Synchrotron Calibration of Microchannel Plate Detectors
for X-ray Astronomy

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This thesis describes the calibration of CsI- and KBr-coated microchannel plate (MCP) detectors using the Daresbury Synchrotron Radiation Source (SRS). This work was carried out as part of the calibration programme for the Advanced X-ray Astrophysics Facility (AXAF). The AXAF High Resolution Camera (HRC) consists of two MCP detectors: HRC-I, optimised as an imaging detector, and HRC-S, optimised as the read-out detector for a dispersive spectrometer. Accurate knowledge of the MCP quantum efficiency (QE) variation with energy is particularly important for HRC-S so that atomic absorption edge-related features in the MCP glass and photocathode are not misinterpreted as emission features in astrophysical spectra.

The MCPs were calibrated on three beamlines at the SRS, which covered the energy ranges 50-350eV, 250-1400eV and 2-6keV. Calibration included measurement of QE as X-ray energy and incidence angle were varied. The ratio of the QE of CsI- and KBr-coated MCPs was also determined and gain decay of the MCPs was measured as charge was abstracted from a small area. Several significant features in QE were noted, a number of which exhibited characteristics such as white lines, slow onset and energy shifts. There were, however, problems with measurement of the monochromator responses at the SRS, which cast doubt upon the accuracy of the QE-energy curves produced.

The variation of QE with energy and angle measured at Daresbury was modelled. An existing model was updated to take account of the channel bias angle and was able to reproduce the general features of the QE-energy curves. An attempt was then made to model linear absorption coefficient and hence reproduce the white lines visible on some of the edge-related QE features.

The final part of the thesis considers and models the effect of thermal annealing upon the QE of CsI-coated MCPs.
Declaration

I hereby declare that no part of this thesis has been previously submitted to this or any other University as part of the requirements for a higher degree. Work described here was conducted by the undersigned except for the contribution of colleagues indicated in the text.

Sarah E. Pearce
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I would like to thank all those who have helped me during the past four years. Particular thanks to Ian, for his occasional support, to my parents, for their astonishment at my career choices and to my brother for his undying scepticism. Thanks also to Simon, Jo and Jacqui for many long coffee breaks, and to Matt, for his unknowing inspiration. Thanks to Jim, John, Adam, Tony and Adrian for the lively discussions on a Friday afternoon. And thanks, of course, to George, for all his help and patience.
Glossary

\( \alpha \) grazing angle of X-ray beam with respect to channel wall
\( \alpha' \) refraction angle for X-ray beam with grazing angle \( \alpha \)
\( \alpha_0 \) central coating angle
\( \alpha_K \) unit decrement in real part of dielectric constant
\( \beta \) unit decrement in complex part of index of refraction
\( \Gamma_0 \) intensity of incident X-ray beam
\( \gamma \) angle of X-ray incidence with respect to MCP front surface
\( \gamma_K \) unit decrement in complex part of dielectric constant
\( \delta \) unit decrement in real part of index of refraction
\( \delta_e \) mean number of secondary electrons emitted by collision
\( \epsilon \) energy required to create a secondary electron
\( \theta \) angle of X-ray incidence with respect to MCP channel axis
\( \theta_B \) bias angle of MCP
\( \lambda \) wavelength
\( \mu \) linear absorption coefficient
\( \mu_m \) mass absorption coefficient
\( \nu \) radiation frequency
\( \rho \) material density
\( \sigma_f \) fraction of energy lost through fluorescence
\( \sigma_{i,j} \) atomic absorption cross-section for atom \( i \), orbital \( j \)
\( \sigma_x \) fraction of energy lost through primary electrons escaping into channel
\( \chi_c \) current quantum yield
\( (\chi_p)_e \) pulse quantum yield due to primary electrons
\( (\chi_p)_s \) pulse quantum yield due to secondary electrons
\( (\chi_p)_T \) total pulse quantum yield
\( \psi \) azimuthal angle between plane of MCP rotation and plane of bias angle (Chapter 3)
\( \omega \) azimuthal angle of MCP channel wall strip (Chapter 5)
\( \phi \) radiation frequency
\( (\omega_{i,j})_k \) fluorescence yield of shell \( j \) of atomic type \( k \)
\( A_{eff} \) effective atomic mass
\( a_0 \) Bohr radius
ACIS-I AXAF CCD imaging spectrometer -imaging
ACIS-S AXAF CCD imaging spectrometer -spectroscopy
AXAF Advanced X-ray Astrophysics Facility
\( C(m) \) number of counts in PHD channel \( m \)
CGCD Crossed grid charge detector
\( D \) MCP channel diameter
\( d \) thickness of interaction region in channel wall (or of surface coating)
\( d_m \) horizontal offset of MCP centre from coating source
\( e \) electron charge
\( E_e \) energy of electron collision with channel wall
$E_f$  
energy of final atomic shell in a transition  
$E_i$  
energy of initial atomic shell in a transition  
$E_n$  
energy of atomic shell n  
$E_p$  
probability that primary electron will escape into channel and initiate an avalanche  
$E_x$  
incident X-ray photon energy  
EPIC  
European photon imaging camera (XMM)  
f  
fraction of energy available to create secondary electrons  
$f_p$  
fraction of incident flux absorbed in coated length of channel  
FWHM  
Full width half maximum  
$G_0$  
variation of coating thickness down central channel  
H  
coating depth down channel  
$H_0$  
coating depth down central channel  
$h_m$  
vertical distance of MCP above coating source  
HETG  
High energy transmission grating (AXAF)  
HRC-I  
High resolution camera - imaging (AXAF)  
HRC-S  
High resolution camera - spectroscopy (AXAF)  
HRI  
High resolution imager (Einstein or ROSAT)  
HRMA  
High resolution mirror assembly (AXAF)  
$I_0$  
intensity of incident X-ray beam  
K  
complex dielectric constant  
k  
momentum of photoelectron  
l  
angular momentum quantum number  
L  
MCP channel length  
$L_s$  
secondary electron escape length  
LETG  
Low energy transmission grating (AXAF)  
m  
magnetic quantum number  
MEG  
Medium energy grating (AXAF)  
METG  
Medium energy transmission grating (AXAF)  
n  
principal quantum number (Chapter 1)  	n  
complex index of refraction (Chapter 5)  
P  
geometric probability of electron escaping from channel wall into channel  
$P_s(0)$  
surface escape probability of secondary electron  
PSF  
point spread function  
p  
MCP channel pitch  
$p_a$  
probability that electron batch initiates detectable pulse  
p_{i,j}  
probability of electron being emitted from shell j of atomic type i  
p(n)  
probability of n electrons being emitted per absorbed photon  
QE  
Quantum efficiency  
$R(\alpha)$  
fraction of incident flux reflected at grazing angle $\alpha$  
$Re$  
photoelectron range  
r  
radius of MCP channel  
RGS  
Reflection grating spectrometer (XMM)  
$S_{i,j}$  
probability of batch of photoelectrons entering channel, initiated by interaction involving j shell electron of atomic type i  
$S(n)$  
sum of counts in first n PHD channels
SAO  Smithsonian Astrophysical Observatory
SIM  Science instruments module (AXAF)
SRS  Synchrotron radiation source
T_{i,j}  energy of photoelectron emitted from shell j of atom i
Tm  MCP mesh transmission
Tw  Proportional counter window transmission
UVIS  UV/ion shields (AXAF)
V0  electron accelerating voltage along channel
V(r)  atomic potential
V*  mean energy of secondary electron upon escape into channel
W_{fi}  transition probability from state i to f
XMM  X-ray multi-mirror mission
XRCF  X-ray calibration facility
Z  atomic charge
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Chapter 1

Introduction

Without knowledge of the systematic errors in a measuring instrument, any quantitative measurement becomes, if not impossible, at least misleading. In many respects calibration is a never-ending task, with the final goal of perfect accuracy constantly approached but never quite attained. The calibration problem applies particularly to those instruments which will operate in space, where no physical intervention is possible. For on-orbit X-ray calibration, standard, well-known sources such as the Crab Nebula are utilised, along with internal calibration aids built into the instrument. For these reasons it is vital that a space-based instrument be as well calibrated as possible before launch. This also enables the instrument to return useful data right at the start of its operating life.

