Stoner excitations, or any sort of spin dependent scattering, cannot be important in the cascade process for non magnetic transition metals, since equation 4.5 is independent of magnetic order. For magnetic metals, Figure 4.3 shows only the spin averaged scattering cross section.
4.4 SPIN DEPENDENCY IN TRANSPORT PROCESSES

Advances in the spin analysis of photoemission experiments led in 1979 to the first observations of enhanced spin polarisations in ultra-violet photoemission from ferromagnets. Bringer et al. were the first to investigate the electron spin polarisation of the photoyield of the nickel (111) surface. They used incident photon energies of 16.8 and 21.2 eV and found a spin polarisation some 60% greater than that anticipated from the bulk magnetisation of nickel. This work was taken as the first experimental evidence for a spin dependency in the IMFP of electrons scattering within a ferromagnetic material. This research was supported soon afterwards by similar experimental findings for cobalt and iron single crystal surfaces and amorphous iron-boron alloys, together with a theoretical study by Matthew. These findings have been reviewed in detail by Landolt; at this early stage the favoured interpretation of the experimental data was that the low energy enhancement of polarisation was the result of Stoner, or spin flip, transitions in the cascade process.

The model of IMFP behaviour in transition metals in general, discussed in Section 4.3, has been extended by Siegmann to include ferromagnetic transition metals. A ferromagnetic transition metal is characterised by a greater occupancy of the majority spin subshell of the d-band, than of the minority spin subshell. If the difference between the two subshell populations is denoted by \(2\Delta n\), then Equation 4.5 can be rewritten as

\[
\sigma^{(\pm)} = \sigma_0 + \sigma_d \left[ 5 - (n (\pm) \Delta n) \right]
\] (4.6)

where \(\sigma^{(\pm)}\) represents the spin dependent scattering cross sections for majority (\(+\)) and minority (\(-\)) spins respectively. The Bohr magneton number, obtained through conventional magnetometry, enables calculation of \(2\Delta n\) from the relation

\[
n_B = n^+ - n^- = 2\Delta n
\] (4.7)
since the contributions of s- and p-band electrons to the magnetisation can be neglected. The different scattering cross sections result in differing intensities, $I^+$ and $I^-$, for majority and minority spin electrons travelling a distance $x$ through the material

$$I^+ = I_0^+ \exp(-\sigma^+ x) \text{ and } I^- = I_0^- \exp(-\sigma^- x)$$

(4.8)

where $I_0^+$ and $I_0^-$ are the initial spin dependent intensities of the beam. If we consider a polarised beam of low energy electrons propagating through a ferromagnetic material, the initial polarisation of the beam, $P_0$, is given by the relation

$$P_0 = \frac{(I_0^+ - I_0^-)}{(I_0^+ + I_0^-)}$$

(4.9)

As a consequence of the differing scattering cross sections the polarisation will change such that, after traversing a distance $x$, the new polarisation is given by

$$P = \frac{[I_0^+ \exp(-\sigma^+ x) - I_0^- \exp(-\sigma^- x)]}{[I_0^+ \exp(-\sigma^+ x) + I_0^- \exp(-\sigma^- x)]}$$

(4.10)

In a practical overlayer experiment, where the IMFP is indeed spin dependent, Equation 4.10 increases linearly for small overlayer thicknesses where $x < \lambda$. When $x \to \infty$ the resultant polarisation approaches unity, but under this condition the intensity of transmitted electrons tends exponentially to zero. Clearly, if the spin dependent IMFPs are especially large, then the resulting spin filter effect can potentially offer a means by which to perform measurements of spin polarisation.

Provided that $P_0$ is much less than unity, that is $I_0^+ / I_0^- \approx 1$, then $P$ can be regarded as being composed of $P_0$ together with an additional component, $P_t$, gained through transport processes

$$P = P_0 + P_t$$

(4.11)
The transport component, $P_t$, is given by the relation

$$P_t = \frac{\{\exp (\sigma^- - \sigma^+) x\} - 1}{\{\exp (\sigma^- - \sigma^+) x\} + 1}$$

Experimental verification of this model of low energy spin dependency requires that the separate overlayer and substrate contributions to the measured intensities can be clearly identified. To this end the use of noble metal substrates, such as copper and gold, in conjunction with ferromagnetic transition overlayers is ideal since the $d$-bands of each are well separated: tungsten offers a viable alternative.$^{47}$

To date the spin dependent overlayer approach has been applied by four groups. Three of these utilised spin polarised photoemission. The fourth based their investigation on the spin polarised inverse photoemission technique. The results of these investigations are summarised below and have also been reviewed by Hopster.$^{47}$

The earliest study was that of Pappas et al., who investigated both spin averaged and spin dependent low energy attenuation lengths in perpendicularly magnetised ultrathin iron overlayers deposited upon a copper (100) surface.$^{432}$ They used both synchrotron radiation and gas discharge line photon energies in the energy range 12 - 44 eV. Contrary to the Universal Curve, spin averaged attenuation lengths failed to exhibit an exponential increase towards lower energies. The increase of spin dependent attenuation lengths, towards lower energies, was found to be more pronounced for majority spin electrons than for minority spin; at 14 eV the respective attenuation lengths were approximately 5.9 Å and 4.5 Å.

Getzlaff et al. studied the spin dependent IMFP in iron and cobalt overlayers on a tungsten (110) surface.$^{433}$ They used the Ne1 line, at 16.85 eV, from a resonance lamp and were able to take data as a function of increasing overlayer thickness in the range 0 - 20 monolayers. Spin dependent effects were clearly evident in the measured attenuation lengths; the majority and
minority spin attenuation lengths were found to be 9.2 Å and 6.3 Å respectively for iron, and 9.0 Å and 6.6 Å for cobalt.

Vescovo et al. worked with cobalt overlayers on a copper (111) surface, and used synchrotron radiation to measure spin resolved spectra over the electron kinetic energy range 7 - 50 eV. Again, the expected increase in spin averaged IMFP towards lower energy was not observed, and spin dependent effects were only observed for electron kinetic energies below 30 eV.

The spin dependent inverse photoemission experiment of Passek et al. involved iron overlayers on the tungsten (110) surface, and utilised the polarised electron beam from a GaAs source. In this configuration the polarised beam impinges upon an iron overlayer and the transmitted electrons induce Bremsstrahlung radiation in the substrate. The intensity of the Bremsstrahlung is a function of the transmission of electrons through the overlayer. The inverse photoemission from the tungsten was observed to become spin dependent upon deposition of an iron film. The ratio of minority spin to majority spin attenuation lengths, for an electron energy of 12.6 eV above the Fermi level was found to be 1.7 ± 0.3.

Data compiled from the above experimental work is illustrated in Figures 4.4 and 4.5, which respectively show plots of measurements of spin dependent IMFP and spin asymmetry against electron kinetic energy. The increasing asymmetry between majority and minority spin electrons with decreasing energy is apparent, especially in the region below 10 eV. This is also in agreement with results for spin resolved photoemission from ferromagnetic single crystal surfaces; the IMFP of majority spin electrons is always found to be larger than that of minority spin electrons.
Figure 4.4. Compilation of spin-dependent IMFP measurements. \(4^{7}\). Filled symbols represent spin-up measurements, while open symbols represent spin-down values. The references are those discussed above, as indicated by the symbols:

- square; Fe/Cu(100) \(4^{32}\)
- triangle up; Co/W(110) \(4^{33}\)
- circle; Co/Cu(111) \(4^{34}\)
- triangle down; Fe/W(110) \(4^{33}\)
- hexagon; Fe/W(110) \(4^{35}\)

Figure 4.5. Compilation of measurements of spin asymmetry in the IMFP \(4^{7}\). The symbols correspond to those used in Figure 4.4.
Furthermore, band structure calculations for threshold photoemission from ferromagnetic crystal surfaces predict a negative polarisation of electrons at the Fermi level. However, Grobli et al. have demonstrated that, in the case of cobalt, a spin dependent IMFP can influence the photoemission process so strongly that the sign of the emitted polarisation is reversed \(^4\) \(^{37}\).

The energy dependences in both spin dependent IMFP and spin asymmetry, reported independently by Pappas \(^4\) \(^{32}\) and Vescovo \(^4\) \(^{34}\), are seen to be in good agreement, though the scatter in the data is greater at lower energies. The independent results for iron on tungsten (110) are in poor agreement, although the lack of error information for the data make comparison difficult. It is worth noting that the errors in polarisation calibration, between the various groups, are likely to be at least of the order of 10 %, as discussed in Chapter 2, Section 2.3.1. The error in determination of overlayer thickness will also be significant.

Schonhense and Siegmann \(^4\) \(^{24}\) \(^{25}\) have calculated the transport polarisation, \(P_t\), for iron and cobalt overlayers. Their results are comparable with the experimental results of the Pappas and Getzlaff teams.

The Siegmann model can also be extended to the enhancement of low energy secondary electron polarisations from bulk ferromagnetic materials \(^4\) \(^{24}\) \(^{45}\), an alternative means of calculation of the transport polarisation, \(P_t\), is to measure the polarisation \(P_c\) of the secondary electron maximum. \(P_0\), in Equation 4.11, then becomes the average spin polarisation of the \(N\) valence band electrons of the ferromagnetic material in question. This polarisation may therefore be calculated

\[
P_0 = \Delta n / N \tag{4.13}
\]

where \(N\) includes the \(s\) and \(p\) band valence electrons, and \(\Delta n\) can again be deduced from the Bohr magneton number. The cascade electrons are excited from all depths, \(x\), but the intensity from any given depth decreases according to
\[ I(x) = I_0 \left[ \exp(-\sigma^+ x) + \exp(-\sigma^- x) \right] \] (4.14)

The average transport polarisation acquired by an electron is then given by

\[ A = \frac{\int_0^{\infty} P_t(x) I(x) \, dx}{\int_0^{\infty} I(x) \, dx} = \frac{\sigma^- - \sigma^+}{\sigma^+ + \sigma^-} \] (4.15)

Substitution into Equation 4.6 then gives

\[ P_{t_{\text{ave}}} = \Delta n / \left[ \sigma_0 / \sigma_d + (5 - n) \right] \] (4.16)

This then enables calculation of the average transport polarisation, \( P_{t_{\text{ave}}} \), and together with Equations 4.10 or 4.11, the calculation of the cascade polarisation \( P_c \). Siegmann \(^{42,45}\) demonstrates that, when allowance is made for the effects of finite temperature upon surface and bulk magnetisations, adjustment of only the \( \sigma_0 / \sigma_d \) ratio is necessary in order to fit calculated \( P_c \) data with the experimental observations for iron and cobalt.
4.5 SPIN FILTER SYSTEMS

Whilst the precise nature of the spin dependent mechanisms at work in the transport of low energy electrons remain unclear, it is apparent that ferromagnetic films can be regarded as transmission spin filters. If a high enough structural quality can be assured for films of a thickness at which the attenuation of transmitted electrons still leaves a measurable exit intensity, then a polarimeter becomes a realistic possibility. The direction of quantisation of the polarimeter, against which polarisations would be referenced, is given by the direction of magnetisation of the spin filter film.

Kuch et al. demonstrated spin filtration using an adaptation of the overlayer type experiments described in the previous section. The polarised source was a copper (100) substrate irradiated by normal incidence circularly polarised synchrotron radiation in the energy range 10 - 24 eV. A four monolayer thick iron film, which is known to exhibit perpendicular magnetic anisotropy, was deposited upon the substrate. Spin polarised electrons, originating from the copper 3d-band, were collected in normal emission geometry. This enabled Kuch et al. to use spin filtration to investigate the spin dependent bulk band structure of the copper 3d states.

An experiment with similar geometry, but utilising a GaAs substrate, was performed by Grobli et al. The use of a semiconductor substrate permits the straightforward generation of polarised electrons and avoids the need for an external magnetic field for polarisation reversal, which would of course influence the ferromagnetic overlayer. A buffer layer of silver, in between an iron overlayer and the substrate, was utilised in order to prevent interdiffusion of the iron and the GaAs which disrupts the overlayer magnetic order. The magnetisation of a five monolayer thick iron film was oriented perpendicular to its surface and a spin dependency in the transport of polarised electrons through the overlayer was successfully demonstrated. The photoyield was shown to depend upon the relative orientation of the electron spin and the magnetisation direction of the iron film. Close to photothreshold, transmission
was found to be 1.7 times greater for spins oriented parallel to the magnetisation direction than for spins oriented antiparallel.

An alternative semiconductor based spin filter configuration has been demonstrated by Filipe et al. They deposited an iron layer upon oxidised GaAs, and demonstrated that the whole structure acts as a transistor with spin dependent transport in a magnetic base. The magnetisation of the 3.5 nm thick iron layer was in-plane. A GaAs polarised electron beam source was utilised to inject transversely polarised electrons from vacuum into the iron overlayer, the electron polarisation being either parallel or antiparallel to the magnetisation direction. The current gain behaviour of this transistor configuration was measured as a function of incident electron energy, along with its spin dependency through reversal of either the beam polarisation or the device magnetisation. The current gain was observed to increase with increasing energy, over the range 5 - 15 eV above the Fermi level. However, the spin filter efficiency, analogous to the Sherman function of conventional spin polarimetry, was found to decrease. The spin filter efficiency, for an incident energy of 5 eV, was found to be approximately 25%.

The above experiments demonstrate the potential of ultrathin ferromagnetic films as spin filters for the purpose of polarimetry. However, the use of ultrathin overlayer films is subject to inherent difficulties. The growth of transition metal films on noble substrates is generally found to produce films of poor structural quality, due to island growth, intermixing and phase transitions. The uniform saturation magnetisation of such films is correspondingly unreliable. Complications also arise from the use of buffer layers, due to the large background signals that result. A similar background contribution arises in all photoemission experiments, restricting study to a small range of overlayer thicknesses. This prevents discrimination between bulk and interfacial effects. Furthermore, the experimental configuration of Grobli et al. cannot support remanent magnetisation of the ferromagnetic layer, and involves continuous application of a high magnetic field.
The use of free standing ferromagnetic films and transmission geometry offers a means to overcome these difficulties. Furthermore, this approach enables separation of the inelastic and the elastic contributions to any spin dependent transmitted currents.

Only the research groups of Lampel, at the Ecole Polytechnique, France and Siegmann, at the ETH Zurich, Switzerland have approached this area with experiments investigating the spin dependent transmission of electrons through ultrathin free standing films. These studies represent the first attempts to achieve and characterise a spin filter system in transmission geometry. However the results of these two groups show a remarkable disparity.

4.5.1 TRANSMISSION EXPERIMENTS AT THE ECOLE POLYTECHNIQUE

Consider firstly the work of the Lampel group at the Ecole Polytechnique. They measured the spin dependence of the intensity of polarised electron beams transmitted through free standing ferromagnetic films. Their experimental configuration is illustrated in Figure 4.6.

The films consisted of a perpendicularly magnetised cobalt layer, 10 Å thick, sandwiched between two gold layers, 210 Å and 20 Å thick respectively. The total film thickness utilised was approximately 240 Å. The experimental configuration enabled control of both the primary electron energy and polarisation, and incorporated the capacity to analyse the energy and spin polarisation of the transmitted electrons. In particular, the use of caesium of the exit face of the film ensured a reduction in the vacuum level of the gold surface to 2 eV, thus fractionally extending the range of measurements towards lower energy. Easy reversal of both the incident beam polarisation, and the direction of magnetisation of the ferromagnetic cobalt layer, was a design feature of the experimental apparatus.
Cobalt is used as the material for the ferromagnetic layer since its majority spin subshell is fully occupied and, compared to nickel, it has a large number of minority spin holes. It has been shown that for spin polarimetry purposes, the optimum thickness for cobalt is 8 Å. The corresponding optimum thickness for an iron layer is 5 Å; this is more difficult to achieve experimentally with the required high structural quality.

Drouhin and his team have reproducibly demonstrated the spin filter effect using this experimental set-up. The effect favoured transmission of majority spin electrons and was largest for primary electron energies below 10 eV, comparable to the energy of the 3d-band. The spin filter effect is illustrated with data from two separate films as shown in Figures 4.7 and 4.8. In Figure 4.7 the total transmitted current is plotted against retarding potential, together with the differential transmitted current (DTC), for a primary energy of 6.4 eV.
A DTC plots the difference between transmitted intensities for two opposing magnetisations of the ferromagnetic film, with the beam polarisation held constant. The symmetry of a pair of DTCs, taken with opposite incident electron beam polarisations, indicates the absence of instrumental asymmetry.

In Figure 4.8 the transmitted current is plotted again versus retarding potential, but for two primary energies. For each of these two energies the beam polarisation has been reversed at regular intervals. In the upper curve, for the incident energy of 2.9 eV, the film magnetisation direction has been reversed at the point indicated by the arrow. The lower curve is for a primary energy of 3.8 eV. The spin asymmetry is seen to be reduced with respect to that obtained at the lower incident energy.

