

Pushing the Boundaries of Condensed Matter
Electron Momentum Spectroscopy

A thesis submitted for the degree
of Doctor of Philosophy of
the Australian National University

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This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text.

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Abstract

An electron momentum spectrometer at the Australian National University has been used to study various aspects of different solid state systems. EMS is a transmission mode technique and involves the collision of the incident electron with a bound electron, after which both electrons are ejected and measured in coincidence. Through well defined reaction kinematics the complete valence spectral momentum density ($A(\epsilon, \mathbf{q})$) can be measured. The spectrometer has been used to measure the spectral momentum densities (spectral functions) of single crystal targets, as well as targets in disordered states. A new spin polarised electron source was constructed and implemented in the ANU spectrometer, which was used to measure spin dependent features of ferromagnetic samples.

This thesis is divided into seven chapters, the first chapter is an introduction into the field of electron momentum spectroscopy, highlighting what has been measured before and how the technique has progressed to its present state. Some comparisons to other experimental techniques will be made.

The second chapter describes the ANU EMS spectrometer in detail. The technique requires some technical and advanced equipment that is often used in novel ways. The production of thin (20 nm) free standing targets will be detailed, along with the experimental chamber and electronics used to run the apparatus and collect data. The determination of the energy and momentum resolution of the experiment is also described.

The third chapter will detail the design and construction of the new spin polarised

electron source. The results of commissioning and characterizing the new source will be presented.

Chapters four through six will present the measured results. The fourth chapter will detail the single crystalline measurements for the group eleven noble metals (Cu, Ag and Au). Each sample was measured along three high symmetry directions and compared to a DFT calculation using the LDA and a FP-LMTO basis. The fifth chapter will include the results from samples that were in disordered states, a measurement which is unique to the EMS technique. The polycrystalline and amorphous states of the Si and Ge semiconductors are presented and conclusions are made to the degree of difference in the results and to which theoretical approach to the unique amorphous state of the semiconductors best matches the EMS results. The sixth chapter includes results of ferromagnetic iron, measured using the spin polarised electron source. The spectrometer was used to measure spin-polarised electron-energy-loss-spectroscopy (SPEELS) and magnetic electron-Compton profiles. A theoretical investigation is also presented in chapter six which details the advancements required in the spin polarised electron gun to measure an accurate spin-polarised EMS spectra of a ferromagnetic Fe sample.

Chapter 7 includes the summary of all the results presented and conclusions reached from the comparison of the measured EMS spectra and various theoretical calculations. A discussion is presented about the future directions and possibilities of the EMS technique.

Glossary of Abbreviations

The following tables contain a majority of the abbreviations and variables used throughout this thesis. It is intended for readers to have a quick point of reference, to avoid the need to unnecessarily repeat definitions throughout the text.

abbrev.	definition	abbrev.	definition
(e,2e)	electron interaction, 1 incident, 2 emitted electrons	FWHM	full-width-half-maximum
(p,2p)	proton interaction, 1 incident, 2 emitted protons	HV	high voltage
amC/a-C	amorphous carbon	IPA	independent particle approximation
ANU	Australian National University	LCR	liquid crystal retarder
AREDC	angular-resolved energy-distribution -curve	LDA	local density approximation
ARPES	angular-resolved photoemission spectroscopy	linear-DOS	linear density of states
au	atomic units	LSDA	local spin density approximation
BCC	body-centred cubic	MCP	micro-channel plate
BZ	Brillouin zone	MFP	mean free path
CFD	constant fraction discriminator	NEA	negative electron affinity
CP	Compton profile	PSD	position sensitive detector
CRN	continuous random network	PWIA	plane wave impulse approximation
DAQ	data acquisition card	QE	quantum efficiency
DFT	density functional theory	RAE	resistive anode encoder
DOS	density of states	RGA	residual gas analyser
EELS	electron-energy-loss spectroscopy	RMS	root-mean-squared
EMS	electron momentum spectroscopy	SCCD	self-consistent charge density
eV	electron volt	SIC	self interaction correction
FCC	face-centred cubic	SMD	spectral-momentum density
FESEM	field-emission scanning-electron -microscope	SPEELS	spin-polarised electron-energy-loss spectroscopy
FP-LMTO	full-potential linear-muffin-tin-orbital	SPEMS	spin-polarised electron momentum spectroscopy
		TAC	time to amplitude convertor
		UHV	ultra high vacuum
		XPS	x-ray photoemission spectroscopy

Variable	Definition
$A(\boldsymbol{\varepsilon}, \mathbf{q})$	spectral momentum density
$e_{0,1,2}$	the incident and outgoing electrons
$E_{0,1,2}$	energy of incident and outgoing electrons
ε	binding energy of bound electron
$\varepsilon(\mathbf{q})$	band dispersion
$f(\mathbf{k}_0, \mathbf{k}_1, \mathbf{k}_1)$	scattering amplitude function
f_{ee}	spin-averaged Mott-scattering cross section
\mathbf{G}	the reciprocal-space lattice vector
$\Gamma - \mathbf{X}$	the 100 direction from a FCC sample in momentum space
$\Gamma - \mathbf{K}$	the 110 direction from a FCC sample in momentum space
$\Gamma - \mathbf{L}$	the 111 direction from a FCC sample in momentum space
$\Gamma - \mathbf{H}$	the 100 direction from a BCC sample in momentum space
$\Gamma - \mathbf{N}$	the 110 direction from a BCC sample in momentum space
$\Gamma - \mathbf{P}$	the 111 direction from a BCC sample in momentum space
$I(q_x, q_y)$	the momentum profile as measured by positron annihilation
$J(q_z)$	the Compton profile
$\mathbf{k}_{0,1,2}$	momentum of incoming and outgoing electrons
K	momentum transfer from incident electron to ejected electron
\mathbf{p}	momentum of residual target ion
\mathbf{q}	momentum of bound electron an instant before collision
$\rho(\mathbf{q})$	momentum distribution
$S(\vartheta)$	Sherman function
$S(E_s, \mathbf{p}_s)$	the solid target
$S^+(E_s, \mathbf{p}_s)$	the residual ion
T	transition matrix element
θ	polar angle of outgoing electrons in xz plane (44.3°)
$\phi_{1,2}$	azimuthal angles of 2 outgoing electrons in yz plane
$\phi_i(\mathbf{q})$	momentum space one-electron wavefunction of electron in orbital i