This body of work considers part of the calibration effort for the Advanced X-ray Astrophysics Facility (AXAF). At the time of its launch (September 1998) AXAF will be the most sensitive X-ray telescope ever constructed, both in terms of its imaging and spectroscopy capabilities, and must therefore be calibrated extremely accurately. The AXAF High Resolution Camera (HRC) is one of two AXAF focal plane instruments. HRC consists of two detectors: an imaging detector (HRC-I) and the readout detector for a dispersive spectrometer (HRC-S). The HRC is a microchannel plate (MCP) based detector. For MCP X-ray detectors it is particularly important to calibrate the quantum efficiency (QE) as a function of incident X-ray energy and incident angle. The QE can vary rapidly around the energies of atomic absorption edges present in either the MCP glass or in any photocathode coating. These variations can lead to significant
localised increases in QE, over an energy range of as little as 20eV. If these localised changes in QE are not mapped accurately, particularly for HRC-S, they could be misinterpreted as emission features in astrophysical spectra.

The 'traditional' method of X-ray detector calibration involves illuminating the detector with a monochromatic X-ray source, at a number of spot energies. Over the AXAF operating energy range of 0.1-10keV, 22 such energies will be considered [1]. But this method has distinct disadvantages. Simple interpolation or a very basic model is used to fill in the gaps between the spot energies, but this is unlikely to include all of the features to be found in the 'missing' energy range. The spot energies considered are limited by the X-ray emission lines produced by the X-ray source, which are rarely close enough together to allow measurements to be taken close to either side of an absorption edge related feature.

Synchrotron measurements have been made of the current yield (electrons per input photon, as opposed to pulse quantum yield - number of pulses per photon) of bare (Fe and Cr electrode coated) MCP detectors by Cho et al. [2] and Hirata et al. [3]. However, the AXAF MCPs will be run in photon counting mode, and mapping photon counting QE from current yield is far from simple. Previous work at Leicester [4] has proved the feasibility of using the Daresbury Synchrotron Radiation Source (SRS) in low ring current mode (approximately 1μA compared to 200mA in standard SRS operation) in order to obtain MCP QE versus energy maps in photon counting mode. These previous measurements were made with bare MCPs. The use of the SRS enables quantum efficiency measurements to be taken with increments in energy as small as 1eV (the minimum energy increment is determined by the monochromator used). Thus QE can be mapped with accuracy on either side of the atomic edge features, and these features can be considered in the instrument response. For the AXAF HRC the synchrotron measurements discussed here will be used to identify regions of interest and to interpolate between measurements made at spot energies.

This thesis describes measurements made with KBr- and CsI- coated MCPs, fully representative of the HRC detector geometry. At the time this work was started, the baseline photocathodes for AXAF were CsI for the HRC-I and KBr for the HRC-S. Partly as a result of the work reported here, both HRC detectors will now use CsI photocathodes.
Three energy ranges are considered here, using three different beamlines of the SRS. Beamline 6.1 was used to take measurements between 50 and 350eV, beamline 1.1 between 250 and 1400eV and beamline 4.2 between 2000 and 6000eV. These energy ranges cover all the atomic absorption lines in CsI relevant to the 0.1-10keV AXAF energy range, and most of those in KBr. The data is analysed and discussed in Chapters 2 to 4. Gain degradation due to charge abstraction is a concern for MCPs where a long operating life is required [5]. Thus, charge abstraction lifetests were performed on both the CsI and KBr coated halves of the detector on beamline 6.1. High resolution imaging allowed the beam spot size to be estimated and the charge abstracted per unit area to be determined.

The second part of the thesis consists of modelling the data, initially using a model developed by Fraser [6, 7, 8, 9]. This model is then extended to consider AXAF-like MCPs with a channel bias angle of 6° (Chapter 5). The model is further extended in Chapter 6 to include near edge structure, specifically ‘white lines’, using a model for the photocathode linear absorption coefficient developed by Shah [10] and Gurman [11].

The final part of the thesis (Chapter 7) describes experimental and theoretical work undertaken to determine the effects of thermal annealing upon CsI coated MCPs.

This chapter begins with an introduction to microchannel plate detectors. AXAF is then discussed and compared to previous and future X-ray telescopes. The Daresbury Synchrotron Radiation Source is described and the chapter ends with a brief summary of the relevant atomic theory.

1.1 An Introduction to Microchannel Plate Detectors

Microchannel plates (MCPs) are imaging electron multipliers of high gain and excellent spatial resolution, commonly used in X-ray, EUV and UV astronomy, both as direct imagers and as readout detectors for transmission grating spectrometers.

MCPs consist of large numbers (up to several million) channels of lead glass, each between 10 and 50 microns in diameter [12, 13]. The channels are produced by drawing a glass fibre, filled
with a core of acid soluble glass and an acid insoluble cladding tube. The drawn glass is known as a monofibre. A number of monofibres are combined to produce a hexagonal structure, and this is again drawn out. The product is called a multifibre. Hundreds of multifibres are fused together in a high temperature vacuum process, to form a boule. The boule is then sliced into thin layers and polished, before the channels are etched to produce the open matrix. The MCP lead glass is then reduced by hydrogen firing, which produces a semi-conductive surface layer. In order that an accelerating voltage can be applied to the MCP, the front and back of the plate are coated with a nichrome layer.

Microchannel plates are operated in a vacuum (below $\sim 10^{-5}$ mbar), and when an accelerating voltage is applied to the MCP each channel acts as a photomultiplier. When the MCP is illuminated by X-rays, EUV or UV light, primary photoelectrons are produced in the channel walls. If they escape the channel wall, they are then accelerated along the channel, and impact upon the opposite wall, producing secondary electrons if they have enough energy. This can produce an avalanche of electrons, which can be collected at the back of the MCP by a resistive anode or a crossed grid charge detector [12]. Comparison of the charge collected at various points on the charge anode gives the position of the charge cloud, and hence the position of incidence of the photon. In this way the MCP produces distortionless imaging, with spatial resolution approaching the channel pitch.

The MCP channel resistance is approximately $10^{14}\Omega$ and plate resistance a between a few tens and a few hundred $M\Omega$. The MCP can also be used to detect ions or electrons. The ratio of the channel length to its diameter is an important figure in determining the efficiency of the MCP, and varies between $40:1$ and $200:1$. The maximum possible quantum efficiency is determined by the ‘open area’ of the MCP front surface (63% for channels of 12.5$\mu$m diameter hexagonally packed with a channel spacing of 15$\mu$m). This can be increased by the use of a repeller grid on the MCP front surface, which repels electrons produced on the inter-channel grid back to the front surface, where they may enter a channel.