In all the spectra so obtained two distinct features in the total transmitted intensity emerged, namely a high energy edge and a low energy step. The former is due to transmitted electrons that have undergone only elastic or quasielastic scattering within the foil. The latter corresponds to those electrons that have been subject to inelastic scattering. If the primary energy is less than 96 eV...
Figure 4.8. Transmitted current versus retarding potential for incident energies of 2.9 eV, upper curve, and 3.8 eV, lower curve, and a caesiated structure. The spin polarisation of the primary beam is reversed periodically for both curves. In the upper curve, the structure magnetisation direction is reversed as indicated. Zero signal levels have been shifted for clarity.

approximately 6 eV above the vacuum level, the two parts cannot be separated; with caesiation of the film exit surface the two components can be distinguished down to approximately 3 eV. Caesium deposition also increases the transmission by more than an order of magnitude to $6 \times 10^4$. This leaves the elastic peak unaffected but increases greatly the inelastic contribution, such that it becomes dominant.

At a primary energy of 3.5 eV, achieved with caesiation, spin dependent transmission was observed in both the elastic and inelastic regions of the transmitted spectrum. At primary energies above this level, spin asymmetries could be detected only in the inelastic step.

Lampel et al. have further expressed their data in terms of spin polarimetry, reporting for their apparatus an effective Sherman function of 0.6 and a figure-
of-merit (FOM) of $1.7 \times 10^{-4}$. This performance is comparable with that of the best Mott scattering based polarimeters.

More recently this same group has advanced the design of their experimental configuration with the addition of a second cobalt layer to their ferromagnetic films. The second cobalt layer possesses a slightly greater thickness than the first, but it still exhibits remanent magnetisation perpendicular to the plane of the film. Accordingly it requires a slightly greater coercive field to reverse its magnetisation. This more complex bilayer film can therefore be switched between a ferromagnetic and an antiferromagnetic alignment of the two constituent cobalt layers. Some surprising benefits emerge from this capability. The antiferromagnetic configuration of the bilayer results in the cancellation of interfacial contributions to the spin dependent scattering; in consequence Drouhin and coworkers were able to report that spin dependent transmission appeared to be primarily a bulk effect. More importantly, the effective Sherman function can be obtained directly in all measurements with such a structure, through measurements taken in both ferromagnetic and antiferromagnetic configurations: the device is therefore self calibrating. Lampel et al. report an effective Sherman function of 0.7 for this experimental configuration, and an FOM of approximately $10^{-4}$.

4.5.2 TRANSMISSION EXPERIMENTS AT THE ETH ZURICH

Siegmann and coworkers, at the ETH Zurich, have pursued a similar line of experimental investigation to that described above. They too have utilised spin dependent transmission through ultrathin ferromagnetic films, and again with cobalt as the spin filter medium. Their experimental configuration differs from that of Lampel et al. through the use of in-plane remanently magnetised ferromagnetic films, with the incident electron beam polarisation correspondingly aligned either parallel or antiparallel to this magnetisation. In addition, this configuration enables the spin analysis of the transmitted electron beam, through high energy Mott scattering.
Siegmann and coworkers investigated spin dependent transmission through a number of films, with cobalt layer thicknesses in the range 1.5 - 6 nm. Their experimental set-up for the production of these films differs significantly with that of Lampel et al. A silicon wafer, containing a number of 0.5 mm diameter apertures, is used as the substrate. This wafer supports a layer of nitrocellulose upon which the ferromagnetic films are deposited. After deposition of the film, the nitrocellulose layer of each aperture is dissolved in pentyl acetate. Once loaded into the experimental chamber, a number of films become simultaneously available for experimentation; only mild sputtering is required to remove contaminants acquired during the dissolution of the nitrocellulose. This system therefore provides experimental flexibility and, with such small apertures, significantly reduces the risk of torn or damaged films.

Their results for a film with a cobalt layer of 4 nm thickness are illustrated in Figure 4.9.

Figure 4.9. The distribution with energy of; left: intensity, $I(E)$, and relative polarisation, $P / P_0$, for a polarised electron beam transmitted by a 20 nm thick gold film; right: the spin dependent intensity curves, $I^\uparrow(E)$ and $I^\downarrow(E)$, for a polarised electron beam transmitted by a ferromagnetic film containing a 4 nm thick cobalt layer.  

The left hand graph illustrates the energy distribution of both the intensity, $I(E)$, and the relative polarisation, $P / P_0$, for a polarised electron beam transmitted through a 20 nm thick gold film. $P_0$ denotes the incident electron beam.
polarisation. The right hand graph illustrates the variation with energy of the spin dependent intensities, $I^+(E)$ and $I^-(E)$, for a polarised electron beam transmitted through a ferromagnetic film containing a 4 nm thick cobalt layer.

Transmission through the gold film alone results in the generation of secondary electrons, but an elastic peak can still be distinguished at 7 eV. Importantly, the polarisation of the elastic peak is not diminished. For transmission through the ferromagnetic film, the elastic peak shows a huge spin asymmetry which decreases towards lower energy. In stark contrast to the results of Lampel et al., Siegmann and coworkers obtained very large transmission asymmetries of up to 80 %, readily identifying a spin dependent asymmetry in the elastic peak throughout the 5 - 15 eV energy range of their measurements.

Furthermore, for the condition of incident electron polarisation perpendicular to the film magnetisation but still transverse to the axis of propagation, they report the precession of the spin polarisation vector $\mathbf{4}_{46}$. This precession, around the magnetisation direction of the cobalt layer, is identified as analogous to the Faraday rotation of polarised light transmitted through a magnetised medium.

Their experimental approach also lends itself to an elegant means of testing the importance of Stoner transitions in the transport process. This is possible since a polarising spin filter must be equivalent to an analysing spin filter, in the absence of spin productive scattering events such as Stoner transitions. Siegmann et al. were thus able to demonstrate that the contribution of Stoner transitions, to the transmitted spin asymmetry, was below 5 % and therefore of minor importance.

4.5.3 DISCUSSION

Lampel et al. have demonstrated an experimental facility for complete elimination of instrumental asymmetry in measurements of spin dependent transmission through ultrathin ferromagnetic films. This, together with their
spin asymmetry data, provides convincing evidence of the efficacy of their experimental approach. In their work, inelastic scattering at energies close to the d-band of cobalt appear to be the most significant concerning the origin of the transport spin dependency.

The assertion of Siegmann et al. 444, that the Lampel group are witnessing the effects of pinholes in their data, does not bear up to close inspection. Since a retarding field analyser is used in the latter's experimental set-up, pinholes would result in the spin asymmetry being completely swamped across the entire measured (integrated) spectrum.

The question has nonetheless to be asked: why are the results of the two groups so markedly different? Upon first inspection the efforts of the Siegmann group appear to be of an exceptionally high standard. However, their use of a Mott polarimeter, for spin analysis of transmitted electrons, would not enable unambiguous identification of their claimed electron precession with their cited experimental geometry. Their claims, of discovery of the electron analogue of the Faraday effect, might therefore benefit from more substantive experimental evidence. Furthermore, Siegmann and coworkers do not refer at any point to reversal of cobalt layer magnetisation as a means to eliminate instrumental asymmetry. The lack of this feature suggests a degree of uncertainty in the accuracy of their data. They might simply have witnessed the effects of stray fields upon opposing electron spin polarisations.

However, if the data of the Siegmann group is correct, the conclusion must be that elastic scattering processes are dominant in the spin dependent transport of electrons through ferromagnetic transition metals. Furthermore, the importance of Stoner transitions has been shown to be of minor importance. There is in any case now universal agreement that such transitions result in only very small energy losses, and therefore cannot be responsible for the very large spin dependent effects observed.
4.6 CONCLUSIONS

It has been clearly demonstrated that at low energy there exists a substantial spin dependency in the transport of electrons through ferromagnetic materials. Spin polarised overlayer experiments in both photoemission and inverse photoemission configurations show the mean free path for majority spin electrons to be greater than that for minority spin electrons. The largest spin dependency is found at energies close to the Fermi level, where spin asymmetries greater than 20% may be readily achieved. The spin dependency decreases rapidly with increasing electron energy.

There remains considerable debate about the precise mechanisms involved. The importance of Stoner transitions has been refuted by more recent studies. The influence of elastic scattering, identified in the recent transmission studies of Siegmann and coworkers, is now a contentious issue.

A sound foundation has been established for the implementation of electron spin polarimetry using spin dependent transmission through ultrathin ferromagnetic structures. Unlike Mott scattering, such structures can be used to filter either transversely or longitudinally polarised electrons, depending upon the remanent magnetisation of the ferromagnetic layer. However, much work is required to elucidate the mechanisms involved, in order to fully understand, control and interpret the spin filtering process.

The possibility of a self-calibrating polarimeter with a Sherman function of 0.7 and an FOM of the order of $10^{-4}$ is highly attractive. Other polarimeter configurations are conceivable in the light of the utility of ultrathin ferromagnetic structures for this purpose. The deposition of such a structure directly upon a microchannel plate detector for example. Alternatively, as described in Chapter 5, the use of a ferromagnetic structure as both a spin filter and Mott scattering foil in a combined polarimeter system; this system could offer in a single instrument the capability to recover all three axes of spin information for an incident polarised electron beam.
CHAPTER 5

THE DESIGN AND COMMISSIONING OF THE HYBRID POLARIMETER

5.1 INTRODUCTION

Many research activities exist that are fundamentally limited by the capacity of most polarimeter systems to measure, at best, only two transverse components of electron spin polarisation. One such example is the transition of the magnetisation direction in epitaxial films of iron, deposited upon the copper (100) surface, from perpendicular to in-plane with increasing film thickness. A second example, discussed in more detail in Chapter 6, resulted from the SPS group’s own research into amorphous ferromagnetic ribbons. Despite saturation magnetisation of the samples, magnetic moments were found that were not aligned with the axis of magnetisation.

Figure 5.1. The three orthogonal vector components of the spin polarisation of a beam of electrons.

Full characterisation of spin polarisation is illustrated in Figure 5.1, where the three orthogonal components are shown with respect to the direction of propagation of a beam of electrons. The three vector components of
polarisation are labelled as follows; $P_{TV}$ and $P_{TH}$ for the vertical and horizontal transverse components, and $P_L$ for the longitudinal component.

As discussed in Chapters 2 and 3, the polarimeters of the SPS group are based upon Mott scattering and are therefore sensitive only to the two transverse components of polarisation. Careful attention was therefore given to a means of achieving full polarisation analysis. Three options were considered in detail:

- The construction of, for example, an optical polarimeter that is sensitive to all three polarisation components.\(^{52}\)

- The addition of a switchyard and second polarimeter to an existing instrument.

- The incorporation of a Wien filter within an existing polarimeter.\(^{53}\)

The first option, rather than building upon existing facilities, would involve a departure into the realm of optical technology and was deemed unlikely to result in rapid progress. The second option involves the use of the switchyard technique as pioneered by Pierce.\(^{54}\) This is illustrated schematically in Figure 5.2.

![Figure 5.2. Schematic illustration of the use of a 90° spherical sector electrostatic deflector as a switchyard device.](image)
The incident electron beam is deflected such that the longitudinal component becomes a transverse component, suitable for analysis by a second polarimeter. The switchyard is usually a 90° spherical sector electrostatic deflector. In this device the spin angular momentum of the electron beam is conserved, and thus the longitudinal spin component becomes transverse to the new direction of propagation. This technique requires two polarimeters and is therefore expensive and space consuming.

The third option of incorporating a Wien filter is illustrated in Figure 5.3. The Wien filter utilises crossed electric and magnetic fields to induce precession of the spin polarisation vector, whilst maintaining the propagation direction of the electron beam. Careful calculation of the required field strengths allows specific rotation of the spin vector. Placed before the polarimeter, it could be switched off for measurement of transverse components, and then powered up for retrieval of the longitudinal spin component. However, in photoemission experiments in general, strenuous efforts are made to minimise the presence of magnetic fields at the interaction region. Therefore the use of a Wien filter, with its significant associated magnetic field, is not attractive.

Figure 5.3. Schematic illustration of the use of a Wien filter for rotation of spin polarisation components with respect to the beam direction.
In the event an alternative and altogether more revolutionary solution to the problem was chosen. This was brought about by recent progress in the field of spin dependent electron transmission, particularly through ultrathin ferromagnetic structures\textsuperscript{55, 56}. This is discussed in detail in Chapter 4, Sections 4.4 and 4.5. It was realised that potentially a Mott scattering polarimeter could be combined with a transmission system, giving rise to a hybrid instrument capable of yielding all three polarisation components. By replacing the gold scattering foil of a Micro-Mott polarimeter with an ultrathin composite gold and cobalt target film, both spin dependent scattering and transmission might prove possible in a single instrument. The requirements for a spin dependent transmission polarimeter are discussed in Chapter 4, Section 4.5. The required configuration of the target film is illustrated schematically in Figure 5.4. It is believed that this configuration would also be suitable as the scattering target of a Mott scattering polarimeter.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure54.png}
\caption{A schematic illustration of the ferromagnetic target film required for a Hybrid Polarimeter.}
\end{figure}

The Hybrid Polarimeter would have two modes of operation; a low energy mode for spin dependent \textit{transmission} analysis of $P_L$ and a high energy mode for Mott \textit{scattering} analysis of $P_{TH}$ and $P_{TV}$. In this latter mode the instrument would operate in an essentially identical manner to the original Micro-Mott polarimeter.
The most significant risk of this approach concerned the suitability of the Micro-Mott electron optical system for use at the energies, 10 eV or lower, required for a transmission experiment. The use of an ultrathin target film, containing a layer of cobalt, would also have implications for the figure-of-merit (FOM) and effective Sherman function, $S_{\text{eff}}$, of the Micro-Mott mode of operation.

The work reported in this chapter was undertaken in collaboration with Professor Georges Lampel and his team in the Condensed Matter Physics Group at the Ecole Polytechnique, Palaiseau, France.
5.2 DESIGN AND CONSTRUCTION OF THE HYBRID POLARIMETER

5.2.1 CONFIGURATION AND DESIGN

The Micro-Mott 2 instrument of the SPS group was utilised as a chassis on which to develop the Hybrid Polarimeter, as this would save both money and development time. However it was desirable that the Micro-Mott 2 instrument itself should not in any way be compromised by the new instrumentation. Therefore the transmission polarimeter was visualised as a removable modular unit, compact in design in order to fit into the limited space available.

![Diagram of Hybrid Polarimeter](image)

Figure 5.5. A sectional assembly drawing of the Hybrid Polarimeter.

The final design of the Hybrid Polarimeter is shown in Figure 5.5, which illustrates an on-axis sectional assembly drawing of the instrument mounted upon a concentric hemispherical analyser (CHA). A photograph of the assembled instrument is shown in Figure 5.6.
Figure 5.6. The Hybrid Polarimeter; part of the electrostatic shield has been removed to reveal the polarimeter detector systems.

The transmission polarimeter design was guided by the experimental arrangement used by Lampel et al. in their study of spin dependent transmission through ultrathin ferromagnetic structures. The experimental configuration is illustrated in Figure 5.7. The essential elements are as follows. The input electron optics provide a monochromated low energy, 10 eV or less, electron beam that is incident upon a self supporting, ultrathin and perpendicularly magnetised ferromagnetic target film. The target film consists of a cobalt layer of approximately 10 Å thickness, sandwiched between two gold layers of thickness 20 Å, front face, and 210 Å, rear face,
respectively. Electrons transmitted through this structure are energy analysed, in a retarding field type analyser, prior to detection.

Figure 5.7. The experimental configuration of the apparatus for analysis of spin dependent electron transmission through an ultrathin ferromagnetic structure.

The base of the outer hemisphere of Micro-Mott 2 was reengineered to enable mounting of the transmission polarimeter. This entailed a new bolt-on design of the baseplate of the inner hemisphere. The only other modification to the design of Micro-Mott 2 itself was the incorporation of x/y deflector plates in place of the third lens of the polarimeter input optics, as shown in Figure 5.5 above. The deflectors were included to enable beam steering, and thus provide the facility to avoid defects in the target film.

The transmission polarimeter is required to be ultra high vacuum (UHV) compatible and is therefore constructed from suitable materials: oxygen free high conductivity copper (OFHC), aluminium, macor machineable ceramic, titanium and phosphor bronze. Magnetic materials were avoided in the construction of the instrument.

When the transmission polarimeter is installed, the Micro-Mott inner hemisphere is held in place by an annular disk of macor. This enables the inner hemisphere to support the applied high tension (HT) necessary for the scattering mode of operation. The same bolts that locate this macor disk also hold the retarding field analyser (RFA) assembly in position at the rear of the inner hemisphere.

The baseplate of the inner hemisphere has two important features. The first is its annular construction; on this is mounted an aperture plate that in turn
supports a target film. A single screw holds the aperture plate firmly in place without causing distortion that might otherwise rupture the ultrathin target film. The second feature is the presence of a twenty turn solenoid. This serves to allow reversal of the magnetisation direction of the target film. The installation of a solenoid in such close proximity to the inner hemisphere requires careful attention to detail to prevent breakdown of the applied HT when in Mott scattering mode. Rather than attempting to insulate the solenoid, it was decided that for high voltage operation it would be allowed to float up to the applied HT potential. Therefore the solenoid cables follow the same path out of the Hybrid Polarimeter, and indeed the vacuum vessel, as the HT cable. All three cables terminate at a three way HT feedthrough.

In the design of the Hybrid Polarimeter great care was taken to ensure that a separation of at least 7.5 mm is maintained between any surface carrying HT and its low potential neighbours. Furthermore, surfaces supporting or facing HT components were all manufactured with a highly polished finish in order to suppress the possibility of electrical breakdown: rough surfaces and burring acts to concentrate lines of electric field strength, increasing electric field gradients, and thereby increasing the risk of breakdown.

The Hybrid Polarimeter design was also tailored to prevent the possibility of ceramic components, used as insulation between electron optical elements, becoming charged by the electron beam under investigation. This was prevented by avoiding direct lines of sight between the electron beam and such ceramic elements. Wherever line of sight is unavoidable, for example in the RFA, the ceramic spacers were placed as far as possible from the electron beam, thus presenting as small a surface area as possible.

The RFA assembly has been designed to enable operation of the Hybrid Polarimeter with its target film activated to negative electron affinity. As discussed in Chapter 4, Section 4.5, caesium of the rear surface of the target film lowers its workfunction, increases its transmission and extends by a few eV the energy range of the polarimeter. To this end the RFA assembly was
designed to mount two electrically controlled caesium dispensers, as shown in Figure 5.5. The operation of these dispensers presents the possibility that the ceramic insulators will become coated with caesium and thus become conducting. In order to prevent this problem the polarimeter was designed with the dispensers enclosed within concentric baffles. An additional operational difficulty associated with the caesium dispensers is that of the degassing required after bakeout of the system. During this process significant contamination may be emitted by the dispensers. The direct line of sight to the target film means its transmissive property could be impaired. The severity of this problem has yet to be evaluated.

Finally, in order to prevent stray electrons from entering the RFA and the channeltron detector, it was necessary to place the whole of the transmission polarimeter within an enclosure. The enclosure was designed with a large conduit for the HT, solenoid and RFA cabling. This conduit can itself be sealed against stray electrons with shaped screens of polytetrafluoroethane sheet.

5.2.2 ENERGY ANALYSIS AND DETECTION

Whilst the concept of spin dependent transmission is remarkably straightforward, its practical implementation is, in contrast, demanding. The thicknesses of the self supporting target films required for the Hybrid Polarimeter are such that an attenuation of the incident beam of the order of $1 \times 10^5$ is found. The Vacuum Science Workshop HA50 CHA of the Micro-Mott 2, that is to provide initial energy selection in the Hybrid Polarimeter, is not capable of the transmission of input signal rates above 100 MHz. Therefore a maximum transmitted signal of only a few hundred Hertz is expected for the transmission mode of the Hybrid Polarimeter. A consequence of this is an overriding design issue that the electron optics of the Hybrid Polarimeter have as high a transmission as possible.
A retarding field analyser (RFA) was chosen for energy analysis of the electrons transmitted through the target film. This type of analyser was regarded as ideal for this application because of its attributes of high transmission, good resolution, compactness and simplicity of design and construction. It also performs well with a large area electron source.

5.2.2.1 Theory of Operation of a Retarding Field Energy Analyser

An RFA operates as a high pass filter; only those electrons having a kinetic energy higher than a set potential barrier are transmitted through to a detector. An inherent drawback with this method of energy analysis is its lack of sensitivity to the total electron momentum. Rather it determines only the component of electron momentum perpendicular to the potential barrier. It can be shown that the limit of resolution of a parallel plate type RFA is given by

\[ \frac{\Delta E}{E} = \sin^2 \left( \frac{r}{4d} \right) \]

where \( r \) is the aperture radius, and \( d \) is the separation of the potential barrier and detector.

A schematic illustration of this type of analyser is shown in Figure 5.8.

![Figure 5.8. A schematic illustration of the retarding field analyser design.](image-url)
In this design, lens elements 1 and 4 act to screen the retarding field from the effects of external electric fields, for example the especially high field due to the electron detector. This screening is improved by the use of a fine conducting mesh placed over the apertures. Energy analysis is achieved by generation of a retarding potential on lens elements 2 and 3. These elements also have mesh covered apertures, in this case to ensure that the electric potential is uniformly distributed across the apertures. Twin lens elements are used for this purpose, as this dramatically improves the resolution of the instrument through reduction of the effects of field penetration.

The RFA design suffers from numerous disadvantages. These arise principally because of secondary emission effects, in large part resulting from the use of gridded electrodes. The use of mesh also clearly acts to reduce the transmission. The generation of large numbers of secondary electrons at the meshes has the effect of obscuring measurements. In particular, since an RFA allows all electrons of energy greater than the applied barrier to be detected, the resulting (shot) noise level is extremely high. This severely restricts the performance of the RFA in comparison to band pass type analysers. Ideally RFAs should be operated in conjunction with modulation and lock-in techniques in order to filter out this noise.

5.2.2.2 Construction of the Retarding Field Analyser

A parallel plate type implementation was chosen for the RFA in order minimise the size of the device. The analyser is mounted, on three bolts, within a cylinder of OFHC. A photograph of the RFA is illustrated in Figure 5.9. Four planar lens elements constitute the RFA, fabricated from 0.005 inch thick titanium foil, each with an aperture of 5.1 mm diameter. The apertures are covered with MC-17 electroformed copper mesh, supplied by BMC Buckbee-Mears St. Paul, USA: wire diameter, 0.00073 inches; wire spacing, 0.01355 inches (70 wires per inch); transmission, 90%. These meshes are held in place by a layer of colloidal graphite, used to coat both surfaces of each lens element.
Electron detection is provided by a channeltron type detector, manufactured by the Galileo Corporation. Specifically a Galileo type 7010 is employed, providing a signal gain of $5.0 \times 10^7$. The use of a channeltron detector, in place of the Faraday cup of the original experiment of Lampel et al., confers a greatly increased sensitivity upon the Hybrid Polarimeter. The use of modulation and lock-in signal processing techniques, in conjunction with the RFA, is not therefore viewed as a strict operational requirement.

5.2.3 ELECTRON OPTICAL DESIGN AND MODELLING

The purpose of the electron optics of the Hybrid Polarimeter is first and foremost to provide as efficient transport of electrons through the instrument as possible. The electron optical elements also serve to define the energy of electrons incident upon the target film, to provide energy analysis of
transmitted electrons and to enable detection after this analysis. Inevitably these various requirements are conflicting to some degree and compromise is necessary to achieve a working design. The precise electron optical design specifications were as follows.

- Collection of electrons emitted from the fringe field element of the CHA with an energy of 5 eV. This energy, the selected pass energy of the CHA, was chosen as it provides near optimum energy resolution of the sampled electron beam within the performance of the analyser. Furthermore it is a typical pass energy in surface science experiments.

- Transport and focusing of the electrons onto the target film. As highly focused a beam as possible is required, since the presence of pinholes in the film would allow a diffuse beam to swamp any signal arising from genuine film transmission of electrons.

- Control of the incident electron energy at the target film of between 1 and 10 eV. The work of Lampel et al. suggests that an optimum spin dependent asymmetry in transmission is measured at an incident electron energy of approximately 5 eV.

- Collection of transmitted electrons and their focusing into the RFA.

- Energy analysis in the RFA. The analyser must be able to scan from the high energy edge of the elastically transmitted electrons down to below an energy corresponding to the workfunction of gold. Below this workfunction energy, electrons are unable to escape into vacuum from the outer surface of the target film.

- Collection and detection of energy analysed electrons, with high sensitivity and low noise.
The required performance of the Hybrid Polarimeter electron optics, in terms of energy selection and energy analysis, is illustrated in the energy level schematic of Figure 5.10. This schematic illustrates, from left to right: selection of 2 eV kinetic energy electrons; selection of the incident electron energy at the target film; energy analysis of the transmitted electrons.

Figure 5.10. Schematic illustration of the electron beam kinetic energy as it traverses the polarimeter optics in transmission mode.

In principle, the ideal polarimeter should be able to analyse electron beams of any particular kinetic energy. However, since transmission of electrons through the target film is expected to be attenuated, the Hybrid Polarimeter was designed principally for analysis of low energy electron beams, 2 eV or less, derived from the intense secondary electron cascade maximum that can be generated by electron impact upon a metallic sample.
The process of designing the Hybrid Polarimeter, to meet the above requirements, was evolutionary in its nature. At every stage of the development of the polarimeter design, the viability of the design was tested using SIMION v4.0 electrostatic lens design software. The results of this modelling were used in the assessment of the merits of different design features, and ultimately to assign predicted optimal lens potentials for operation of the completed instrument. The SIMION models for the final design solution, and the potentials applied to each of the electron optical elements, are illustrated in Figures 5.11 through to 5.14. These four models represent the boundaries of the performance envelope required of the instrument: Figures 5.11 and 5.12 show the optimised performance for an incident energy at the target film of 10 eV, with the RFA set for maximum and zero transmission respectively; Figures 5.13 and 5.14 show the equivalent performance for an incident energy of 1 eV. The models pertain to selection of 2 eV kinetic energy electrons by the HAC300, operating with a CHA pass energy of 5 eV.


Figure 5.11. SIMION model of trajectories; 2 eV kinetic energy electrons, 5 eV pass energy, 10 eV incident energy at the target film, 8 V on the RFA.
Lens potentials /V (left to right): 3/8/15/8/0/25/-2/-2/20/2000/-2 (casing)

Figure 5.12. SIMION model of trajectories; 2 eV kinetic energy electrons, 5 eV pass energy, 10 eV incident energy at the target film, -2 V on the RFA.

Lens potentials /V (left to right): 3/8/15/8/-1/0/25/0/0/20/2000/-2 (casing)

Figure 5.13. SIMION model of trajectories; 2 eV kinetic energy electrons, 5 eV pass energy, 1 eV incident energy at the target film, 0 V on the RFA.
Lens potentials /V (left to right): 3/8/15/8/-1/0/25/-2/-2/20/2000/-2(casing)

Figure 5.14. SIMION model of trajectories; 2 eV kinetic energy electrons, 5 eV pass energy, 1 eV incident energy at the target film, -2 V on the RFA.

These models are based on a specific set of incident electron trajectories and energies, which are assumed to be representative of the electron flux output at the fringe field of the CHA. These incident electron trajectories are defined, with respect to the axis of symmetry of the instrument, as follows:

- **start position:** on axis, left hand edge of model.
- **start angle:** -2.0° below to +2.0° degrees above axis.
- **Δ angle:** 0.2°
- **energy:** 5.0 eV
- **trajectories:** 21

It should be noted that the cylindrical symmetry of the Hybrid Polarimeter negates any requirement for modelling of trajectories out of the plane of the diagrams above. The modelling represented in Figures 5.11 through to 5.14 does not take into account inelastic scattering effects within the target film. They illustrate the performance of the apparatus with electrons elastically...
transmitted through the film, and the effects of non-parallel electron paths on transmission. However, Figure 5.13 does show that 1 eV kinetic energy electrons are focused effectively through the RFA and into the channeltron. It is also important to note that the above models do not take into account the workfunction of the gold surfaces of the target film. Since this workfunction has a value of approximately 4 eV, under normal operating conditions electrons with a kinetic energy lower than 4 eV will not escape the film. If caesiumation is used, it is expected that the instrument will be able to analyse transmitted electron kinetic energies lower than 1 eV.

The theoretical viability of the Hybrid Polarimeter, and the effectiveness of the RFA optics, have clearly been demonstrated by the above SIMION modelling. It is therefore concluded that the electron optical elements of the Micro-Mott 2 polarimeter, whose performance is proven and discussed in Chapter 3, may be successfully reconfigured for use in a transmission mode of polarimetry.

5.2.4 POWER SUPPLIES

The operation of the Hybrid Polarimeter in the high voltage scattering mode does not require any alteration to the power supply configuration of the Micro-Mott 2 system. The only operational difference is the requirement for a different insulated plug by which the HT is applied to the target film.

The transmission mode of the Hybrid Polarimeter required the design and construction of dedicated power supplies for the various electron optical elements. The design of these supplies required consideration of the fact that all the electrostatic lens potentials, cited for the SIMION models in the above section, are maintained with respect to earth. Since the various lens elements of the transmission polarimeter are all required to float on the kinetic energy rail of the HAC300, the required potentials must be adjusted accordingly. For example, consider the selection of an electron kinetic energy of 2 eV with the HAC300, and an incident energy at the target film of 10 eV. The latter requires
a potential on the structure of +8 V with respect to earth. Subsequent energy analysis of transmitted electrons requires an applied potential range, at the RFA, of -2 V to +8 V with respect to earth. However the transmission polarimeter optics are all floated on the HAC300 kinetic energy rail, which in this instance is maintained at -2 eV. Therefore a potential of 10 V is required on the target film, together with a potential range of 0 V to +10 V at the RFA, all maintained with respect to the kinetic energy rail. That this is so can perhaps be deduced more easily with reference to the energy level diagram of Figure 5.10 above. The practical benefit of this situation is that, in order to resolve the elastically transmitted electrons, negative potentials with respect to the kinetic energy rail are not required. Therefore if the transmission polarimeter power supply is designed to float on the kinetic energy rail, bipolar supply units are not needed. This simplifies greatly the design of the power supply, and further acts to reduce the cost.

Ultimately it was decided to place all power supplies required for operation of the transmission polarimeter, including those of the electron detector, within a single unit. The specification of this power supply unit, and its corresponding circuit diagram, are given in Appendix C. A schematic illustration of the power supply configuration of the transmission polarimeter is shown in Figure 5.15.

The resulting power supply unit consists of eight 0 to 48 V DC supplies for the electron optics, and a single 3 kV supply which, through a simple potential divider, powers both the front and rear anodes of the channeltron.
Figure 5.15. Schematic illustration of the power supply circuitry for the transmission mode of the Hybrid Polarimeter. The left hand side illustrates the configuration of the HAC300, with the right hand side illustrating that of the transmission mode power supply unit.
5.3 FERROMAGNETIC TARGET FILMS

5.3.1 FABRICATION

The ferromagnetic target films to be used in the Hybrid Polarimeter are manufactured according to the specification of the single ferromagnetic layer structures described in the work of Van Der Sluijs\textsuperscript{57}. This specification is as follows:

- The ferromagnetic layer must be thin enough such that it magnetises preferentially in a direction perpendicular to the plane of the layer.

- The ferromagnetic layer should ideally be of cobalt since, as discussed in Chapter 4, Section 4.5.1, of all the ferromagnetic transition elements this material exhibits the greatest spin dependent transmission effect.

- The total thickness of the target film must be sufficient to enable it to be self supporting on a 3 mm diameter aperture.

- The ferromagnetic layer must be passivated on both sides with layers of gold, in order to protect the ferromagnetic layer.

The structure that complies with this specification is a sandwich of one cobalt layer between two gold layers. The cobalt layer thickness is close to 10 Å. The passivating gold layers on each side are around 220 Å and 20 Å thick respectively. The nominal total thickness of the whole structure is therefore 250 Å, enabling the structure to be self supporting while remaining suitably transmissive to incident low energy electrons.

All samples used to date in the Hybrid Polarimeter development programme have been supplied by the Physique de la Matiere Condensee group at the Ecole Polytechnique, Palaiseau, France. There, under the supervision of Yves Lassailly, the samples are fabricated in a dedicated UHV thin film deposition
It is essential that a UHV process is used in their fabrication, since contamination can render the cobalt layer non-magnetic. The deposition procedure is complicated by the need to deposit a base layer of sodium chloride, upon which the target film layers are deposited. This salt layer, which dissolves readily in water, facilitates removal of the multilayer target film from the substrate and its subsequent transfer onto an aperture plate.

The substrates used in the fabrication of the target films are of float glass, manufactured at the Ecole Polytechnique with an optically flat surface. The initial sodium chloride layer, of 60 - 70 Å thickness, is deposited by Joule heating. The gold layers also are deposited by Joule heating. The first gold layer, of approximately 200 Å thickness, is followed by deposition of the cobalt layer by electron beam heating. The final deposition is of a capping layer of gold. Layer thicknesses are monitored during deposition by a quartz crystal oscillator. Post deposition characterisation of layer thicknesses and interface quality may be carried out by X-ray diffraction studies. Such studies can determine layer thicknesses with a precision of ± 2 Å. Magneto-optical Kerr effect studies of the samples is used to test their possession of a perpendicular magnetic anisotropy. More detail on the deposition and characterisation of the target films is given in the thesis of Van Der Sluijs 57.

5.3.2 TRANSFER ONTO APERTURES

The transfer of target films onto aperture plates is achieved using a flotation technique. A float glass substrate is clamped, with the target film uppermost, at an angle of approximately 45° to a surface of deionised water. The tank containing the water is slowly and smoothly raised and, as the meniscus of water rises across the substrate, the sodium chloride base layer dissolves beneath the target film. The structure then floats off onto the surface of the water. Deposition onto an aperture plate is achieved by a reversal of the flotation process. The manoeuvring of a floating film may be performed by using the flux of vapour that is emitted from an ethanol drop, suspended at the
end of a pair of tweezers. The process is delicate but straightforward. Once the gold surface of the aperture plate makes good contact with a target film, their subsequent separation is impossible; careful alignment is therefore necessary.