MCPs are usually combined into a pair (‘chevron’) or triplet (‘Z stack’), which increases the gain (from $\sim 10^6$ to above $\sim 10^7$) and eases the production of a peaked (‘saturated’) pulse height distribution (PHD). A saturated PHD enables better discrimination between the signal and internal background noise produced by the detector. The channels of the MCP are often biased...
(the boule is cut at an angle other than 90° to the channel axis), so that the channels are not at 90° to the front surface of the MCP. Bias angles typically range from 0° up to 13°. A bias angle increases the probability of photons interacting with the channel wall at incidence angles close to the normal to the MCP front surface. If biased MCPs are combined in a chevron or Z-stack, this also has the advantage of reducing ion feedback, when positive ions are created in a channel and accelerate back towards the MCP front surface, producing afterpulses. The MCPs to be used for AXAF are a chevron pair, with the front plate having a bias angle of 6°. This angle gives the highest QE for the AXAF incident X-ray cone angle. Both plates have an electron accelerating voltage along the channels, and there is also an accelerating voltage in the 125μm gap between the plates which reduces the pulse height distribution FWHM.

The lowest count rate detectable by an MCP detector is determined by the background noise. The highest count rate is determined by the speed with which electrons removed from the channel walls can be replaced, and is thus dependent upon the accelerating voltage and the channel resistance. If the count rate is higher than this, then degradation in the gain will be seen [12].

A major disadvantage of bare MCPs is their low quantum efficiency (between 1 and 10% at X-ray energies), especially when compared to gas proportional counters and CCDs. However, during the last two decades MCP detector efficiency has been improved by depositing a coating of a material with high photoelectric yield on the front face and down the channels of the MCP. This increases the number of primary and secondary electrons, especially the number of low energy secondary electrons, and thus the probability of an electron avalanche. Initially MgF₂ was the photocathode of choice [14], mainly because of its stability in a laboratory atmosphere. However, more recently both CsI [15] - [22] and KBr [22] - [25] have been shown to have greater positive effects on MCP quantum efficiency at X-ray energies, and the AXAF MCPs will be coated with CsI. CsI is a hygroscopic substance, and coated MCPs are handled in dry conditions, stored in N₂ and vacuum baked before coating. Coating with CsI has also been shown to impart some degree of energy resolution to MCP detectors, albeit with E/ΔE~1 [26]. Other recent work has shown improvement in EUV QE when MCPs are coated with a range of photocathodes, including CsCl and Rbl [27], but CsI remains the photocathode of choice.
1.2 Previous MCP detectors

The AXAF High Resolution Camera owes much of its heritage to the high resolution detectors on two previous X-ray telescopes: the Einstein High Resolution Imager (HRI) and the ROSAT High Resolution Imager. This section introduces the MCP detectors on ROSAT and Einstein, and gives a short overview of the development of X-ray astronomy.

1.2.1 A brief history of X-ray astronomy

This topic has already been covered in some detail by a number of authors, [12, 28, 29, 30] so only the major factors in the development of X-ray astronomy will be considered here. The first cosmic X-ray source, Sco X-1 was observed by a sounding rocket flown from New Mexico in 1962 [31]. The X-ray detector of choice during the 1960s was the proportional counter, which could detect X-ray energies up to 10keV, and was mechanically collimated with an angular response of a few degrees FWHM. The next major step in X-ray astronomy was the launch of a dedicated X-ray astronomy satellite, Uhuru, in 1970 [28, 12]. This enabled observations to be taken for months, as opposed to the hours available on balloon flights, and minutes on sounding rockets. Uhuru carried two proportional counters, which could detect sources between 2-20keV over 0.5°x 5° and 5°x 5° fields of view (FWHM). Uhuru identified both the first X-ray binary system and the first diffuse X-ray emission from clusters of galaxies [28]. After Uhuru, a number of small satellites were launched with at least some X-ray astronomy capabilities. These included Copernicus, the Astronomical Netherlands Satellite, Ariel V and SAS-C (Uhuru being SAS-A before launch). Ariel-V carried two proportional counter instruments, an all sky monitor and a Bragg crystal spectrometer and polarimeter [12].

The next major step in X-ray astronomy came with the launch of NASA’s High Energy Astronomy Observatories (HEAO), particularly HEAO-2 (Einstein). HEAO-1 was a large satellite, which undertook three scans of the whole sky during its lifetime [28]. But it was the Einstein Observatory which revolutionised X-ray astronomy, for Einstein carried the first focusing non-solar X-ray telescope, and contained two imaging detectors. Einstein is discussed in more detail below, but it enabled high resolution spectroscopy and imaging of supernova remnants, the resolution of discrete sources in Andromeda and detection of X-ray jets from active galactic nuclei.
The 1980s saw no new large X-ray astronomy observatories launched, but several small X-ray telescopes were successful, including the European EXOSAT and the Japanese Ginga [28, 12, 30]. EXOSAT was launched in 1983, and carried 0.16m² of proportional counters with a 0.75° FWHM field of view, a gas scintillation proportional counter for improved spectral resolution and transmission grating spectrometers. EXOSAT's orbit (apogee 190,000km, perigee 350km) allowed single observations to last for days rather than minutes. Ginga was the third Japanese satellite of the period, and was of considerably greater sensitivity than its predecessors Hakucho (launched 1979) and Tenma (launched 1983). Ginga was launched in 1987 and carried a large area proportional counter (LAC) (0.4m²), an all-sky monitor and a gamma-burst detector. The LAC had a 1°x2° FWHM field of view and an energy range of 1.5-37keV. One of Ginga's most fortuitous observations was of X-rays from SN1987a, which exploded in the same month as Ginga's launch.

The dominant X-ray observatory of the 1990s so far has undoubtedly been ROSAT, launched in June 1990 and discussed in more detail below. Other current missions worthy of mention include the Japanese ASCA (ASTRO-D before launch), XTE and SAX [28, 12, 30]. ASCA was launched in February 1993 and utilises four mirror systems with large effective area. Its sensitivity is complemented by its array of imaging detectors: two CCD systems and two gas scintillation PCs, giving excellent spectroscopic imaging capabilities. XTE and SAX were both launched in 1996, and are smaller spacecraft. XTE is particularly suited to the observation of temporal variability, with timing resolution of 10μs and an energy span of 2-200keV. It carries proportional counters, phoswich detectors and a scanning sky monitor. SAX, an Italian led mission, covers the 0.1-200keV band with its combination of spectrometers, phoswich detectors, coded-mask detectors for wide-field viewing and a gas scintillation counter.

### 1.2.2 Einstein

Einstein, launched in 1978, carried the first cosmic X-ray telescope to utilise Wolter Type 1 optics, in which the incident X-rays are reflected twice, from a parabola/hyperbola combination, and are thus focused. Einstein had four nested mirrors manufactured from quartz and coated
with a chrome-nickel alloy. The mirror had a focal length of 3.4 m [12], on-axis resolution of 2 arcseconds rms blur circle, with a 1° field of view and effective area of 0.04 m² at 0.25 keV and 0.02 m² at 2 keV. The energy range covered was 0.1-4 keV [28]. The focal plane contained four detectors, two imaging and two spectroscopic. The two spectroscopic detectors were a Bragg focal plane crystal spectrometer (FPCS) and, with lower spectral resolution, an Si(Li) solid state spectrometer. The Imaging Proportional Counter (IPC) produced images of resolution up to 1' with a 1° field of view and had energy resolution of approximately ΔE/E=100% at 1.5 keV. The second imaging detector was the HRI discussed below. There were two other components to the Einstein payload: a non-focusing monitor proportional counter which measured high energy emission between 2-15 keV, and the objective grating spectrometer which was situated between the mirrors and the focal plane and was read-out by the HRI. The resolution of the spectrometer was λ/Δλ ~50, peaking below 250 eV.