The aperture plates manufactured for the Hybrid Polarimeter are made of OFHC and are highly polished to present a smooth surface to the target films. The plates are also sputter coated with gold to provide a non-tarnishing surface to which the target films will adhere readily. As the coefficient of thermal expansion of the OFHC is comparable to that of gold its use minimises the risk of rupture of a target film during bakeout. An aperture of 3 mm is machined into each plate, with the plate thickness tapered finely into the aperture itself. This tapering reduces the effects of surface tension that may otherwise rupture a target film upon removal of the plate from the water.
5.4 OPERATION OF THE HYBRID POLARIMETER

Operation of the Hybrid Polarimeter, with a 250 Å thick target film at its heart, inevitably requires special consideration with regard to the extreme fragility of this structure. Whilst at atmospheric pressure draughts were avoided at all cost. Pumping down of the Hybrid Polarimeter experimental chamber was conducted very slowly, to avoid a severe pressure gradient across the target film. Furthermore, excessive vibration was avoided and great care was exercised when tightening flanges and opening valves. As the Hybrid Polarimeter must operate under UHV conditions, a bakeout of the apparatus is required. In order to avoid excessive thermal gradients across the target film during bakeout, the chamber temperature was ramped carefully and was not allowed to exceed 120 °C.

5.4.1 SCATTERING MODE

Operation of the Hybrid Polarimeter in the scattering mode is identical to the procedure described for Micro-Mott 2 in Chapter 3, Section 3.5. The only practical difference between the two systems is one of hardware; a different HT plug is required for the Hybrid Polarimeter, which has the HT supplied via one pin of a three-way feedthrough.

At present the scattering mode of operation is limited to a maximum HT of 15 kV. Above this level the HT breaks down due to an as yet undetermined fault. Although an applied HT of 15 kV does reduce the $S_{\text{eff}}$, the instrument is nonetheless functional as a polarimeter.
5.4.2 TRANSMISSION MODE

5.4.2.1 Operation in Transmission Mode

Conversion from the scattering mode to the transmission mode requires only the reconfiguration of the external power connections and the installation of the transmission mode power supply unit. The necessary connections are illustrated in Figure 5.15 above. A photograph of the Hybrid Polarimeter, mounted in the Surf-0 UHV experimental chamber and connected to its ancillary power supplies, is illustrated in Figure 5.16.

Figure 5.16. A photograph of the Hybrid Polarimeter mounted in the Surf-0 experimental chamber, together with its ancillary power supplies.

Specifically, the M2, M3 and M4 lenses of the transport optics require connection to outputs 1, 2 and 3 of the transmission mode supply. Output number 4 replaces the HT connection of the scattering mode. The remaining
two connections on the HT feedthrough, those of the solenoid, should be connected to a low voltage supply. Outputs 5, 6, 7 and 8 of the transmission mode supply, together with the lens (V2), fringe field, and inner and outer hemisphere outputs of the HAC300, are connected to the polarimeter via a screened input box on the analyser optics 11-way feedthrough. The details of these, and all other electrical connections, are listed in Table 5.1. The remaining two connections of the transmission mode supply are the high and low voltage outputs to the channeltron. These also are connected via the analyser optics 11-way feedthrough. During normal operation a voltage of 2.0 kV should be applied to the channeltron. This voltage may be increased as necessary in order to compensate for ageing of the channeltron. Finally, both the transmission mode supply and the polarimeter casing must float upon the HAC300 kinetic energy rail. This is best achieved via the microchannel plate (MCP) input box which, as part of the configuration of the Micro-Mott 1 polarimeter, is wired to enable connection to the casing. The connection is made via pin 10 of the MCP 11-way feedthrough. Any one of the three remaining SHV type connections on the MCP box may then be reconfigured in order to tap into the kinetic energy rail supply for its transfer to the transmission mode supply unit. It should be noted that a redundant connection to the polarimeter casing is available via pin 9 of the analyser optics 11-way feedthrough.
Table 5.1. Electrical connections for the transmission mode of the Hybrid Polarimeter.

In order to achieve a high yield of secondary electrons, a bias of typically -20 V is applied to the sample, with the HAC300 then set to select 22 eV kinetic energy electrons. Electrons are transmitted through the CHA with a pass energy of 5 eV. Operation with the sample biased in this way results in an increased potential on the fringe field lenses of the CHA, necessary to maintain...
the pass energy, and therefore electrons are ostensibly accelerated away from
the exit fringe field lens at a higher energy than without a sample bias.
However, as all lens elements potentials are floated upon the kinetic energy
rail, the effective kinetic energy of the electrons emerging from the CHA is not
actually affected by the sample bias.

The measurement of a spin dependent asymmetry is achieved by scanning the
RFA potential to a suitable position in the region of inelastically transmitted
electrons, and then reversing either the incident spin direction or the
majority/minority spin direction in the target film. The former is achieved by
suitable magnetisation of the sample, the latter by reverse pulsing the solenoid
with a current in excess of 150 A. The transmission mode supply has been
provided with a feature to enable computer control of the potential applied to
the RFA, and automation of kinetic energy scans in transmission mode.
However, the appropriate modifications to the Micro-Mott control software have
not yet been made.

5.4.2.2 Calibration of Transmission Mode

As for the Mott scattering mode of operation, the transmission mode will
require calibration in order to determine accurately the \( S_{\text{eff}} \), and thus determine
accurate values of longitudinal electron beam polarisation. There are three
straightforward means of performing the calibration.

- The SPS group polarised electron beam source, currently under
  construction as detailed in Chapter 7, will offer a direct, reliable and accurate
  means by which to perform a calibration procedure, once its polarisation has
  been established using the high energy Mott polarimeter of the SPS group.
  It would be instructive to compare calibration data so obtained with the data
  of Lampel et al., \(^55^,\, ^58\) obtained with a similar experimental configuration.
• It may also be possible to directly apply the data of Lampel et al. for calibration purposes. However this approach has three drawbacks. Firstly, the majority of the asymmetry data of Lampel et al. were obtained from caesiated target films, with correspondingly higher asymmetries than for non-caesiated films. Secondly, this approach would also require the application of identical incident energies at the target film, as those used to obtain the calibration data. Finally, small differences in the layer dimensions of the target films involved are likely to influence the results; direct comparison of data from non-identical target films is not likely to provide an accurate calibration.

• An alternative calibration technique, that may be implemented in the future, is that of the self-calibrating bilayer technique. This technique involves a twin ferromagnetic layer target film, one layer being slightly thicker than the other. The two layers therefore possess different coercivities, and their magnetisation state with respect to each other may therefore be switched between a parallel and an antiparallel configuration. The value of $S_{\text{eff}}$ for the spin sensitivity of this target film can be deduced from measurements of the transmitted electron current in these two magnetisation configurations, even with an unpolarised incident electron beam.

5.4.3 TRANSFER BETWEEN SCATTERING AND TRANSMISSION MODES

The transfer between the scattering mode and the transmission mode requires completion in full of the following procedure.

1) HT 3-Way feedthrough:

Scattering: Connection of the inner pin to the 20 kV supply via the 3-Way Tufnol safety plug.
Transmission: Connection of the inner pin to output 4 of the transmission mode supply, and connection of the two outer pins to a suitable power supply for target film magnetisation reversal.

2) MCP 11-Way feedthrough and input box:

Scattering: Connection of the polarimeter casing to the Delta E output of the Sussex power supply, and connection of the MCP and kinetic energy rail supplies.

Transmission: Connection of the polarimeter casing to the kinetic energy rail supply, and extension of the kinetic energy rail supply to the transmission mode supply.

3) SHV feedthroughs:

Scattering: Connection of the right hand SHV, of the 4-way, to the M2 supply of the Sussex supply unit. Connection of the left hand SHV, of the 4-way, to the M4 supply. Connection of the deflector plate supply to the M3 supply.

Transmission: Connection of the right hand SHV, of the 4-way, to output 1 of the transmission mode supply. Connection of the left hand SHV, of the 4-way, to output 3. Connection of the deflector plate supply to output 2.

4) Reconfigure one channel of detector electronics as necessary.

5) Adjust the pass energy as necessary - the transmission mode requires a pass energy of 5 eV.
5.5 TESTS, BENCHMARKING AND COMMISSIONING

The complexity of the Hybrid Polarimeter necessitated a correspondingly complex programme of testing. Separate test programmes were prepared for the two modes of operation, and a number of different target films were manufactured for this purpose. The programme of testing was as follows:

1) The validation and characterisation of the scattering mode of operation, using a target film of pure gold.

2) The validation of the electron optical integrity of the transmission mode of operation. No target film was required for this stage of testing.

3) The verification of a satisfactory transmitted electron beam intensity, and the validation of the operational integrity of the RFA energy analyser, for a target film of pure gold.

4) The validation and characterisation of the transmission mode of operation, using a ferromagnetic target film.

5) The characterisation of the scattering mode with a ferromagnetic target film.

5.5.1 EXPERIMENTAL DETAILS

The experimental set-up used for initial commissioning work on the Hybrid Polarimeter was identical to that used for commissioning the Micro-Mott 2 polarimeter, as detailed in Chapter 3, Section 3.7.1. This was maintained in order to facilitate alignment of the instrument with the source of polarised electrons, namely secondary electron emission from a sample of as-cast Fe$_{80}$B$_{20}$ ribbon. In particular, the continuity of the arrangement enables satisfactory electron beam alignment with a characterised region of the sample,
guaranteeing a measurable transverse polarisation. Furthermore, it is suspected that amorphous alloy ribbons might exhibit out-of-plane magnetic anisotropies. It was therefore anticipated that regions of the Fe$_{80}$B$_{20}$ sample would exhibit an out-of-plane component of magnetisation, suitable for analysis with the transmission mode of the Hybrid Polarimeter.

5.5.2 PREPARATION OF TARGET FILMS

A number of pure gold target films were prepared for use with the Hybrid Polarimeter. These were manufactured by deposition of gold onto float glass substrates, using an oil diffusion pumped evaporator. The gold films were deposited both with and without a sodium chloride base layer of 100 Å thickness, and deposition was followed by annealing up to 180 °C in vacuo. Film thicknesses were monitored during deposition with a quartz crystal oscillator; all the test structures were prepared with a nominal thickness of 250 Å.

Flotation of the gold target films proved to be quite easy; they were deposited onto aperture plates without difficulty, whether a sodium chloride base layer was present or not.

Two samples of ferromagnetic target films were prepared for use in the Hybrid Polarimeter. The first ferromagnetic target film was prepared without a sodium chloride base layer, in the expectation that the poor adhesion of gold to glass would enable its successful flotation in the manner described in Section 5.3.2. This target film was prepared with dimensions of 208 Å of gold, 9.2 Å of cobalt and 35 Å of gold. The second target film was deposited on a 70 Å thick sodium chloride base layer, with thicknesses of 200 Å of gold, 10 Å of cobalt and 20 Å of gold.

The target film without sodium chloride proved impossible to remove from the substrate. The second target film was floated from its substrate with some
difficulty; it was prone to tearing during the process. The deposition of portions of this film onto the aperture plates proved even harder. It is believed the plates had become contaminated in some way, preventing adhesion with the films. Two portions did adhere satisfactorily, but both broke as the plates were lifted from the water tank.

It is believed that residual oil from the deposition chamber diffusion pump is responsible for the ease of flotation of the pure gold target films. The ultraclean deposition environment used for preparation of the ferromagnetic target films clearly does not permit flotation of the samples without a sodium chloride base layer.

To date all commissioning work has been performed using pure gold target films. The handling and mounting of aperture plates containing these structures was not found to be problematic.

5.5.3 COMMISSIONING OF THE SCATTERING MODE OF OPERATION

The first test of the Hybrid Polarimeter was to determine whether or not the inner hemisphere could support an applied HT of up to 20 kV under UHV conditions. In fact breakdown was found to occur consistently at a level of approximately 15.5 kV. Below this level however, provided that the HT was ramped slowly, breakdown was not a problem.

The shield arrangement around the transmission polarimeter optics, and the proximity of the HT cable as it passed through this shield, were initially regarded as the weakest link in the arrangement for application of the HT. More space was made around the HT pin that passed through the shield, and cables were re-routed in an attempt to increase clearance of HT components. These efforts failed to improve the situation, suggesting that breakdown was occurring either within the polarimeter itself or in the region of the HT feedthrough.
Whilst an applied HT of 15 kV is substantially lower than the designed capacity of 20 kV, it is nonetheless sufficient to enable operation of the instrument as a polarimeter, albeit with a slightly reduced $S_{\text{eff}}$. The performance of the polarimeter was therefore investigated, with an applied HT of 15 kV, by measurement of the spin asymmetry of the secondary electron emission from the Fe$_{80}$B$_{20}$ ribbon sample. As with the investigations of Micro-Mott 1 and 2, discussed in Chapter 3, Section 3.7.1, an incident electron kinetic energy of 1.6 keV was applied at grazing incidence to the ribbon sample. The secondary electron emission was collected from the sample at normal incidence. The results are illustrated in Figure 5.17. This shows a secondary electron hysteresis loop, taken at 1 eV kinetic energy, with an inelastic energy window of 200 eV. This loop is believed to correspond to the same area of the ribbon from which the data of Figures 3.17 and 3.18, in Chapter 3, were obtained.

![Figure 5.17](image)

**Figure 5.17.** 1.0 eV energy resolved hysteresis loop for as-cast Fe$_{80}$B$_{20}$ taken with 1.6 keV incident electrons.

In order to achieve the same detector count rates as those achieved with Micro-Mott 2, it was necessary to use an EG5 electron gun filament current of 2.1 A. This is 0.1 A higher than the filament current used in the equivalent
operation of Micro-Mott 2. This suggests that the backscattered electron flux was lower in this test, consistent with the reduced thickness of the target film.

As with the commissioning of the Micro-Mott 2 polarimeter, the calibration of the scattering mode of the Hybrid Polarimeter was performed by the energy window extrapolation technique described in Chapter 2, Section 2.3.1.3. The asymmetry of 1 eV kinetic energy secondary electrons, for an applied HT of 15 kV, was measured for a range of inelastic energy window settings. The inelastic energy window potential was applied to both the detector fronts and the detector lens elements, with a focus potential of 1000 V applied to the outer hemisphere. The results are shown in Figure 5.18.

![Figure 5.18](image)

Figure 5.18. Asymmetry versus inelastic energy window for an applied HT of 15 kV; the results extrapolate to asymmetries of $A_{TH} = 0.017$ and $A_{TV} = -0.015$.

Since the Mott scattering foil was maintained at 15 kV, a theoretical Sherman function, $S_{th}$, of -0.28 is assumed. This leads, through Equations 3.1 and 3.2 of Chapter 3, Section 3.7.2.2, to an $S_{eff}$ value of -0.22 at an energy window of 200 eV. As discussed in Chapter 2, Section 2.3.1, this value of $S_{eff}$ is subject fundamentally to an uncertainty of $\pm 5\%$. 

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This value of $S_{\text{eff}}$ is identical to that quoted for the Micro-Mott 2 instrument in Chapter 3, Section 3.7.2.2. Direct comparison of the two values is not possible since the Micro-Mott 2 commissioning was performed with an applied HT 2 kV higher than that for the Hybrid Polarimeter. Although this is expected to reduce the $S_{\text{eff}}$ for the Hybrid Polarimeter, the ultrathin nature of the target film will act to counter effect of the reduced HT to some degree.\textsuperscript{5,14} The above result appears to substantiate this.

It should be noted that over the course of the above experimentation no deterioration of the target film integrity, in terms of count rate fluctuation, was detected.

5.5.4 COMMISSIONING OF THE TRANSMISSION MODE OF OPERATION

Initial attempts to operate the Hybrid Polarimeter in transmission mode with a gold target film in place produced contradictory results. Energy scans with the CHA revealed an apparently normal secondary electron cascade, albeit superimposed upon a high background noise signal. However, the application of a potential barrier on the RFA failed to reduce the detected signal by more than a few percent. The former suggests that the electron optics of the instrument are working well, whilst the latter indicates that barely any electrons are being transmitted.

These results were explained by the lack of adequate shielding around the transmission polarimeter electron detector, and the resulting collection of stray electrons from the various hot filaments within the vacuum chamber. The polarimeter casing, in the immediate vicinity of the detector, is held at the potential of the kinetic energy rail. Energy scans with the CHA would therefore act to progressively suppress collection of stray electrons towards higher energy, producing a plausible approximation to a true secondary electron cascade signal.
The shielding arrangement for the transmission polarimeter was therefore redesigned in order to completely enclose it in an aluminium canister. With the new shield in place the influence of stray electrons was reduced, from being the dominant contribution, to a level of approximately 5% of the transmitted signal.

In addition to the stray electrons, two significant sources of noise were identified. The turbomolecular pump of the Surf-0 experimental chamber was found to be the origin of the larger background noise component. The HAC300 controller was also responsible for a noise component an order of magnitude smaller. The exact level of these noise components is a function of the discriminator setting of the signal processing electronics; it cannot be removed without simultaneously removing the desired signal. Both items are essential to the running of the Hybrid Polarimeter, and therefore significant noise reduction measures are required.

The turbomolecular pump can be switched off if the sample cleaning procedures, necessary to produce a polarised beam of electrons from the Fe_{80}B_{20} ribbon sample, are not required. Thus it was possible to investigate the performance of the RFA energy analyser for transmission of an unpolarised electron beam through the gold target film. An incident electron beam kinetic energy of 1.6 keV was used at the Fe_{80}B_{20} sample, with a filament current of 2.4 A in order to provide a sufficiently intense transmission signal. An incident kinetic energy at the target film of 10 eV was used. The lens potentials applied to the transmission polarimeter electron optics were adjusted to optimise the transmitted signal, as were the potentials applied to the x/y deflectors. It appeared that a pinhole in the target film could be clearly identified; for a particular x/y deflector setting the signal intensity increased dramatically. This area of the target film could be avoided if necessary. However, in order to test the electron optics, the pinhole was deliberately targeted to provide a high signal intensity. The lens element potentials, in volts, applied to the transmission polarimeter electron optics are given in Table 4.2.
<table>
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<td>Lens 1</td>
<td>5.0</td>
<td>Polarimeter case</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

Table 4.2. Applied lens potentials for optimised transmitted signal intensity through the RFA.

The results of an RFA scan for this experimental set-up are illustrated in Figure 5.19. A background noise level of approximately 3000 Hz, due to the HAC300 controller electronic noise, has been subtracted from the data. The results show that the RFA operates as expected, although a significant component of the signal remains due to stray electrons.

Figure 5.19. Count rate versus retarding potential for an unpolarised electron beam transmitted through a gold target film; a background noise level of 3000 Hz has been subtracted from the data.
CHARACTERISATION OF TARGET FILMS

The first gold target film used in the Hybrid Polarimeter was removed intact from the vacuum chamber after; pump down, a bakeout to 120 °C, operation in Micro-Mott mode at $1 \times 10^{-9}$ mbar pressure and 17 kV applied HT, and subsequent venting of the chamber. This foil, originally prepared by deposition upon a sodium chloride base layer, was inspected by optical microscopy at up to 400x magnification. At 40x magnification seven pinholes were visible, spread randomly over the 7 mm² area of the aperture. At higher magnifications randomly selected areas did not reveal any pinholes. However certain regions appeared to be more transmissive to light, and are therefore thinner than average.

Two other samples of gold target film, from the same sample that provided the target film described above, were deposited onto glass microscope coverslips. In the same way a sample of the ferromagnetic target film was also prepared. A sample of the gold film, and one of the ferromagnetic target film, were then investigated by atomic force microscopy. Scans were made of the edges of the samples, over an area with lateral dimensions of 5 x 5 µm. These scans, illustrated in Figures 5.20 and 5.21 respectively, enabled estimates to be made of the sample thicknesses. A thickness of 38 nm (average of six measurements), was determined for the gold target film. A thickness of 24 nm (average of five measurements) was determined for the ferromagnetic target film. The gold target films are therefore approximately 50 % thicker than the target films that they are intended to mimic. This has an important bearing upon any measurements of transmission through these target films, as the transmission will be significantly reduced in comparison with that possible through ferromagnetic target films.
Figure 5.20. Atomic force microscopy scan of the surface topography of a gold target film; the sections used for the calculation of step heights are also illustrated.

Figure 5.21. Atomic force microscopy scan of the surface topography of a ferromagnetic target film; the sections used for the calculation of step heights are also illustrated.
The second coverslip sample of the gold target film was investigated by scanning electron microscopy (SEM). At low magnification the image of the target film was essentially identical to that of optical microscopy at 40x magnification; a number of pinholes were readily identifiable, some of which appeared to be the result of imperfections on the surface of the coverslip. Magnifications up to 2000x served to confirm the optical investigation. However, high magnifications caused localised heating of the target film, and trapped volumes could be seen to expand, ultimately resulting in punctures of the gold film. Quantification of numbers of pinholes and their dimensions was not therefore possible by SEM.
5.6 CONCLUSIONS AND FUTURE WORK

- The Hybrid Polarimeter functions well in its scattering mode of operation. Although this mode is presently limited by a maximum applied HT at the scattering foil of 15 kV, the instrument nonetheless is found to achieve an $S_{\text{eff}}$ of - 0.22, subject to an uncertainty of ± 5 %, at an inelastic energy window of 200 eV. It is expected that the designed HT level of 20 kV will soon be achieved. As a consequence of the relative thinness of the gold target films, count rates in the Hybrid Polarimeter are reduced compared with those in the Micro-Mott 2 polarimeter.

- The functionality of the transmission polarimeter electron optics has been demonstrated. The principal source of false signal has been identified and eliminated. A significant background noise level remains, principally due to electronic noise induced by the turbomolecular pump controller and the HAC300 CHA controller of the Hybrid Polarimeter. This noise requires reduction, through screening of the appropriate cables and feedthroughs, in order to permit accurate measurement of the small transmitted signal intensities anticipated for the transmission polarimeter.

- Although it was not possible to conduct a spin asymmetry measurement in the transmission mode of the Hybrid Polarimeter, the purchase of further ferromagnetic target films and the above noise reduction requirements are presently the only obstacles to such measurements.

- The fragility of the gold target films does not appear to be as great a problem as originally anticipated. The fact that the gold target films are strong enough to survive loading, pump down, bakeout and venting was a surprise. Although the exact behaviour of the ferromagnetic target films has not been tested, they might also reasonably be expected to be strong enough to survive bakeout and venting.
• Transmission through ferromagnetic target films, prepared with thicker passivating layers of gold, should be investigated. As an alternative means of increasing the robustness of the target films, the aperture plates could be redesigned in order to use a fine mesh of gold to support the film.
CHAPTER 6

AMORPHOUS ALLOYS AS SECONDARY STANDARDS FOR SPIN POLARISED ELECTRON SPECTROSCOPY

6.1 INTRODUCTION

The uncertainties surrounding calibration of retarding potential polarimeters, through inelastic energy loss extrapolations, are significant. Ideally a direct means of calibration should be used, thereby eliminating the need for quantification of the effects of plural and multiple scattering. The utilisation of a source of electrons of known polarisation is an obvious solution to this problem.

For polarimeter calibration purposes a source should ideally possess a number of characteristics: it should be capable of reliably and repeatedly producing a stable polarisation of at least 0.10; the beam should be of an acceptable current, 1 μA or more generally suffices; and it should preferably be easy to use. A number of approaches to the provision of these characteristics are discussed in Chapter 2. In addition, the present laboratory standard for polarimeter calibration, the GaAs based source, is discussed in some detail in Chapter 7.

However, a GaAs source, whilst meeting the primary requirements of polarisation, beam current, stability and repeatability, is not an easy instrument to operate. The creation of a negative electron affinity surface on a wafer of GaAs, the physics of which is poorly understood, is difficult and subject to a high degree of artistry on the part of the operator; though once successfully activated, a GaAs source can be turn-key in its operation.

The concept of a secondary standard has therefore evolved, in which the polarisation of a more straightforward experimental system is determined with reference to a more rigorous primary standard such as a GaAs source. One
approach is to base the secondary standard upon the secondary electron emission from ferromagnetic materials, as this can be highly polarised under appropriate experimental conditions. It is now generally acknowledged that these materials exhibit an enhanced polarisation at electron kinetic energies below 10 eV. This enhanced polarisation, combined with the high intensity of the secondary electron cascade at approximately 1 eV kinetic energy, offers the potential for a standard source with a high figure-of-merit. Such standards may, in principle, be relied upon to provide an easy means of both polarimeter calibration and comparison.

A possible candidate material is crystalline iron. Kirschner and Koike investigated the polarisation of the secondary electron cascade from the (110) surface of a single crystal of iron. A maximum cascade polarisation of 0.50 was reported. However the use of single crystals presents an array of significant experimental difficulties. A crystal of exceptionally high purity and structural uniformity is required. The orientation of the structure must be accurately determined, such that a specific crystallographic face may be prepared. The crystal must then be subjected to rigorous sputter cleaning, followed by annealing to restore crystallinity, at ultra high vacuum (UHV). There are further difficulties associated with magnetisation of the crystal. The use of a yoke arrangement presents difficulties with stray fields and the reliable application of a magnetic field of suitable strength, and may also result in the transfer of contaminants to the crystal surface. These difficulties are not easily surmounted. In addition, there is fine structure in the secondary electron cascade due to low energy diffraction effects. Overall, single crystal sources are not very attractive in this role.

Another option, promoted in 1987 by Hopster, is the use of the secondary electron cascade from commercially available ferromagnetic amorphous alloy ribbons. Specifically, Hopster investigated the alloys Fe_{82}B_{12}Si_{16}, Fe_{80}Ni_{20}B_{20} and Fe_{44}Ni_{37}B_{19}. He found that the secondary electrons from these materials exhibited stable polarisations of 0.22, 0.19 and 0.15 respectively over the electron kinetic energy range 10 - 20 eV. Experimentally these materials
could be easily implemented as polarised sources. As ribbons they may be easily mounted in closed loops, thus forming a closed magnetic circuit with minimal stray field, and they may be easily cleaned by gentle argon ion bombardment.

In 1993 Klebanoff rejected iron based amorphous alloys as secondary standards on the grounds that stress induced effects, arising from sample mounting geometry, lead to irreproducibility of their magnetic properties. In calibrating a new polarimeter instrument he employed the amorphous ferromagnetic alloy Co$_{65}$Fe$_4$Ni$_{14}$Si$_{15}$. This alloy is reported as exhibiting a secondary electron polarisation at 30 eV of $(8.5 \pm 1.0) \times 10^{-2}$. This polarisation is significantly less than that offered by iron based alloys. However, cobalt based alloys close to this composition are known to exhibit essentially zero magnetostriction; this particular alloy might therefore be expected to readily undergo saturation to a uniform magnetic state.

However, doubts exist as to the reproducibility of magnetic properties of even this material. The work of Seddon et al. and Dowling, involving the study of the surface magnetic microstructure of a variety of iron and cobalt based amorphous ferromagnetic ribbons, revealed clear lateral variations in the secondary electron polarisation of these materials. In particular, Dowling expresses concern over the reliability of the saturation magnetisation of such ribbon samples, with evidence that tears, kinks and pinholes, and even sputter cleaning can adversely effect ribbon magnetic properties.

The lateral variations in electron polarisation are believed to be stress induced, through the formation of the ribbon samples into closed loops. Iron based alloys are known to possess significant magnetostriction coefficients, giving rise to rich domain structures in these materials that are strongly influenced by applied stress. The fact that lateral variations have been discovered in the polarisation of the secondary electron cascades of these materials precludes their subsequent use as secondary polarisation standards.
Therefore it was decided that a similar investigation of the Co$_{66}$Fe$_4$Ni$_{14}$B$_{14}$Si$_{15}$ material was also justified, in order to establish whether or not this too would exhibit lateral variations in magnetic properties.

If such variations should indeed be found, there existed two possible methods for their suppression that could be readily investigated. Firstly, it was suggested that variations might be suppressed by suitable annealing of the sample; the concept of field annealing, the annealing of a material in the presence of a saturating magnetic field, was thought to offer a means of improving magnetic homogeneity $^{6,17}$. Secondly, it was proposed that the deposition of thin films of iron upon the ribbon samples might also act to suppress lateral variations in magnetic properties $^{6,18}$. 
6.2 EXPERIMENTAL DETAILS

The experimental set-up for the investigation of Co$_{96}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ ribbons was similar to that for the calibration of Micro-Mott 1 with Fe$_{80}$B$_{20}$ ribbon, described in Chapter 3, Section 3.7.1. The only significant difference was the use of an interchangeable sample system together with a UHV preparation chamber, schematically illustrated in Figure 6.1. The preparation chamber was equipped with a carousel for multiple sample storage, a sample transfer mechanism and a magnetron sputter gun for iron deposition. Ordinarily the preparation chamber was valved off from the main experimental chamber, Station 6.1 of the Synchrotron Radiation Source (SRS), on which all experimental work was performed. The 6.1 beamline provided photons over the energy range 80 to 180 eV.

![Diagram of experimental and preparation chambers](image)

**Figure 6.1.** Schematic illustration of the experimental and preparation chambers used for the investigation of Co$_{96}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ ribbons.
Three different samples of Co$_{66}$Fe$_{4}$Ni$_{1}$B$_{14}$Si$_{15}$ amorphous alloy ribbon$^{6,11}$ were investigated: as-cast ribbon; ribbon field annealed at 350 ºC; and ribbon field annealed at 400 ºC. Samples were cut parallel to the roll axis, with dimensions of 5 mm x 100 mm, from the supplied ribbons. The field annealing of the samples was performed, at the University of Sussex, by Dr. M. Hardiman. Samples were subjected to a magnetic field of 0.08 T under flowing argon at temperatures of 350 ºC and 400 ºC respectively. The magnetic field was applied, parallel to the roll axis of the ribbons, only when the sample had attained the annealing temperature. Similarly the field was not removed until after the samples had cooled to below their Curie temperature. The samples were then mounted in closed loops, shiny side outermost, as described in Chapter 3, Section 3.7.1.1.

All samples were subjected to bakeout of the experimental and preparation chambers up to a maximum temperature of 135 ºC. The surfaces of the ribbon samples were cleaned by argon ion bombardment at an accelerating potential of 1.6 kV and a drain current of typically 10 - 15 µA. All samples were cleaned for an initial period of at least 2 hours, followed by periods of approximately 30 minutes prior to each experimental run. In this way carbon and oxygen contamination of the ribbon surfaces was reduced to 5 % or less, as determined by Auger electron spectroscopy$^{6,19}$. Complete elimination of these contaminants is not possible as the ribbon manufacturing process ensures their presence throughout the bulk of a sample. The deposition of thin overlayers of iron was achieved through magnetron sputter deposition under a pressure of 1 x $10^{-2}$ mbar of argon. Deposition rates were established using a quartz crystal oscillator, enabling estimation of the thicknesses of deposited films.

Energy resolved hysteresis loops (ERHL) and asymmetry versus electron energy spectra were taken using Micro-Mott 1, in conjunction with the fast data collection electronics system described in Chapter 3, Section 3.4.2.2. The ribbon samples were illuminated, at glancing incidence of 5 - 10 º, with either a 1.6 keV electron beam or the SRS photon beam tuned to an energy of either 120 or 135 eV. The ERHLs were collected from different locations transverse
to the roll axis of the ribbon samples, achieved by raising or lowering the sample manipulator. Furthermore, ERHLs were collected for spin asymmetry components both parallel to, $A_{TH}$, and transverse to, $A_{TV}$, the roll axis of the ribbons; the subscripts denote "transverse horizontal" and "transverse vertical" respectively. The different sampling locations, and the two spin asymmetry components, are illustrated schematically in Figure 6.2. A bias potential of either -20 or -30 V was applied to all samples.

Figure 6.2. Schematic illustration of the two spin asymmetry components analysed by Micro-Mott 1.
6.3 RESULTS

Immediately prior to every experimental run, the secondary electron cascade was scanned to establish the correct operation of the apparatus and to establish the electron kinetic energy at which the count rate was maximum. The precise angular alignment of the energy analyser to the sample normal determines the degree of shift of the cascade maximum away from zero energy. Optimum count rates were established between 0.5 and 2.0 eV dependent upon the experimental run concerned; ERHLs were collected at these electron energies. A typical scan of the secondary electron maximum is illustrated in Figure 6.3.

Confirmation that the Micro-Mott instrument was targeting the ribbon rather than the sample holder was achieved by monitoring a cobalt Auger transition at 53 eV \(^{620}\); a typical scan of the spectrum of electron counts arising from this transition is shown in Figure 6.4. In this way vertical position limits were established for each sample.

ERHLs taken at two different locations on the surface of an as-cast sample of Co\(_{66}\)Fe\(_4\)Ni\(_{14}\)B\(_{14}\)Si\(_{15}\) ribbon are illustrated in Figures 6.5 and 6.6. The scans were taken using 1.6 keV incident electrons as the means of excitation. The results show hysteresis in both transverse components of electron spin asymmetry, \(A_{TH}\) and \(A_{TV}\). This demonstrates that total magnetic saturation of the sample has not been achieved along the roll axis of the ribbon. Furthermore, the ERHLs reveal distinct lateral variations of both remanence and coercivity.
Figure 6.3. The secondary electron cascade from Co56Fe4Ni18B14Si15 amorphous ribbon, illustrating the secondary electron maximum at approximately 20.5 eV. The sample is biased at -20 V.

Figure 6.4. The secondary electron cascade from Co56Fe4Ni18B14Si15 amorphous ribbon, for the electron kinetic energy range 40 - 60 eV. This illustrates the cobalt Auger peak at 53 eV. The sample bias has been removed to give actual electron kinetic energies.
Figure 6.5. 1.0 eV ERHL for as-cast Co_{66}Fe_{4}Ni_{1}B_{14}Si_{15} taken with 1.6 keV incident electrons at \( Z = 144.5 \) mm.

Figure 6.6. 1.0 eV ERHL for as-cast Co_{66}Fe_{4}Ni_{1}B_{14}Si_{15} taken with 1.6 keV incident electrons at \( Z = 146.5 \) mm.

ERHLs taken with 135 eV incident photons are shown in Figures 6.7 and 6.8. These results are similar to those taken with 1.6 keV electrons. The presence once again of distinct lateral variations in both polarisation components indicates that these results are independent of the means of excitation. The data further indicates that the variations are not related solely to the topmost
surface layer of the ribbon, since ERHLs excited by incident electrons with energies in excess of 1 keV are known \(^6.2^1\) to be more representative of the bulk.