The High Resolution Imager consisted of three redundant MCP chevron detectors, each sensitive in the 0.2 to 4 keV energy range [14, 32, 33] with a 25x25 arcminute field of view and a resolution of approximately 4 arcseconds. The MCPs were operated in single photon counting mode. Each detector consisted of two MCPs, each with L:D ratio 80:1, the front MCP having a bias angle of 0° and the back MCP a bias angle of 13°. X-rays were incident upon the detector at angles between 2.5 and 5° from the normal to the front of the plate (and from the channel axis). The MCPs had a channel diameter of 12.5 μm, with a pitch of 15 μm [14](exactly the same channel dimensions as the AXAF HRC-S detector) and the front MCP was coated with MgF₂ to enhance its quantum efficiency, which was ~10% at 1.54 keV. The MCP temporal resolution was 8 μs, with a background count rate of 0.2 counts cm⁻² s⁻¹ [14]. The detectors were read out by a crossed grid charge detector (CGCD), consisting of planes of wires, with the wires in one plane perpendicular to those in the other. The wires were of 0.1 mm diameter with a 0.2 mm diameter spacing and were wound on a ceramic substrate. Many aspects of the AXAF HRC (described in Section 1.3.6) can be traced to the Einstein HRI, particularly the readout technique.

1.2.3 ROSAT

ROSAT was launched in 1990 and is a joint German/US/UK project. Its major aim was to perform a whole sky survey over the energy range 0.15-2 keV [12, 28, 34, 35, 36]. ROSAT, like
Einstein, is a Wolter I X-ray telescope, with four nested mirrors, but it also contains a smaller EUV telescope. The X-ray telescope (XRT) has four mirror pairs with focal length 2.4m, a geometric aperture of 0.11m² (nearly three times larger than that of Einstein) and an angular resolution of 5 arcseconds (half power width). The mirrors are made of Zerodur, are coated with gold and have apertures ranging from 0.37 to 0.83m [12, 34].

The focal plane contains three imaging detectors: two position sensitive proportional counters (PSPCs) and the MCP-based High Resolution Imager (HRI). The PSPCs have an angular resolution of approximately 30 arcseconds and a 2° field of view. With an energy resolution of $\Delta E/E \sim 45\%$ at 1keV, they can resolve four different colour bands, and have an nett effective area of 0.02m² at 1keV [28, 34]. The High Resolution Imager is a copy of the Einstein HRI, with one significant improvement. The MgF₂ photocathode has been replaced by CsI, which is significantly more efficient (see Section 1.1) and is also the photocathode of choice for AXAF (Section 1.3.6). The net effective area for the HRI and XRT is 0.01m² at 1keV, and the HRI has angular resolution matching that of the XRT (~5 arcseconds)[28]. ROSAT’s sensitivity in its HRI mode exceeds that of Einstein by a factor of ~2.

The EUVE telescope (known as the Wide Field Camera, WFC), had a primary goal to perform an all sky survey covering the energy range 41eV to 210eV. The telescope has a nested set of three Wolter type 1 mirrors, with a focal length of 53cm and a 511cm² geometrical collecting area. The resolution is ~1 arcminute rms. on-axis and the field of view is 5°[35]. The detector is an MCP of active diameter 45mm, with a 14,000Å CsI coating (the same thickness as the AXAF MCPs), and curved to a 165mm radius so that its surface matches the focal plane of the mirrors. Like the ROSAT and Einstein HRIs and the AXAF HRC-S, the MCPs have channel diameter 12.5μm with a pitch of 15μm. The L:D ratio is 120:1, and the front MCP has a 0° bias angle whilst the back MCP has a bias angle of 13°. The charge is not collected by a CGCD, but by a resistive anode which is curved to match the MCP [35]. The detector also includes a repeller grid on the front face to direct primary electrons produced on the MCP’s front (inter-channel) surface towards the channels, and hence increase the QE. The incident X-rays strike the MCP at 30° to the normal to the front surface (and to the channel axis). The WFC also includes thin film filters which enable rejection of background and division of the signal into several bands.

A comparison of the Einstein and ROSAT HRIs with the AXAF HRC can be found in Section
1.3 The Advanced X-ray Astrophysics Facility (AXAF)

1.3.1 History

The Phase A study for the Advanced X-ray Astrophysics Facility (AXAF) was completed in 1978 [37]. In 1980, the projected launch date was 1987. In 1992, the project was split into two halves: AXAF-I, for high resolution imaging, and AXAF-S intended to provide high resolution spectroscopy. Perhaps unsurprisingly, budgetary constraints led to the cancellation of AXAF-S in 1993. However, at the time of writing, AXAF-I (now renamed simply AXAF) is due for launch in less than a year. In its current configuration, AXAF will utilise the highest angular resolution X-ray mirror ever flown, and will provide extremely high resolution imaging and spectroscopy to the astronomical community for a five year period [38]. Along with the Compton Gamma Ray Observatory (GRO) and the Hubble Space Telescope (HST), AXAF will be one of NASA’s ‘Great Space Observatories’ [39]. Apart from the lack of a polarimetry capability, the current AXAF does bear some resemblance to the observatory proposed in 1978.

1.3.2 Overview

AXAF is scheduled for launch by the space shuttle in September 1998, into a final orbit with an inclination of 28°, 10,000km perigee and 140,000km apogee. This highly elliptical orbit will have a period of 64 hours, allowing continuous observations for up to 50 hours, with 85% of time outside the Earth’s radiation belts and only being occulted by the earth infrequently [37]. The shuttle will place AXAF into a low earth orbit, from which it will be boosted into a transfer orbit by the Inertial Upper Stage (IUS), and hence will propel itself into the final orbit using its Integral Propulsion System (IPS) [39].

The AXAF programme is directed by the Observatory Projects Office at NASA’s Marshall Space Flight Center (MSFC). Science operations will be conducted by the AXAF Science Center at the Smithsonian Astrophysical Observatory (SAO) and the Massachusetts Institute of Technology.
The spacecraft prime contractor is TRW Space and Electronics Group. The Project Scientist is Martin Weisskopf (MSFC), and the Telescope Scientist is Leon Van Speybroeck (SAO)[39].

The observatory consists of three systems: the spacecraft system (TRW), the Telescope System (principal subcontractor Eastman Kodak Company) and the Integrated Science Instruments Module (principal subcontractor Ball Aerospace Systems Division). A view of the spacecraft is shown in Figure 1.1. Fully deployed, AXAF will be 13.8m long, and have a solar array span of 19.5m. This makes it similar in length to HST [37, 39].