Figure 6.7. 0.5 eV ERHL for as-cast Co\(_{66}\)Fe\(_4\)Ni\(_{14}\)B\(_{14}\)Si\(_{15}\) taken with 135 eV photons at \(Z = 144.5\) mm.

Figure 6.8. 0.5 eV ERHL for as-cast Co\(_{66}\)Fe\(_4\)Ni\(_{14}\)B\(_{14}\)Si\(_{15}\) taken with 135 eV photons at \(Z = 145.0\) mm.
Attempts were made to obtain hysteresis loops using magneto-optical Kerr effect apparatus (MOKE) \(^ {6,22}\), a technique that probes 100 - 200 Å into the sample. However, these attempts were confounded by the surface texture of the \(\text{Co}_{66}\text{Fe}_{4}\text{Ni}_{1}\text{B}_{14}\text{Si}_{15}\) samples which caused extensive diffuse scattering of the incident laser illumination.

Thin overlayers of iron were deposited upon the as-cast \(\text{Co}_{66}\text{Fe}_{4}\text{Ni}_{1}\text{B}_{14}\text{Si}_{15}\) ribbon in an attempt to achieve a more uniform spin asymmetry in the secondary electron cascade. Figures 6.9 and 6.10 illustrate the corresponding ERHLs for a 10 - 20 Å thick iron overlayer on the ribbon. Both these ERHLs are similar in form to the above results for the clean surface of the as-cast sample, indicating that the domain structure of the iron overlayer reflects that of the underlying substrate. Furthermore, iron possesses a magnetic moment larger than that of the cobalt in \(\text{Co}_{66}\text{Fe}_{4}\text{Ni}_{1}\text{B}_{14}\text{Si}_{15}\) alloy. The spin polarisation of the secondary electron cascade is therefore enhanced, in confirmation of the work of VanZandt et al. \(^ {6,23}\).

![Graph](image)

**Figure 6.9.** 0.5 eV ERHL for as-cast \(\text{Co}_{66}\text{Fe}_{4}\text{Ni}_{1}\text{B}_{14}\text{Si}_{15}\), with 6 Å thick Fe overlayer, taken with 135 eV photons at \(Z = 144.5\) mm.
Figure 6.10. 0.5 eV ERHL for as-cast Co$_{66}$Fe$_4$Ni$_{14}$B$_{14}$Si$_{15}$, with 6 Å thick Fe overlayer, taken with 135 eV photons at $Z = 145.0$ mm.

The field annealed samples were investigated in order to verify whether or not the annealing process had improved the magnetic homogeneity of the Co$_{66}$Fe$_4$Ni$_{14}$B$_{14}$Si$_{15}$ alloy. ERHLs for these samples are illustrated in Figures 6.11 through to 6.14. The 350 °C annealed sample was probed with 1.6 keV electrons, and the 400 °C annealed sample was probed with 120 eV photons. For both samples the ERHLs are significantly more square than those taken from as-cast ribbons. This indicates an improvement in the alignment of the easy axis of magnetisation with the roll axis of the ribbon, and confirms the results of Herzer $^6,24$. However, as before a significant transverse spin asymmetry is still readily found in both samples, together with lateral variations in the magnitude of the spin asymmetry.
Figure 6.11. 1.5 eV ERHL for 350 °C annealed Co$_{66}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ taken with 1.6 keV electrons at $Z = 145.0$ mm.

Figure 6.12. 1.5 eV ERHL for 350 °C annealed Co$_{66}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ taken with 1.6 keV electrons at $Z = 146.0$ mm.
Figure 6.13. 1.5 eV ERHL for 400 °C annealed Co$_{66}$Fe$_4$Ni$_4$B$_{14}$Si$_{15}$ taken with 120 eV photons at $Z = 146.0$ mm.

Figure 6.14. 1.5 eV ERHL for 400 °C annealed Co$_{66}$Fe$_4$Ni$_4$B$_{14}$Si$_{15}$ taken with 120 eV photons at $Z = 144.5$ mm.
Finally, the enhancement of the cascade polarisation at low energy is illustrated in Figure 6.15, which is a plot of the variation with kinetic energy of the two spin asymmetry components, $A_{TH}$ and $A_{TV}$, for the secondary electron signal from 400 °C annealed Co$_{66}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ ribbon. This further demonstrates the significant asymmetry transverse to the roll axis of the ribbon.

![Asymmetry plot](image)

Figure 6.15. Secondary electron asymmetry profile (0 to 60 eV) for 400 °C annealed Co$_{66}$Fe$_4$Ni$_1$B$_{14}$Si$_{15}$ taken with 1.6 keV electrons. The sample bias of -30 V has been removed to give actual electron kinetic energies.
6.4 DISCUSSION AND CONCLUSIONS

The above results demonstrate that Co_{66}Fe_{4}Ni_{18}B_{14}Si_{15} ribbon samples, whether as-cast or field annealed, possess a rich magnetic domain structure. This magnetic inhomogeneity renders this material unsuitable as a secondary standard for spin polarised electron spectroscopy, since lateral variations of sampled area produce a non-uniform electron polarisation.

Seddon et al.\textsuperscript{625} report that scanning electron microscopy with polarisation analysis images of Co_{66}Fe_{4}Ni_{18}B_{14}Si_{15} samples, from the same batch of as-cast ribbon as used in this study, also reveal significant anisotropy. This anisotropy could not be overcome, even upon the application of a magnetic field fifty times greater than the apparent coercive field. These data provide perhaps the most graphic illustration of the difficulties involved in the use of Co_{66}Fe_{4}Ni_{18}B_{14}Si_{15} amorphous alloy ribbon as a secondary standard.

Flanders and Morito's\textsuperscript{612} observation of creep induced anisotropy, in the amorphous ferromagnetic alloy Co_{66}Fe_{4}Mo_{2}Si_{16}B_{12}, provides an explanation of the existence of magnetic inhomogeneity in low magnetostriction alloys. It is proposed that the action of forming amorphous alloy ribbons, into the loops necessary for spin polarised spectroscopy, creates strains within the bulk that induce random magnetic anisotropies. It is also possible that strains may be induced by the melt-spinning process with which these ribbons are fabricated.

The experimental evidence for magnetic inhomogeneity in ferromagnetic amorphous ribbons in general\textsuperscript{6, 10, 6, 13, 6, 14} indicates that all materials of this type should be regarded as unsuitable for use as secondary polarisation standards.

Finally, the deposition of magnetic thin films of iron upon Co_{66}Fe_{4}Ni_{18}B_{14}Si_{15} alloy substrates is likewise unsuitable as a method for producing a secondary standard, since the magnetic domain structure of the substrate persists in 10 - 20 Å thick overlayers of iron deposited by magnetron sputtering.
CHAPTER 7

A GALLIUM ARSENIDE POLARISED ELECTRON BEAM SOURCE

7.1 INTRODUCTION

The most widespread method for the generation of polarised electron beams, for the purpose of electron spin polarimeter calibration, involves a gallium arsenide crystal as the electron source. The surface of such a crystal, when activated to negative electron affinity\textsuperscript{71} and illuminated with circularly polarised radiation of a suitable wavelength, photoemits electrons with a significant degree of spin polarisation. A thorough review of this technique has been written by Pierce\textsuperscript{72}.

In 1998 it was decided to undertake the construction of a polarised electron source, in order to enable the Spin Polarised Spectroscopy (SPS) group to benchmark its polarimeter developments. In particular, given the Hybrid polarimeter programme, it was deemed necessary that the new source should be easily configurable to give either transversely or longitudinally polarised electron beams.

The work reported in this chapter was undertaken in collaboration with Professor T. J. Gay, of the Physics Department at the University of Nebraska, Lincoln, USA.
7.2 BACKGROUND

The ideal polarised electron source provides a high beam current of 100% polarised electrons. The polarisation, \( P \), is given by

\[
P = \frac{(N\uparrow - N\downarrow)}{(N\uparrow + N\downarrow)}
\]

(7.1)

where \( N\uparrow(\downarrow) \) denotes the number of electrons with spin parallel (antiparallel) with respect to a given axis of quantisation. The polarisation can therefore vary between +1 and -1. In practice all polarised sources fall short of this performance.

By analogy with the figure-of-merit (FOM) used to describe electron spin polarimeters, an FOM may also be assigned to polarised electron sources. For sources

\[
\text{FOM} = P^2 I
\]

(7.2)

where \( I \) is the total beam current.

There are a number of very different techniques available for the production of polarised electron beams\(^73\). By comparison with other methods of producing polarised electron beams, a GaAs based source provides a stable beam of only moderate polarisation but with a high current. Furthermore it has the advantage of providing a high brightness, together with a narrow energy spread, and the beam intensity may be modulated by suitable control of the incident photoexcitation laser illumination. In the context of the work of the SPS group, it also has the major advantage that it is relatively simple to construct and will provide reproducibly a polarisation of approximately 0.25.
7.3 PRODUCTION OF POLARISED ELECTRONS

GaAs based sources rely for their operation upon two distinct properties of this semiconductor: its detailed band structure, and the ability to lower the workfunction of its surface through activation to negative electron affinity.

7.3.1 BAND STRUCTURE

GaAs is a direct bandgap semiconductor, the band structure of which is illustrated schematically in Figure 7.1.

Figure 7.1. Energy level diagram for GaAs illustrating the $4s_{1/2}$ conduction band, the spin-orbit splitting of the $3p$ valence band, and the respective bandgaps at a temperature of 290 K.

The splitting of the $3p$ valence band by the spin-orbit interaction, and the selection rules applicable to transitions induced by circularly polarised light, enable population of the $4s_{1/2}$ conduction band with different numbers of spin-up and spin-down electrons.
The various states available in the GaAs band structure, for occupation by electrons according to their magnetic quantum numbers, $m_J$, are illustrated in Figure 7.2. This diagram further illustrates the possible transitions between those states and the relative frequencies with which those transitions can occur.

![Figure 7.2](image.png)

Figure 7.2. Illustration of the states available for occupation by electrons according to their magnetic quantum numbers. Also shown are the numbers, and relative frequencies, of possible transitions between states due to irradiation by right (left), $\sigma^+$ ($\sigma^-$), handed circularly polarised light.

In order to achieve unequal population of the $4s_{1/2}$ band, the incident illumination must be of such a wavelength that only transitions from the $3p_{3/2}$ level are possible; for the GaAs (100) surface a wavelength of approximately 800 nm is suitable. The selection rules for atomic transitions $^{74}$ require that $\Delta m_J = +1$ for right hand circularly polarised radiation, and $\Delta m_J = -1$ for left hand circularly polarised radiation; angular momentum is transferred from the incident photons to the photoexcited electrons. Under illumination with right hand circularly polarised radiation of 800 nm, transitions to the $4s_{1/2}$ level are possible only from two states of the four-fold degenerate $3p_{3/2}$ level, namely those with $m_J = -3/2$ and $m_J = -1/2$. The relative frequencies with which these
transitions may occur are given by the Clebsch-Gordan coefficients; those from the $m_i = -3/2$ state are three times as likely as those from the $m_i = -1/2$ state. Thus, with reference to Equation 7.1, the $4s_{1/2}$ conduction band can achieve a theoretical polarisation $P$ given by

$$P = \frac{(1 - 3)}{(1 + 3)} = -0.5$$

(7.3)

If the wavelength of the illumination is reduced, the photon energy increases and transitions from the $3p_{1/2}$ state contribute to the conduction band population. This reduces the polarisation to zero. It should be noted that the spin polarisation that arises is perpendicular to the surface of the GaAs crystal.

### 7.3.2 ACTIVATION TO NEGATIVE ELECTRON AFFINITY

Photoexcitation of a GaAs surface results only in an increase of the population of the conduction band. This lies at least 4 eV below the vacuum level, because of the workfunction of the surface, and therefore the electrons are unable to escape. The workfunction may, however, be reduced to lie just below the top of the conduction band through activation to a state known as negative electron affinity (NEA).

![Diagram](image)

Figure 7.3. The effect of the NEA condition upon the workfunction, $\phi$, of the GaAs surface. The electron affinity, $\chi$, and the apparent electron affinity, $\chi_a$, are also indicated.
The NEA activation of GaAs is directly analogous to the lowering of the workfunction of a gold surface, by caesium deposition, as discussed in Chapters 4 and 5. Under these conditions, the electrons of the conduction band can spontaneously escape into vacuum. The effect of the NEA condition upon the workfunction of the surface is illustrated schematically in Figure 7.3.

The NEA condition may be achieved by treatment of a p-type GaAs crystal surface with submonolayer quantities of caesium and oxygen. However, the physical mechanisms underlying the reduction in workfunction are not thoroughly understood. The physics of NEA are discussed in detail by Bell\textsuperscript{7.1} and issues concerning its application to spin polarised photoemission experiments have been investigated at length by Drouhin et al.\textsuperscript{7.5,7.6}
7.4 OPERATIONAL ISSUES

The performance of a GaAs polarised electron source is highly dependent upon many experimental factors. The salient considerations for achieving optimum performance are as follows.

7.4.1 SAMPLE ILLUMINATION

The photoexciting radiation incident upon the GaAs crystal must be highly circularly polarised. Furthermore, for use in calibrating polarimeters, the polarisation of the incident radiation must be readily reversible. The standard reversal technique uses a 1/4 wave plate and 1/2 wave plate combination; the former converts the polarisation of the incident radiation from linear to circular, whilst the latter enables conversion between left- and right- handed circular polarisation. Polarisation reversal may, however, be performed with greater accuracy by the use of either a Pockels cell or a photoelastic modulator. These methods are both compatible with modulation techniques for the elimination of noise and optimisation of sensitivity.

The photon energy of the incident radiation should be within 0.1 eV of the bandgap energy. If the energy is too high the polarisation reduces to zero. Too low an energy results in quite a high polarisation but also a low photoexcited beam current: this is due to the inability of the radiation to excite transitions across the band gap. The behaviour of a GaAs polarised source, between these limits of photon energy, is of critical interest. The quantum efficiency, or yield, of a source may be defined as the number of electrons photoexcited into the conduction band by a single incident photon. Figure 7.4, taken from Maruyama et al. 77 shows a typical plot of the variation of both quantum efficiency and electron beam polarisation with incident photon energy.
Figure 7.4. Polarisation (data points) and quantum efficiency (solid curve) as a function of photon energy for a strained layer of GaAs on a GaAsP buffer layer.

### 7.4.2 SAMPLE CLEANLINESS

The activation of a GaAs photocathode to the condition of NEA is critically dependent upon the state of cleanliness of its surface. At best contamination reduces both the quantum efficiency of the photocathode and the lifetime of the activation. At worst it prevents NEA activation altogether. It is therefore vital that the photocathode be maintained at a pressure of $1 \times 10^{-10}$ mbar, or better, in order to prevent quenching of NEA activation by residual gases within the ultra high vacuum (UHV) chamber.

The photocathode surface itself must be cleaned thoroughly prior to being placed under vacuum. A typical cleaning procedure for a GaAs crystal involves its etching for approximately thirty minutes, in a 1:8:1 ratio solution of concentrated hydrogen peroxide, concentrated sulphuric acid and distilled water. The crystal must then be rinsed thoroughly in deionised water. Once
clean the crystal must be loaded immediately into the source chamber and pumped down to UHV pressure

Prior to NEA activation the photocathode must be baked at a temperature of approximately 600 °C for several hours in order to reduce surface and bulk levels of contamination to a minimum. The photocathode temperature must not, however, exceed 660 °C; above this temperature arsenic evaporates preferentially from a GaAs crystal, destroying the crystal stoichiometry.

Alternative preparation techniques exist for the production of an atomically clean photocathode surface under vacuum; for example, in-situ cleaving of the GaAs crystal or the use of arsenic capping layers. These are generally harder to implement experimentally than the standard technique outlined above.

7.4.3 NEA ACTIVATION AND LIFETIME

The established method for activation to NEA is known colloquially as the “yo-yo” technique. This involves the alternate deposition of caesium and oxygen upon the photocathode surface whilst simultaneously monitoring the photoinduced drain current. The photocurrent is maximised by deposition of caesium. A slight excess of caesium quenches the photocurrent. The photocurrent is then restored by admission of oxygen to the chamber, until once more it is quenched by a slight excess. The alternate dosing of caesium and oxygen is repeated until the photocurrent reaches a stable maximum level which is typically of the order of 10 μA.

The lifetime of the NEA state, defined as the time required for the quantum efficiency to fall to 1/e of its initial value, may range from a few hours to a few hundred hours. Continuous low level caesiation of the photocathode is required in order to achieve a long lifetime. Reactivation of the photocathode is normally possible if the vacuum has been maintained at better than 1 x 10⁻⁹.
mbar. However, contamination of the photocathode surface will ultimately necessitate that it be heat cleaned in order to restore optimum performance.

7.4.4 IMPROVING THE POLARISATION

The standard (100) GaAs surface is restricted to a theoretical polarisation of 0.50. In practice a maximum polarisation, at room temperature, of 0.25 is more realistic. This is due to depolarisation effects that arise from electron scattering within the crystalline structure of the photocathode. Nevertheless, the polarisation may be improved in a number of ways.

Depolarisation effects are minimised at low temperature. Operation of a GaAs source with the photocathode cooled to 77 K with liquid nitrogen increases the achievable polarisation to approximately 0.40.7

Similarly, depolarisation effects may be minimised by a reduction in the thickness of the GaAs layer, and thereby also of the path lengths of scattered electrons within the crystal. Deposition by molecular beam epitaxy of thin, high quality GaAs crystal films has enabled a polarisation of 0.49 to be achieved.7

However, this increase was achieved with a significant reduction in quantum efficiency as most of the incident radiation was absorbed by the substrate.

The fundamental restriction of the polarisation to an absolute maximum of 0.50 may be overcome through band bending of the light hole and heavy hole bands of the valence band maximum of GaAs. This removes the degeneracy of these two states, permitting a theoretical maximum polarisation of 1.00. This effect is best achieved by the introduction of a degree of strain in the crystal structure of the photocathode layer. Many combinations of materials have been investigated in the course of efforts to optimise this effect, and polarisations as high as 0.90 have been reported.7,10,11

The standard GaAs source configuration utilises the (100) surface of GaAs which, in conjunction with illumination at 800 nm, typically produces an electron
beam with a polarisation of approximately 0.20 - 0.30 and a quantum efficiency of between 1 and 10 %. The polarised electron beam current can be 10 μA or more and is normally stable and reproducible. This performance is sufficient for purposes of polarimeter calibration. The use of advanced, complex and expensive techniques to improve polarisation are not thought at this stage to be appropriate.
7.5 THE DARESBURY POLARISED ELECTRON SOURCE

7.5.1 DESIGN

The design of the source is due to Professor Gay of the Physics Department at the University of Nebraska, Lincoln, USA. He has many years of experience in designing and operating GaAs polarised sources, principally for use in experimental molecular physics applications.

The primary design requirement was for the source to be easily configurable to give either transversely or longitudinally polarised electron beams. Simplicity of construction and operation was achieved by the use of as few electron optical elements as possible. Furthermore, experience has shown that it is difficult to achieve reliable performance with sources that are small in size. Therefore the overall size of the Daresbury source was deliberately kept relatively large. A schematic of the electron optics of the source is shown in Figure 7.5. The GaAs crystal holder, mounted on a rotary feedthrough, may be located in either a horizontal or vertical position for provision of transversely and longitudinally polarised electrons respectively. Illumination of the sample with polarised light is achieved either directly from above, or indirectly from the side after reflection from the polished inner surface of the final lens element. Caesium may be applied using electrically activated dispensers \(^{7.12}\), whilst oxygen may be applied via a gas line system.

The electron optical elements, with the exception of the crystal holder, are all mounted on two shafts bolted into one of the flanges of a six way cross. The lens elements are separated by suitable insulating spacers. It is intended that the source will operate with a p-type, zinc doped, GaAs(100) crystal surface as the electron source; a carrier concentration of the order of \(2 \times 10^{19} \text{ cm}^{-3}\) is required. Such crystals may be obtained readily from commercial sources \(^{7.13}\). Illumination with polarised light will be provided by a Lasiris DLS-500 laser, with an output of 50 mW at a wavelength of 780 nm. Polansation reversal will be
achieved with a liquid crystal variable retarder, model no. LVR-100, manufactured by Meadowlark Optics.

![Diagram](image)

Figure 7.5. Sectional assembly drawing of the source electron optics.

### 7.5.2 CONSTRUCTION

The electron optics of the source are manufactured entirely from non-magnetic stainless steel. The source optics are mounted within a six way cross with 6 inch conflat flanges. The six flanges of the source chamber provide variously for: pumping; rotation of the crystal; electrical feedthroughs for electron optics, heater, thermocouple and caesium; viewports for laser illumination; and output of the polarised electron beam. Pumping is achieved by a Varian MacroTorr 70 turbomolecular pump backed by an Edwards 18 l s\(^{-1}\) rotary pump. The entire apparatus is mounted on a dedicated mobile frame; total dimensions do not exceed 0.75 m (width) x 0.75 m (length) x 1.50 m (height).
7.5.3 ELECTRON OPTICAL MODELLING OF THE SOURCE DESIGN

The lack of rotational symmetry of the source design required that electron optical modelling be performed with a more advanced software program than that used, as discussed in Chapter 5, for the design of the Hybrid Polarimeter. SIMION v6.0 \(^7.14\), as against SIMION v4.0, was therefore employed for this purpose.

The objective of the modelling was to find electron optical lens potentials, for both source configurations, that would focus as many electron trajectories as possible into an on-axis beam of minimum divergence. Initial lens potentials were chosen through intuition, and then iterated to final optimum values by examination of their effects upon the above electron trajectories in the SIMION model of the source.

Modelling was performed for both longitudinal and transverse configurations of the source. For both configurations the electron trajectories utilised within the models originate on the surface of the photocathode. All the illustrations that follow correspond to eleven electron trajectories emerging from a diagonal line across the crystal surface. This line is 0.10 inches in length with the trajectories separated by 0.01 inches, as shown in Figure 7.6. The trajectories are all initiated perpendicular to the photocathode surface. This set-up provides effective modelling for both on- and off-axis electron trajectories. An initial electron kinetic energy of zero eV was chosen for all modelling.
The original design required only one lens element, the second from the left in Figure 7.5, to be split for purposes of vertical deflection of the electron beam. The SIMION modelling showed at its earliest stages that this system was not viable. In the transverse configuration, a single split lens was unable to provide sufficient focusing to maintain a non-divergent beam. Suitable vertical deflection is only achievable with both the second and third lens elements split into two, as illustrated in Figure 7.5. The split third lens enables control over both beam divergence and beam direction.

The dimension of the SIMION model along the axis of the beam was set at 400 mm. This corresponds to source to target distances of 300 mm and 310 mm for the transverse and the longitudinal modes of operation respectively, the difference arising in consequence of the variable geometry involved. These distances are representative of the experimental arrangements in which the instrument is likely to operate. In all models a small positive potential applied to the final lens element provides useful focusing control over the electron trajectories. In any case the modelling demonstrated that, over any reasonable path length of the beam, suitable adjustment of the split lens potentials is possible.
7.5.3.1 Longitudinal Polarisation Configuration

The SIMION model of the source in its longitudinal configuration is illustrated in Figure 7.7. This view of the source also illustrates the final optimised lens potentials, in volts, applied to each of the electron optical elements.

Figure 7.7. Vertical section through the SIMION model of the source in its longitudinal configuration. Optimised lens potentials are quoted in volts for all lens elements.

Figures 7.8 and 7.9 illustrate, in on-axis vertical and horizontal sections, the electron trajectories corresponding to the optimised lens potentials. Twenty electric field contours are also shown; these are equispaced across the range of applied potentials. It should be noted that these two views do not illustrate any information not contained within the vertical and horizontal sections; only the portions of trajectories that run along these sections are visible.
Figure 7.8. Vertical section illustrating twenty equispaced electric field contours and the eleven electron trajectories.

Figure 7.9. Horizontal section illustrating twenty equispaced electric field contours and the eleven electron trajectories.

Figure 7.10 shows a three-dimensional view of the electron trajectories alone, with the structure of the model removed. This view shows every electron trajectory in full.
Figure 7.10. Three dimensional view of the electron trajectories alone.

7.5.3.2 Transverse Polarisation Configuration

The SIMION model of the source in its transverse configuration is illustrated in Figure 7.11. This view of the source also illustrates the final optimised lens potentials, in volts, applied to each of the electron optical elements.

Figure 7.11. Vertical section through the SIMION model of the source in its transverse configuration. Optimised lens potentials are quoted in volts for all lens elements.
Figures 7.12 and 7.13 illustrate, in on-axis vertical and horizontal sections, the electron trajectories corresponding to the optimised lens potentials.

Figure 7.12. Vertical section illustrating twenty equispaced electric field contours and the eleven electron trajectories.

Figure 7.13. Horizontal section illustrating twenty equispaced electric field contours and the eleven electron trajectories.
Again twenty electric field contours are also shown, equispaced across the range of applied potentials. Likewise it should be noted that these two views do not illustrate any information not contained within the vertical and horizontal sections.

Figure 7.14 shows a three-dimensional view of the electron trajectories alone, with the structure of the model removed. This view shows every electron trajectory in full.

Figure 7.14. Three dimensional view of the electron trajectories alone.

7.5.3.3 Discussion

The SIMION modelling, for both configurations, demonstrates that the source design provides good beam focusing and directional control. For the longitudinal configuration all electron trajectories, that originate within 0.05 inches of the photocathode centre, can be focused to within 0.10 inches of the desired beam axis over a 300 mm path length. For the transverse configuration, more than 50 % of the electron trajectories can be focused to within 0.10 inches of the beam axis. These results demonstrate clearly that the current design is viable for both longitudinal and transverse source configurations.
7.6 CONCLUSIONS AND FUTURE WORK

GaAs based polarised electron beam sources are ideal for polarimeter benchmarking and calibration purposes on account of their adequate polarisation of 0.20 - 0.30, their high beam currents of 10 μA or more, and their stability and reproducibility. This type of source is thoroughly proven in concept, and is in use in a number of spin polarised electron spectroscopy laboratories throughout the world.

A source of this type is under construction by the SPS group at the Daresbury Laboratory. Specifically a dual configuration instrument, capable of producing either longitudinally or transversely polarised electron beams, has been designed using SIMION v6.0 electrostatic lens modelling software.

All structural components of the source have been manufactured, and all ancillary equipments have been delivered, permitting assembly of the complete instrument. The source currently awaits successful vacuum testing. This will be followed by the introduction of a GaAs photocathode into the source optics, conditioning of the chamber with caesium and oxygen, and preliminary attempts to obtain an electron beam from the NEA activated crystal. Once a satisfactory beam performance has been obtained, the polarised incident light system will be commissioned. The resultant polarised beam parameters will then be investigated through measurements with a Micro-Mott polarimeter.
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APPENDIX A

THE CONCENTRIC HEMISPHERICAL ANALYSER

The physics of the CHA has been described in detail by Purcell ^1^ . Briefly, a CHA functions through the energy dispersive properties of the $1/r^2$ electrostatic field between two concentric hemispherical electrodes. Electrons traversing the analyser describe circular or elliptical orbits between these electrodes. A basic CHA consists of inner and outer hemispheres of radius $R_1$ and $R_2$, held at potentials of $V_1$ and $V_2$ respectively, as illustrated in the schematic of Figure A1.

![Figure A1. Schematic illustration of a concentric hemispherical analyser.](image-url)
Electrons are injected tangentially, mid-way between the hemispheres at the mean radius $R_0$. Electrons possessing the selected energy, $E_0 = eV_0$, will pass successfully through the instrument if $^{A2}$:

$$V_1 = V_0 \left[ 3 - 2 \left( \frac{R_0}{R_1} \right) \right]$$

and

$$V_2 = V_0 \left[ 3 - 2 \left( \frac{R_0}{R_2} \right) \right]$$

Electrons with energy $E_0$, if emitted from a point source at $S$, will all be focused upon the exit plane at $F$, regardless of the plane of their trajectory.

The resolution, $\frac{\Delta E}{E_0}$, of the instrument is given to first order by:

$$\frac{\Delta E}{E_0} = \frac{W}{2R_0}$$

where $W$ is the width of the entrance and exit slits.

The passband, $\Delta E$, of a CHA is a linear function of transmitted energy $^{A3}$. Therefore the energy resolution may be improved by retardation of the incident electrons prior to their entering the analyser. This preretardation is set in practice by the potential applied to the fringe field optics at the input and exit planes of the analyser. The fringe field also serves to subject the transmitted electrons to a uniform acceleration as they pass through the analyser.

The scanning of the electron kinetic energy is achieved in one of two modes; fixed analyser transmission (FAT) or fixed retardation ratio (FRR). The Micro-Mott 2 is operated normally with the CHA in the FAT mode, providing constant instrumental transmission and energy resolution irrespective of the selected kinetic energy. This is achieved by variation of the preretardation of the electron beam entering the analyser. The pass energy, $E_0$, may be selected from a range of values. A high pass energy provides an improved transmission at the expense of resolution. In the FAT mode it is important to note that the
analysed area of the sample and the emission angle of the electrons vary slightly with their kinetic energy.

The FRR mode is achieved by adjustment of the pass energy $E_0$ such that electrons entering the analyser are retarded by a constant proportion of their kinetic energy. In the FRR mode the energy resolution is inversely proportional to the selected kinetic energy; however, the analysed area of the sample remains constant.

A1  E. M. Purcell; Phys. Rev. 54, p818 (1938)
APPENDIX B

THE MICROCHANNEL PLATE Detector

The detectors deployed on Micro-Matt 2 are microchannel plate (MCP) devices manufactured by Hamamatsu, model number F1551-21S. These are twin plate devices mounted in a back-to-back, or chevron, configuration as illustrated in Figure B1.

![Microchannel Plate Detector Diagram](image)

Figure B1. Schematic section through a microchannel plate detector; an electron cascade is illustrated.

An MCP is made up of a two-dimensional array of millions of glass capillaries, or channels, that are fused together and sliced into a thin disc. The channels are typically several micrometers in diameter and less than one millimetre in length. The inside surfaces of the channels are processed such that they behave as a scintillator; an incident charged particle initiates a secondary electron cascade upon impact with the channel surface. Electron cascades are accelerated along the length of the device by a large potential difference held across its input and output planes. Further collisions with the channel walls amplify the cascading charge such that a single incident electron results in a charge pulse of sufficient amplitude to be counted by conventional...
electronics. The outgoing pulse is normally collected by a biased anode situated behind the second plate. The channels are inclined by between 5 - 15° to the input plane normal in order that the MCP will function for normally incident radiation. The deployment of two MCP devices, in a chevron configuration, acts to prevent quenching of electron cascades by ionic feedback.

MCP detectors offer compact detection of electrons with high efficiency, whilst maintaining a low dark count rate of typically less than 3 s⁻¹. They are further capable of detection of positively charged particles and electromagnetic radiation, such as ultra-violet or X-ray photons. It should be noted that the detector efficiency varies with incident electron energy; electrons with energies in the range 0.2 to 2 keV are detected with 50 to 85 % efficiency B2. Detection efficiency is also sensitive to the angle of incidence. The F1551-21S type MCP provides a gain in signal intensity of 10⁶ when operated with an applied potential of 1500 V.

B1 Hamamatsu Photonics Technical Information; Hamamatsu Photonics K. K., Shimokanzo, Iwata-gun, Shizuoka-Ken, 438-01, Japan
B2 F. Bordoni; Nucl. Inst. Meth. 97,p405 (1971)
APPENDIX C

SPECIFICATION AND CIRCUIT DIAGRAM OF THE TRANSMISSION MODE POWER SUPPLY UNIT

1) Eight low voltage channels are required, referenced to the kinetic energy rail of the HAC 300. These must be manually adjustable between 0 to +48V. Include link facility to improve the setting resolution at later date, when the required potentials have been precisely identified. The power supply ripple is to be less than 5mV.

2) One of the above eight supplies is to be switchable between the manual setting mode, and a PC controlled mode via a DAC card.

3) All eight supplies are to be monitored via a DVM that is built into the supply case. This DVM is to be switchable between all eight supplies, allowing identification of applied potential to within 200mV.

4) A manually set high voltage supply is to be included, referenced to ground, to allow operation of a channeltron. This is to be based on a simple potential divider, 1MΩ/10MΩ, providing 200V to the channeltron neck and 2.2kV to the channeltron body respectively. The supply must be able ultimately to deliver 30kV to enable extended operation of an ageing channeltron.

5) The setting of the high voltage supply is to be monitored via a second DVM.

6) Outputs are to be via MHV or SHV coaxial connectors.

7) A mains indicator light is required.
Figure C1. Circuit diagram of the transmission mode power supply unit.
Amorphous alloys as secondary standards for electron spin polarimetry

E A Seddon†, A E R Mallin‡, M Petty§, M D Crapper‡, I R M Wardell¶‖, A K Hide‖, M Hardiman‖, Y B Xu++, P Hucknall*, D Greig*, S Clowes# and E M McCash#

† CLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, UK
‡ Loughborough University, Loughborough, Leicestershire LE11 3TU, UK
¶ Physics and Astronomy Division, University of Sussex, Brighton BN1 9QH, UK
‖ Department of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
# Chemistry Department, The University of York, Heslington, York YO1 4DD, UK

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Abstract. The surface magnetism of as-cast and field annealed amorphous CoMFeNiB14Si15 in ribbon form has been studied by spin-polarized secondary electron spectroscopy, by recording energy-resolved spin asymmetry hysteresis loops and by scanning electron microscopy with polarization analysis. Large lateral variations in surface magnetization have been detected, indicating that CoMFeNiB14Si15, in particular, and ferromagnetic melt-spin ribbons, in general, are not suitable as standard sources of polarized electrons. Deposition of an iron film onto the CoMFeNiB14Si15 did not result in a more uniform surface but rather served to emphasize the substrate magnetic structure. Thus utilization of ferromagnetic melt-spin amorphous alloys as substrates for the growth of thin magnetic films should be undertaken with caution.