1.3.3 The Spacecraft System

The spacecraft system provides the physical environment required by the telescope. This includes electrical power, thermal control, propulsion, communications and data management. The two solar arrays, each of three panels, provide more than 2kW of power, and this is augmented by three 30 Amp-hour batteries. Internally AXAF has a real-time telemetry rate 32kbps, of which 24kbps is used for science and 8kbps for engineering. Its communications with the ground are by way of the NASA Deep Space Network, with downlink rates of 256kbps and 512kbps, and downloads occurring every 8 hours [39]. The attitude of the spacecraft is determined by the Pointing Control and Aspect Determination subsystem (PCAD). The scientific programme requires that AXAF have a pointing stability of 0.25 arcseconds, with an accuracy of 1.0 arcseconds. These tight constraints are met by the Aspect Camera Assembly, which optically images the source with a four-inch optical telescope and CCD detector. The Aspect Camera will also be used to obtain photometry of the X-ray source. Attitude is referenced by two Inertial Reference Units.
(IRUs), with a total of four gyros. Torquing and momentum storage are accomplished by six reaction wheels, and momentum is unloaded by thrusters. There are five coarse sun sensors, which give whole sky coverage and are supplemented by fine sun sensors. The scientific instruments are protected from potentially damaging sources by a Bright Object Detector, and the radiation environment is continuously monitored by a charged-particle detector [38].

1.3.4 The Telescope System

The telescope system includes the High Resolution Mirror Assembly (HRMA) and the Objective Transmission Gratings (OTG), both mounted on the optical bench. The optical bench is made from graphite composite, and aligns the mirrors and transmission gratings with the science instruments in the focal plane.

The High Resolution Mirror Assembly

The HRMA consists of four Wolter-1 (paraboloid-hyperboloid) X-ray mirror pairs, nested and co-axial. The mirrors are fabricated from Zerodur (Schott Glaswerke, Germany), which has a low coefficient of thermal expansion. The mirrors are then coated with Iridium, which has a significantly higher effective area at high X-ray energies than the usual gold coating [37]. The focal length is 10m which allows X-ray focusing up to an energy of 10keV, and the diameter of the outer mirror is 1.2m. The effective area is 123 cm$^2$ at 8keV, and 900 cm$^2$ at 0.25keV [38]. The mirrors have been fabricated to high precision, with an rms surface roughness of less than 4 Å. Preliminary tests carried out on a prototype of the outer mirror pair in 1991 demonstrated an angular resolution (FWHM) of 0.19 arcseconds: much better than the required 0.5 arcseconds [39]. The AXAF mirrors can be compared to those of ROSAT and JET-X (for a further description of JET-X see Section 1.4): the AXAF HRMA has an on axis resolution (FWHM) of 0.5 arcseconds, with the comparable figures being 3 arcseconds for ROSAT and 20 arcseconds for JET-X. The HRMA also includes the fiducial-light transfer system, which enables the transmission of light from the fiducial lights on the science instruments to the Aspect Camera.
The Transmission Gratings

The Telescope System includes two objective transmission gratings, mounted immediately behind the HRMA. Both gratings are retracted for imaging, and for spectroscopy either grating can be inserted into the light path. The Low Energy Transmission Grating (LETG) is optimised for spectroscopy in the 0.09 to 3keV energy range, and the High Energy Transmission Grating (HETG) is optimised for the 0.4 to 10keV range [37, 38, 39]. Each grating consists of a large number of facets mounted upon four concentric circles, corresponding to the four HRMA mirror pairs, which match the Rowland torus. This minimises any geometrical aberration. The HETG will be read out by the AXAF CCD Imaging Spectrometer (ACIS), and the LETG by HRC-S.

The HETG contains two grating structures: the Medium Energy Grating (MEG), operating between 0.4 and 5keV, intercepts light from the two outer mirror shells, whilst the High Energy Grating utilises the inner two mirror shells, where the reflectivity extends to higher energies, between 0.9 and 10keV. Both gratings operate at the same time, but their spectra cross at an angle in the focal plane and so can be separated. The HETG has 336 2.5cm square facets, and the spacing is provided by gold grating bars. For the MEG, these gold bars have a 4000Å period, which gives a dispersion of 2.85 Åmm⁻¹ in the focal plane. The HEG has a 2000 Å period, leading to a dispersion of 5.70 Åmm⁻¹ [39]. The resolving power of the grating will be up to $E/\Delta E = 1000$.

The LETG has 540 1.6cm diameter facets, with both the grating bars and supporting grid made of gold. The gold bars have a 9920Å period, which results in a dispersion of 1.15 Åmm⁻¹. The LETG provides the highest resolving power on the spacecraft ($E/\Delta E$ of greater than 1000 at 0.1keV)[39]. The grating has an efficiency of about 10%. The readouts for both the HETG and LETG will be discussed in Section 1.3.5.

1.3.5 The Science Instruments Module (SIM)

The Science Instruments Module (SIM) contains the two X-ray detectors used by AXAF: the AXAF CCD Imaging Spectrometer and the High Resolution Camera. The SIM is mounted in the focal plane, and provides the thermal and mechanical interface between the spacecraft and
the science instruments. Either of the two detectors can be placed at the telescope focus, with a positioning accuracy of 0.25mm in the transverse direction (mapping to 5 arcseconds angular positioning accuracy)\cite{39}. A particular feature of AXAF, and a first for an X-ray observatory, is that the SIM can also move along the optic axis, so that accurate focusing is guaranteed on-orbit. The SIM has a range of \(\pm 1\)cm along the axis, with a 25 micron accuracy. This ability should allow compensation for any shrinkage of the optical bench during the mission. The SIM also includes a baffling system, which ensures that a negligible amount of stray UV or visible light is incident upon the detectors.

The AXAF CCD Imaging Spectrometer

The AXAF CCD Imaging Spectrometer (ACIS) has two CCD arrays, one primarily for imaging (ACIS-I) and one for grating spectroscopy (ACIS-S), although each device can serve as a back-up readout for the other. The Instrument Principal Investigator is Gordon Garmire from Pennsylvania State University, and the detectors are being provided by the MIT Center for Space Research and Lincoln Laboratories. The CCD arrays are tilted to match the appropriate telescope focal surface.

ACIS will be a combination of 10 CCDs, each of which is 25mm square. ACIS-I will be a 2x2 array, and ACIS-S a 1x6 array. The arrays will contain both front-illuminated and back-illuminated CCDs. The front-illuminated CCDs have better energy resolution, but lower quantum efficiency at low energies and lower and spatial resolution. Quantum efficiency varies for front-illuminated CCDs between less than 1\% at 0.277keV and 71\% at 1.49keV. For back-illuminated CCDs the corresponding figures are 18\% at 0.277keV, up to 80\% at 1.49keV \cite{39}. The CCD pixels are 24 microns square (mapping to 0.5 arcseconds in the AXAF focal plane), with 1024 x 1024 pixels per CCD. Apart from a diagnostic mode, the CCD arrays have two readout possibilities. In standard mode, the charge is accumulated over a 0.1-10s period (with a nominal period of 6.5s), but there is also a continuous readout mode which enables time resolution of up to 2.6ms for bright sources \cite{39}. The ACIS has an extremely low non-X-ray background, of less than 0.01 counts/s/cm\(^2\).

ACIS-I has a 17 arcminute square field of view, and will be used for medium spatial resolution
imaging spectroscopy, with an energy resolution of \( \frac{E}{\Delta E} = 18 \) at 1keV and 48 at 5.9keV [37].

ACIS-S is a 25mm x 150mm array, with an 8 arcminute field of view in the cross dispersion direction. It will be used mainly to readout the HETG, with a resolving power of 1000 at 0.4keV, but can also be used as a back-up readout for the LETG, and as a narrow field spectroscopic imager when both transmission gratings are withdrawn.

1.3.6 The High Resolution Camera (HRC)

Overview

Most of this thesis is concerned with the calibration of the AXAF High Resolution Camera (HRC), so it will be considered in slightly more detail than the other components of AXAF. The HRC consists of two arrays of microchannel plate detectors - HRC-I optimised for imaging and HRC-S, optimised as a spectroscopy readout for the LETG. The HRC will cover the whole energy range of the mirror array, from below 0.1keV to 10keV. The HRC has the highest spatial resolution of any of the AXAF detectors (0.5 arcseconds, matching the FWHM of the mirror point spread function), although it has much poorer spectroscopic resolution than the ACIS. The HRC MCPs use specially developed low-noise glass, reducing the internal background to about 0.04 counts/s/cm², and have a time resolution of 16 microseconds. Beta emission from potassium (\(^{40}\)K) has been found to be the main cause of MCP background noise in standard plates [40]. These low noise MCPs are therefore manufactured from material without radioactive isotopes. The HRC Principal Investigator is Dr Stephen Murray of the Smithsonian Astrophysical Observatory [37, 39, 38, 41, 42].

A schematic of the HRC is shown in Figure 1.2 [41] and a more detailed view of the detector structure in Figure 1.3.

The Microchannel Plates

The MCPs for the two HRC detectors are manufactured by different companies and have slightly different geometries. The HRC-S MCPs were manufactured by Philips Photonics, Brieve, France.
Figure 1.2: Schematic of the AXAF High Resolution Camera

Figure 1.3: The housing of the MCP detectors for the AXAF HRC
They have a 12.5 μm diameter pore size, hexagonally packed with a 15 μm spacing and a length:diameter ration of 120:1. The HRC-I MCPs were manufactured by Galileo Electro Optics Corporation of Surbridge, MA, USA. They have a 10 μm diameter pore size, hexagonally packed with a 12 μm spacing and a length:diameter ration of 120:1. Both detectors are arranged in chevron pairs. For both HRC-S and HRC-I the front plate has a 6° bias angle. For HRC-S the bias angle is in the cross-dispersion direction of the MCPs, so that QE variations with angle are minimised. Both detectors have their front plates coated with a CsI photocathode to increase the quantum efficiency. The MCPs have some intrinsic energy resolution (E/ΔE~1). The front MCP has an accelerating voltage of 1400V across it, there is an inter-plate gap voltage of 50V and the back plate has a 1250V drop across it. Development of the Philips low-noise MCP glass is described in Fraser et al. [40].

The UV/Ion Shields

The UV/ion shields (UVIS) are placed in front of the MCPs, to block UV radiation, ions and low energy electrons. They are coated with conductive material and held at +100V with respect to the top MCP so that they can collect extraneous electrons from the MCP front surface, reducing any halo on point images. The UVIS are made by Luxel Corporation, USA.

The HRC-I UVIS consists of layers of aluminium, polyimide and carbon, in the proportions shown in Table 1.1 [41, 42]. The HRC-S UVIS has four separate parts, as shown in Figure 1.4, and in Table 1.1. The thin strips at the sides of MCP have a higher thickness of Al, so that low energy photons are rejected from these strips. The spectra can then be compared between the strips and the rest of the MCP, to assist in distinguishing higher order spectra. There are also two different compositions in a central 'T' shape. The top of the T performs the same function as the side strips, and the central part of the T has an even thicker layer of Al, so that the highest energy lines and the 0th order can be distinguished.

The detector is also shielded by tantalum to reduce background from high energy X-rays (below 20keV). An anti-coincidence detector is used to remove the background due to cosmic rays. Events which register in the HRC and the anti-coincidence shield with 500ns are rejected. The anti-coincidence detector is made from two types of Bicron plastic scintillator [42].

24
<table>
<thead>
<tr>
<th>Detector</th>
<th>Polyimide(Å)</th>
<th>Aluminium(Å)</th>
<th>Carbon(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRC-I</td>
<td>5000</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>HRC-S Inner ‘T’</td>
<td>2500</td>
<td>700+300</td>
<td>0</td>
</tr>
<tr>
<td>HRC-S Inner</td>
<td>2500</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>HRC-S Outer edge ‘Strip’</td>
<td>2000</td>
<td>2000</td>
<td>0</td>
</tr>
<tr>
<td>HRC-S Outer edge</td>
<td>2000</td>
<td>300</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1.1: UV/ion shield thicknesses for the AXAF HRC

Figure 1.4: The High Resolution Camera UV/ion shields
The HRC-I

HRC-I consists of one chevron MCP, made of 100x100mm square plates. It will be used for high resolution imaging, with a wide field of view (31 arcminutes x 31 arcminutes). The MCP detector is read-out by a Crossed Grid Charge Detector (CGCD), made from orthogonal Au alloy wires. Every eighth wire is connected to a charge sensitive amplifier, with 64 such connections per axis. The wires are wound on a alumina-ceramic block, upon which an Au plane is placed and biased to act as a reflector electrode [42]. The HRC-I is arranged so that it can be used diagonally as a back-up readout for the LETG.

The HRC-S

The HRC-S microchannel plate array consists of three 30x100mm chevron pairs, made by manually scribing and cracking 100mx100mm plates. The MCPs are arranged lengthwise, to produce a 20x300mm rectangular readout for the LETG. The high efficiency of the MCPs at low X-ray energies makes them a better readout for the LETG than ACIS. The outermost two MCP pairs are tilted to conform approximately to the Rowland circle of the grating. In conjunction with the LETG, the HRC-S will be able to perform spectroscopy with an energy resolution of E/\Delta E>1000 between 75 and 300eV [42] (comparable to the ACIS energy resolution at 1keV). The array has a 7 arcminute x 97 arcminute field of view.

The HRC-S has a CGCD readout, also tilted to approximate the Rowland circle. In the cross-dispersion direction the charge is collected on an Au alloy wire grid, as for HRC-I. Along the dispersion direction, the readout is composed of gold strips deposited on a ceramic substrate. Again every eighth wire or strip is connected to a charge sensitive amplifier [42].

1.3.7 The AXAF Calibration Programme

AXAF calibration is taking place in three phases: calibration of the individual instruments, calibration of the mirror array separately and in combination with the instruments and calibration on-orbit.
Each instrument and its subcomponents will be calibrated by the developing body for the instrument, using the facilities of the instrument developer and any other co-operating institutions. This will include calibrations of spatial uniformity, quantum efficiency, energy resolution, temporal stability and temporal resolution. The results will be used to produce theoretical models of the instruments’ responses, which can be combined with the HRMA performance model to predict the combined response of the HRMA and the instrument [37]. The HRMA itself was calibrated at the X-ray Calibration Facility (XRCF) at NASA Marshall Space Flight Center in March-April 1997. The XRCF consists of a 520m long evacuated tunnel and an instrument vacuum chamber which is 18.3m long and 7.3m in diameter. The X-rays are produced by an electron bombardment source. The chamber is large enough that the completed HRMA could be calibrated, alone and with the various instruments. Calibrations included the effective area as a function of energy, the profile of the point spread function and the energy resolution [37].

Although the 520m distance between the X-ray source and the HRMA is a reasonable approximation of a source at infinity, it is not accurate enough for the AXAF calibration, and so on-orbit calibration will also be undertaken. This also allows for inclusion of any effects from the launch and microgravity environment. Calibration will use well known cosmic sources to determine the point of best focus, and any changes in effective area.

1.3.8 HRC Calibration

Most of the component calibration for the HRC has been carried out at the Smithsonian Astrophysical Observatory (SAO) by the team responsible for the HRC. Additional calibration of the UV/ion shields has been undertaken by a team at the Osservatorio Astronomico di Palermo G.S. Vaiana. Further MCP calibration has also been conducted at Leicester University, some of which is the main topic of this thesis.