Keywords: spin polarization of photoelectrons, spin polarized secondary electron spectroscopy, spin asymmetric hysteresis, SEMPA, surface magnetism

1. Introduction

During the last 5 years the use of spin-resolving, low-energy electron spectroscopy has expanded, leading to a demand for a reliable, easy-to-use, standard source of polarized electrons for polarimeter calibration. The use of GaAs-based polarized electron sources is becoming more widespread, but they are not yet easy to use owing to the artistry required in generating a negative-electron-affinity surface and the sensitivity of this surface to contamination.

Since the overall efficiencies of polarimeters are always rather low, an attractive option is to use the relatively high polarization and intensity of the secondary electron (SE) cascade from a ferromagnet. To a first approximation, this polarization is proportional to the magnetization and hence the sample must be uniformly magnetized in order that the polarization is independent of the position across the surface. Although the SE polarization emission spectrum has been measured accurately for single-crystalline Fe [1], the fine structure in this and the complications introduced by the use of single crystals have prompted a search for a more convenient standard.

As early as 1987, Hopster had suggested that commercially available Fe–B-based ferromagnetic amorphous metal ribbons (e.g. Fe22B12Si6, Fe60Ni20B20 and Fe44Ni17B19) could be used as ‘calibrated’ spin-polarized electron sources [2]. These materials have many advantages; they can be conveniently mounted as closed loops which are easy to magnetize and give minimal stray fields, the isotropic SE emissions have high polarizations which vary smoothly with energy and the surface cleaning is very simple. However, these Fe-based materials have moderate-to-high magnetostriiction coefficients and thus, in the as-cast (strained) state, they exhibit rich domain structures [3,4] which are strongly influenced by any subsequently applied stresses [5,6]. The anisotropies induced by stress can be very large and it is difficult to produce samples with a spatially uniform magnetization, even when the sample is apparently magnetically saturated. We have reported previously [7] that amorphous Fe60B20 in the as-cast state exhibits strong local variations in SE polarization which are clearly incompatible with its use as a standard. Field annealing of the Fe-based materials can improve their magnetic homogeneity [8–10], but the procedures are highly material specific and there is often a degree of recrystallization, rendering them brittle.
More recently, Klebanoff has advocated the use of unannealed (as-cast) amorphous Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} ribbon as a polarized electron standard [11]. Although the SE polarization from this material is only about a third that from the high-concentration Fe-based alloys (corresponding to the differences in saturation magnetization), the Co-based alloys close to this composition have essentially zero magnetostiction and so might be expected to be easily saturated to a uniformly magnetized state.

Another role for amorphous ribbons is as substrates for the deposition of thin magnetic films [12,13] In this case the strong exchange coupling between the film and the easily magnetized substrate can be used to magnetize the deposited film. We report here on the feasibility of using Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} ribbon for each of the above purposes Measurements both on the as-cast and on field-annealed material were made using spin-polarized secondary electron spectroscopy (SPSES) and SEMPA (scanning electron microscopy with polarization analysis).

2. Experimental details

Amorphous ribbon samples of Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} (Alhed Signal Inc) were used either as-cast or after field annealing at 0.08 T under flowing argon at temperatures of up to 350 °C for 5 min. For each type of experiment, 5 mm wide strips were cut parallel to the long (roll) axis of the ribbon and these were then formed into closed loops with the overlapping ends clamped together. The samples were arranged with the shiny (air) side outwards and they could be magnetized in the longitudinal direction of the loop by passing a current through a small coil wrapped around the strip.

The SPSES experiments were performed on Station 61 of the Synchrotron Radiation Source (SRS), which was designed for UHV (base pressure 2 × 10^{-10} Torr) photoemission work over the photon-energy range 80–180 eV. As a consequence of the baking out of the experimental chamber, all samples measured in it were subjected to a heating cycle after mounting (135 °C maximum). Emission was stimulated either with 135 eV photons or with 1.6 keV electrons, in each case at near glancing incidence (5–10°) and with incident beam diameters of about 0.5 mm. The spin polarization at normal emission was measured with a 'microMott' polarimeter mounted at the exit of a rotatable 50 mm radius hemispherical electron-energy analyser. Four data-acquisition channels allowed the simultaneous determination of two mutually perpendicular polarization components, \( P_{\text{Long}} \) and \( P_{\text{Trans}} \), which are defined as longitudinal and transverse with respect to the long axis of the ribbon (both components are in the surface plane). The asymmetry, \( A \), the directly measured parameter in a spin polarimeter, is related to \( P \) by \( A = S_{\text{eff}} P \) and the instrument was operated with an effective Sherman function, \( S_{\text{eff}} \), of 0.12. This equipment has been described in detail elsewhere [14]. The SPSES data were recorded either as asymmetry spectra, \( A_{\text{Long}}(E) \), from samples in a fixed magnetic state, or as energy-resolved (asymmetry) hysteresis loops (ERHL), \( A_{\text{Long}}(I) \), by using SEs with well-defined kinetic energies, \( E_{k} \). Before the SPSES measurements, the samples were cleaned \textit{in situ} by argon-ion etching for a period of at least 2 h. This resulted in a minimization (to less than about 5%) of the C and O impurity levels detected by Auger spectroscopy.

The SEMPA images were obtained in a separate apparatus using a 1 nA unpolarized 5 keV primary electron beam focused to a 5 μm spot. Secondary electrons of energies up to about 60 eV were collected at near-normal emission and their longitudinal (with respect to the ribbon) polarization component measured in a 20 keV retarding field Mott detector (with \( S_{\text{eff}} \approx 0.14 \)) and of similar basic design to that utilized above. Data were obtained as 128 × 128 pixel \( A_{\text{Long}}(x,y) \) images with a dwell time of 150 ms per pixel, as line scans, \( A_{\text{Long}}(x) \), and as fixed position (spot-mode) \( A_{\text{Long}}(I) \) hysteresis loops. The SEMPA apparatus is described in more detail elsewhere [15].

3. Results and discussion

The spin-integrated photoemission spectrum of the valence band and a 30 eV ERHL for Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} have been reported previously [12]. We have measured the secondary electron polarization spectrum, \( P(E_{k}) \), of this material at the SRS on a number of occasions, using either electron or photon excitation, and have consistently found the usual increase in polarization below 10 eV. However, the unexpected presence of a significant transverse asymmetry component indicated that the mean magnetization of the area probed was not collinear with the longitudinal axis of the ribbon. This prompted a more detailed investigation of lateral variations in spin asymmetry.

Our first studies of the uniformity of the ribbons were made by recording electron-excited ERHLs at various positions along the transverse (short) axis of a sample; typical results for the as-cast material, taken at 1 eV, are shown in figure 1. Clearly, these loops reveal considerable variations in squareness, symmetry about zero field, coercive field and, most importantly, in the asymmetry changes \( \Delta A_{\text{Long}}(I) \) and \( \Delta A_{\text{Trans}}(I) \). At only one position do the latter two parameters have values close to the expected ones of about ±0.017 and zero, respectively. This exercise was repeated but using 135 eV photons as the primary excitation source and selecting 0.5 eV SEs. Similar lateral variations were observed, see figure 2, indicating that the problem is unrelated to the particular excitation source used. It is also unlikely that the variations are related to the topmost surface layer since ERHLs taken at these very low \( E_{k} \) values are more representative of the bulk [16]. We have attempted to make magneto-optical Kerr effect (MOKE) measurements on Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} ribbon in the same manner as reported for Fe_{90}B_{20}, however, it proved impossible to obtain hysteresis loops from this material.

In order to investigate the fine-scale spatial variation of the magnetization in the as-cast state, SEMPA data were obtained from this material. Figure 3 shows a sequence of images from the same 1.9 mm × 2.6 mm area in different magnetic states. The middle two panels are of the remanent state and show clearly that the upper portion of the imaged area of this particular (closed loop) sample is demagnetizing at zero magnetizing current. We note especially that the streak-shaped region at the very top of these images is always antiparallel to its surroundings in the remanent state. This
Amorphous alloys as secondary standards

Figure 1. Transverse and longitudinal ERHLs at 1 eV for as-cast Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} obtained using 1.6 keV primary electrons. The errors in this and the following figures are comparable in magnitude to the size of the data points.

Figure 2. Transverse and longitudinal ERHLs at 0.5 eV for as-cast Co_{66}Fe_{4}Ni_{11}B_{14}Si_{15} obtained using 135 eV photons.

Incorrect, since the magnetization direction remains fixed over a large proportion of the imaged area, independent of the magnetizing current direction. In particular, the bottom right-hand corners of both these images (and also of the remanent state images) are largely white, so a spot-mode hysteresis loop from most points within this area would not exhibit any significant change in asymmetry with applied current. (Although this region is predominantly blocked in the positive direction, there are some changes occurring on a finer length scale, indicated by the appearance of some reverse-oriented regions in the positive 'saturated'-state image.) It is clear that, despite the very low magnetostriction of this material, there is significant frozen-in anisotropy in its as-cast state which cannot be overcome at 50 times the apparent coercive field.

These SEMPA data are qualitatively similar to those we obtained from as-cast Fe_{80}B_{20} [7], although in that case there was little difference between the remanent- and 'saturated'-state images. Both sets demonstrate graphically
Figure 3. SEMPA images $A_{\text{Long}}(x, y)$ from an as-cast sample of Co$_{65}$Fe$_{4}$Ni$_{7}$B$_{14}$Si$_{15}$. Negative (a) and positive (d) "saturated" state images, respectively, recorded with the maximum magnetizing current (0.5 A) applied to the sample. Negative (b) and positive (c) remanent-state images, respectively, taken with zero magnetizing current. The longitudinal (roll) axis is indicated by the double-headed arrow and XX shows the direction of the linescans of figure 4.

Figure 4. (a) Asymmetry line scans $A_{\text{Long}}(x)$ along the line XX in figure 3 for the positive (full line) and negative (broken line) remanent states. (b) Spot-mode hysteresis loops $A_{\text{Long}}(I)$ at three points along the line XX. The vertical scale is common to both sections.

the problems involved in using either the remanent or (apparently) saturated states of as-cast metglas ribbons as polarization standards for electron spectroscopy, particularly when broad-beam techniques are used.

In an attempt to improve the magnetic homogeneity of the sample, field annealing of pre-cut ribbons was carried out to temperatures below the crystallization temperature of the alloy. The field was applied parallel to the long axis of the sample once it had reached the annealing temperature and was removed only when the sample had cooled to below the Curie temperature. Field annealing has been applied to nanocrystalline Fe$_{73}$Cu$_{17}$Nd$_{1}$Si$_{13}$, for example, and shown to result in squarer hysteresis loops [17]. Figure 5 presents electron-excited ERHIs from the field-annealed material which still reveal large lateral variations in polarization. There is evidence that there has been a slight improvement in homogeneity, leading to squarer loops and slightly higher asymmetry amplitudes over some of the sampled areas. However, there are still areas where the amplitude is very small and the data from areas with large values of $A_{\text{Long}}$ also have significant $A_{\text{Trans}}$. This is further demonstrated clearly by the asymmetry spectra $A_{\text{Long}, \text{Trans}}(E_t)$, given in figure 6, which are very similar to those from as-cast samples. In particular, a large transverse asymmetry is still observed at low secondary electron energies.

We have also investigated the possibility of achieving a reproducible asymmetry by deposition of a thin film of iron onto the surface of unannealed Co$_{65}$Fe$_{4}$Ni$_{7}$B$_{14}$Si$_{15}$. Although this approach lacks the simplicity of a single ribbon sample as a source of polarized electrons, it is still easier than the use of a single-crystalline sample or a negative-electron-affinity polarized electron source. This experiment also has
structure due to locked-in anisotropy. The lateral scale of these structures is larger and they are less complicated than those found in the high-concentration iron metglasses, but in both cases they have clear correlations to the roll direction and they change after annealing. In the light of Flanders and Monto's observation [19] of creep-induced anisotropy in Co66Fe4Mo2Si16B12, a material which exhibits zero (bulk) magnetostriiction, we therefore attribute the locked-in anisotropy we observe at the surface of Co66Fe4Ni1B14Si15 to residual strains resulting both from the melt-spinning fabrication process itself and from forming the material into a closed loop (which is necessary in order to minimize stray magnetic fields). We are at present unable to ascertain to what extent such anisotropy persists away from the surface.

4. Summary

The secondary electron polarizations of Co66Fe4Ni1B14Si15, in particular, and melt-spun amorphous ribbons, in general, are strongly position dependent, indicating that they are not suitable as standard sources of polarized electrons. Deposition of iron onto the ribbons does not result in a more magnetically uniform surface—rather it serves to emphasize the substrate magnetic structure—thus utilization of ferromagnetic melt-spin amorphous alloys as substrates for the growth of thin magnetic films should only be undertaken with caution.

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References

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THE POLARIMETER DEVELOPMENT PROGRAMME AT CLRC
Daresbury Laboratory

Andrew F. R. Malins, Elaine A. Seddon, Michael D. Crapper

(1) Physics Department, Loughborough University, Loughborough, UK
(2) CLRC Daresbury Laboratory, Warrington, UK

ABSTRACT
A novel polarimeter for full 3D analysis of electron spin polarisation is described. This instrument will be sensitive to transverse electron spin polarisations through Mott scattering and to longitudinal polarisations through spin dependent electron transmission in an ultrathin cobalt film. The figure-of-merit ($S^2_{\parallel}/I_0$) of the instrument, for transverse measurements, is expected to be approximately $1 \times 10^{-4}$. The figure-of-merit for longitudinal measurements is expected to be between $5 \times 10^{-4}$ and $1 \times 10^{-4}$.

INTRODUCTION
The existing facilities for spin polarised electron spectroscopy at Daresbury Laboratory are all Mott-scattering based systems. These are respectively: a 100kV conventional Mott polarimeter on Beamline 1.2 of the Synchrotron Radiation Source (SRS), a 20kV conical retarding potential polarimeter known as “MicroMott-1” and a 20kV spherical retarding potential polarimeter known as “MicroMott-2”. Each of these three instruments has four backscattering detectors allowing determination of the two transverse components of the electron spin polarisation. Mott scattering is insensitive to longitudinal spin polarisations and there are, as yet, no facilities on the SRS for analysis of these.

DESIGN OF A THREE-AXIS ELECTRON SPIN POLARIMETER
Full polarisation analysis of electron beams has to date required either the use of a “switchyard” of two polarimeters or the introduction of some electron optical means to convert the longitudinal spin polarisation component to a transverse one. This latter has conventionally been achieved through the use of a 90 degree spherical sector or the crossed E and B fields of a Wien filter. However, such spin rotation systems involve increased complication of the experimental geometry and deterioration of the electron beam quality. An alternative less intrusive means of achieving a full analysis of electron polarisation is therefore desirable. We have undertaken an adaptation of MicroMott-2 that will enable it to operate in two modes: a high voltage scattering mode in which the two transverse polarisation components are measured at a low voltage transmission mode in which the longitudinal component is measured. Thus, by two measurements - on one piece of equipment - both transverse and longitudinal spin polarisations can be analysed. The full spin analyser is known as the “Hybrid Polarimeter”. The design of the adaptation is based upon the results of experimental work by Lampel and workers on electron transmission through ultrathin ferromagnetic layers exhibiting pendendicular anisotropy [1,2,3]. By careful work on self-supporting Au/Co/Au films they showed at the inclastic mean free path for very low energy transmitted electrons is spin dependent. Thus demonstrating longitudinal electron spin filtering, addition to a small change to the input lens stack of MicroMott-2 (including inclusion of x/y reflector plates to enable beam steering) the thick gold scattering foil has been replaced by a thin and 20Å thicknesses respectively. This self-supporting thin film structure, or “trilayer”, sits on a 3mm diameter aperture and a solenoid immediately to its rear enables reversal of the magnetisation of the cobalt layer. Electrons transmitted through the trilayer are energy analysed in a compact retarding field analyser prior to detection by a channeltron detector. The design includes various dispensing devices to enable activation of the rear gold surface of the trilayer to negative electron affinity. Such activation significantly increases both the transmission and measured asymmetry of the instrument. The longitudinal electron spin analyser design is based on an incident beam energy range of 1 to 12eV, since it is within this range of operating energies that both transmission and measured asymmetry are found to be a maximum. The electron optics of the hybrid polarimeter have been modelled using SIMION version 4.0 ray-tracing software [4].

Satisfactory electrostatic lens potentials have been calculated for both modes of operation. In the high energy mode the electrons are scattered from the thick front-face gold layer and spin sensitivity arises through the spin-orbit term in the scattering potential [5]. In the low energy transmission mode the spin sensitivity arises from exchange coupling in the cobalt layer.

CURRENT STATUS
All of the components for the Hybrid Polarimeter have now been fabricated and it is expected that the instrument will be assembled by October 1998. Commissioning will be undertaken using a GaAs polarised electron source.

CONCLUSION
The Hybrid polarimeter has the potential to enable the determination of all three components of the electron spin polarisation with one piece of equipment. The figure-of-merit ($S^2_{\parallel}/I_0$) for transverse spin measurements is expected to be approximately $1 \times 10^{-4}$. The figure-of-merit for longitudinal measurements is expected to be between $5 \times 10^{-4}$ and $1 \times 10^{-4}$, depending on whether or not caesium is used.

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