Quantum efficiency calibration at SAO consisted of illuminating a gas flow proportional counter and the MCP detector alternately, with foil filters used to remove continuum X-rays and keep the illumination approximately monochromatic. Another proportional counter was used to monitor the source’s temporal stability [1].

Absolute QE measurements were taken at 22 different energies, with four azimuthal angles
(0° to 270° in 90° increments) and five polar angles (0, 1.8°, 2.5°, 2.8° and 3.5°, the HRMA cone angles). A monochromator was also used to illuminate small areas of the MCP with a non-contaminated monochromatic beam, at an number of energies and positions. These absolute QE measurements at point energies can then be combined with the synchrotron QE measurements discussed in this work to produce continuous QE measurements with energy variation across the whole energy range [41, 1, 43].

The absolute QE measurements can also be used to provide data concerning the QE spatial uniformity across the MCP. Other independent calibrations include those of spatial linearity, pixel scale, dead time, background and UV response. Tests undertaken at Palermo include the X-ray and UV transmission and spatial uniformity of the UVIS [44, 45, 46, 47].

There are a number of particular difficulties associated with calibration of the HRC. The focused X-ray beam from the HRMA is of particularly high resolution, and has features of similar size to the MCP pore size. Thus the QE is expected to vary as the illumination moves between the MCP channel and the inter-channel grid. A similar effect would be expected on the ACIS. It has not been possible to calibrate the HRC or the ACIS to this small scale. The second problem arises from the gain decay expected on the MCP as charge is extracted. If a large amount of charge is extracted from a small area, that area can see a significant degradation in gain. Both these problems can be solved by spatial dithering. At the XRCF the ISIM was moved with a ±0.75mm range, which is comparable to the dithering on orbit (15 arcseconds). This moves the X-ray beam, averaging out the local QE variations and reducing the charge extracted from a small area [43].

1.3.9 Comparison of AXAF with previous telescopes

A comparison of the anticipated AXAF performance with its predecessors, ROSAT and Einstein, is shown in Table 1.2 [39]. AXAF’s major advantage is its extremely high precision mirrors, giving a six-fold improvement in angular resolution over ROSAT and an eight fold improvement over Einstein. The gratings also enable an increase in resolving power of an order of magnitude over Einstein. The other point to note is the AXAF mirror’s iridium coating extends its useable energy range to 10keV, compared to 2 and 4 keV for ROSAT and Einstein.
<table>
<thead>
<tr>
<th>Property</th>
<th>AXAF</th>
<th>ROSAT</th>
<th>Einstein</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of mirror shells</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Mirror-coating material</td>
<td>Ir</td>
<td>Au</td>
<td>Ni</td>
</tr>
<tr>
<td>Focal length (m)</td>
<td>10.0</td>
<td>2.4</td>
<td>3.45</td>
</tr>
<tr>
<td>Plate scale (μm/arcsec)</td>
<td>48.8</td>
<td>11.6</td>
<td>16.7</td>
</tr>
<tr>
<td>Mirror diameters (cm)</td>
<td>63-120</td>
<td>51-83</td>
<td>33-58</td>
</tr>
<tr>
<td>Mean grazing angles (arcmin)</td>
<td>27-52</td>
<td>83-135</td>
<td>40-70</td>
</tr>
<tr>
<td>Angular resolution (FWHM) (arcsec)</td>
<td>0.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>50% encircled energy radius @ 1.5keV (arcsec)</td>
<td>0.33</td>
<td>2.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Effective area @ 1.5keV (cm²)</td>
<td>780</td>
<td>350</td>
<td>200</td>
</tr>
<tr>
<td>Maximum energy for effective area &gt; 50cm²(keV)</td>
<td>10</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>High resolution imager</td>
<td>HRC (MCP)</td>
<td>HRI (MCP)</td>
<td>HRI (MCP)</td>
</tr>
<tr>
<td>Medium resolution spectrometer</td>
<td>ACIS (CCD)</td>
<td>none</td>
<td>Si(Li)</td>
</tr>
<tr>
<td>Grating resolving power (E/ΔE)</td>
<td>~1000</td>
<td>none</td>
<td>~100</td>
</tr>
</tbody>
</table>

Table 1.2: A comparison of various X-ray telescopes
1.4 Future X-ray Telescopes

AXAF is not the only X-ray telescope currently in preparation for launch, and the next generation of X-ray telescopes are currently under consideration. This section will discuss the X-ray telescopes that will come in the near future after AXAF.

There are two major missions planned for launch within the next few years apart from AXAF and the European X-ray Multi-Mirror Mission (XMM): the Russian/European/American Spectrum-X and the Japanese ASTRO-E. Spectrum-X was originally planned for launch in the early 90s, but considerable delays have led to a current estimated launch date of 1998. Spectrum-X is a wide ranging mission, with two main instruments. SODART/XSPECT uses conical foil optics, with two 8m focal length modules producing imaging resolution of 2' (HPW) on axis with a 60' field of view. The telescope has a large area per module (1400cm² @ 2keV and 1000cm² at 7keV)[48] and the detectors include Bragg spectrometers, an X-ray polarimeter and imaging PCs. JET-X (the Joint European X-ray Telescope) has a Wolter 1 telescope with a focal length of 3.5m. The telescope also has two modules, each consisting of 12 shells (fabricated from Ni), to give an angular resolution of up to 20'' and a field of view of 40'. The detectors are Si CCDs.

ASTRO-E, like SODART, uses conical foils rather than traditional Wolter 1 optics. There will be five modules, each with 4.5m focal length and with excellent imaging resolution(1' HPW). Four of the modules have CCD readout, capable of imaging spectrometry, to provide large collecting area. The final telescope is read out by a microcalorimeter (an innovative instrument for X-ray astronomy).

Spectrum-X, ASTRO-E, XMM and AXAF are compared in Section 1.4.1.

1.4.1 The X-ray Multi-mirror Mission

The European XMM (the X-ray Multi-mirror Mission) will be launched in late 1999 into an elliptical orbit. Compared to AXAF, it emphasises a large collecting area over angular resolution. Its telescope system is a Wolter 1 type, with 58 shells made of Ni and coated with Au. There are three identical telescope modules, each of which has a 7.5m focal length and mirror radii
between 159mm and 350mm. The angular resolution will be $\sim$10 arcsec FWHM, which is considerably poorer than that of the AXAF mirror ($\sim$ 0.5 arcsec). The field of view of the mirrors is 30 arcminutes [49, 50], and the collecting area is extremely large (6000cm$^2$ at 2keV). The spacecraft will have a pointing accuracy of 3", with a jitter of 0.35".

All three mirror modules will be read-out by imaging CCD cameras placed at the mirror focus (known as EPIC - European Photon Imaging Camera). Reflection grating spectrometers (RGS) will be placed to intercept half the beam from two of the mirror modules, and will be read out by dedicated CCD strip detectors. A unique feature of XMM is that all the instruments can be operated at the same time. The imaging CCD detectors are arranged in two different arrays: the full-beam array consists of 12 pn CCDs, each viewing 13.6 x 4.4 arcminutes. The two half-beam arrays contain 7 Metal-Oxide-Semiconductor (MOS) CCDs, each of which views 10.9 x 10.9 arcminutes. Both of these arrays are arranged onto circles which cover 30 arcminutes in diameter. The MOS cameras have a 40$\mu$m pixel size (1") and the pn camera has 150$\mu$m pixel size (4"). The resolving power of both CCD types is $\sim$50 at 7keV and $\sim$10 at 0.5keV, with a sensitivity range of 0.1-10keV.

The beam from the RGS is incident upon an array of 7 CCDs matching the Rowland circle, which are back illuminated but otherwise the same as the EPIC MOS CCDs. The energy range is 0.35-2keV, with energy resolution between 100 and 1000. The cross-dispersion field of view is 4".

XMM also includes an optical monitor which is an optical telescope with an MCP intensified CCD detector readout, covering a 24' field of view with a 1" resolution. The telescope will be sensitive to UV and UBV. This will enable concurrent X-ray and optical/UV monitoring of sources.

Figures 1.5 and 1.6 show the relative collecting areas of the X-ray mirrors and spectrometers from planned X-ray telescopes (taken from [48]). Considering only one of the modules, it can be seen that XMM has a much greater collecting area than any of the other telescopes, over all the energy range. Also noticeable is great increase on high energy collecting power of the new generation of telescopes compared to ROSAT. In the energy range it covers, ASTRO-E has the greatest spectroscopic resolution, with the XMM RGS having greater resolving power over most
Figure 1.5: A comparison of the collecting area per module for mirrors from recent and future X-ray mirrors. Figure 1 from [48].

of its energy range than the AXAF transmission gratings, but covering a considerable narrower energy range.

Figure 1.7 shows simulations of deep survey images from AXAF and XMM, taken from [48]. Each survey field is 11x11 arcminutes, is in the 2-10keV energy band and taken over a period of 200 and 1000ks. The XMM mirror PSF had a HPW of 16" and the AXAF PSF had a HPW of 0.5". In the XMM 200ks exposure the faintest visible sources are \(\sim 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\), corresponding to 20 counts. The equivalent AXAF image, with the same source energy level, has 7 counts per source, but the sources are much less confused because the mirror PSF is considerably smaller. This illustrates the complementary abilities of AXAF and XMM, with AXAF having very high angular resolution and XMM having much greater photon collection ability.
1.5 The Daresbury Synchrotron Radiation Source

The production and properties of synchrotron radiation are described in many references ([51, 52, 53]). I will discuss the theory of synchrotron radiation briefly, and consider the operation of the Daresbury SRS.

1.5.1 Theory of Synchrotron Radiation

Synchrotron radiation is emitted when a charged particle is accelerated. If the particle is moving at much less than the speed of light it emits radiation as a dipole, symmetric about its position. However, if the particle is moving at close to the speed of light then the radiation is focused in the forward direction of the particle's travel. In a synchrotron radiation source light charged particles, usually electrons, are accelerated close to the speed of light and confined to a circular orbit by a lattice of bending and focusing magnets, giving off synchrotron radiation as they move in the circular orbit. The synchrotron light given off is intense, continuous, linearly polarised, collimated and pulsed as the electrons travel around the ring in bunches.
Figure 1.7: Simulations of XMM and AXAF deep survey observations. Top left - XMM 200ks. Top right - AXAF 200ks. Bottom left - XMM 1000ks. Bottom right - AXAF 1000ks. Figure 4 from [48].
Each orbit of the electrons in the storage ring takes, typically, about 100ns. The electrons lose energy as they travel around the ring, and energy is added in an RF cavity, placed close to the point where electrons are injected into the storage ring. The electrons oscillate in the vertical and horizontal sense as they travel round the ring, and are spread out in time along the beam path. A magnetic field acts to confine the electrons in the radial and vertical directions, and the RF field concentrates the electrons in the time sense.

Insertion devices are placed around the ring to provide X-ray beams of varying energy, intensity and divergence to users. These devices use arrays of magnets to accelerate the electrons in various dimensions and hence to produce different types of synchrotron radiation.

1.5.2 Daresbury

The Daresbury Synchrotron Radiation Source (SRS) is operated by the Council for the Central Laboratory of the Research Councils (CCLRC). It was built in 1962 (although not as a synchrotron source). The SRS is a three stage accelerator, and a schematic of its layout is shown in Figure 1.8. The electrons are produced and accelerated up to an energy of 12MeV in a linear accelerator. They are then stored in the booster ring, where extra electrons are added and they are further accelerated up to 600MeV. After the booster ring the electrons move into the large storage ring, from which the user beamlines fan out [54].

In the 96m circumference of the storage ring the electrons have an energy of 2GeV and are arranged in 160 bunches, with a width (FWHM) of 180psec. The storage ring current is usually 150-300mA, with a minimum of 100mA in multibunch mode and 10mA in single bunch mode (compared to ~ 1μA in low ring current mode). The ring itself has 16 bending magnets and 3 insertion devices (2 X-ray wigglers and 1 undulator), and emits photons between the mm and X-ray wavelengths. The electrons circulate in the ring for 10-20 hours, and each 24 hours the beam is dumped and refilled so that the SRS can be inspected (although this has not always been necessary when the synchrotron is run in low ring current mode). This takes approximately 2 hours. There are over 30 experimental areas, and 2500 registered users of the SRS.
Figure 1.8: Schematic of the Daresbury SRS.
1.6 Atomic Theory and the Interaction of X-rays with Matter

The quantum efficiency of MCPs is determined by the response of the MCP glass and any photocathode to the incident X-rays. In order to understand this response, some knowledge of the materials' atomic structure is necessary. This section gives a brief introduction to atomic theory, and is particularly relevant when considering the experimental data of Chapters 2, 3, 4 and modelling of Chapters 5 and 6.

1.6.1 Models of the Electronic Structure of the Atom

This section summarises the more comprehensive discussions of atomic theory given in books by Azaroff, Agarwal and Teo [55, 56, 57].

The Schrödinger Model

In the Schrödinger theory of the atom the electrons exist in atomic orbitals, characterised by four quantum numbers. The principal quantum number, \( n \), specifies the shell, and hence the coarse energy. In X-ray spectroscopy, the electrons most tightly bound to the nucleus are known as K-shell electrons, with the next, less bound, group being the L-shell, as so on through the alphabet. The principal quantum number, \( n \), is 1 for the K-shell, 2 for the L-shell, etc. A very simple consideration of the nucleus-electron interaction in a one-electron atom with nuclear charge \( Z \) results in an energy for the electron in shell \( n \) of:

\[
E_n = -\frac{1}{2} \frac{Z^2 me^4}{n^2 \hbar^2}
\]  

(1.1)

where \( m \) and \( e \) are the mass and charge of the electron. The radius of each orbit is given by:

\[
r = \frac{n^2 \hbar^2}{Z^2 me^2}
\]  

(1.2)

This value of \( r \) for \( n=1 \) is known as the Bohr radius, \( a_0 \). A shell of principal quantum number \( n \) can hold \( 2n^2 \) electrons.

The orbital, or azimuthal, quantum number, \( l \), specifies the angular momentum of the electron in its orbit. The angular momentum also has an effect on the energy, splitting the coarse orbitals.
into finer subshells. Each value of l has an associated letter, so l=0 corresponds to the s subshell, 
l=1 to p, l=2 to d, then f, g, h and so on. Thus each subshell can be explicitly determined by 
its principal and azimuthal quantum numbers, for example the most tightly bound subshell, 
with n=1 and l=0, is the 1s subshell. The third quantum number is m, the magnetic quantum 
number, which signifies the orientation of the electron’s orbital under application of an external 
magnetic field. This takes values of 0, ±1, ±2..., up to ±l. Finally, the spin quantum number, s 
(or ms), specifies the orientation of the electronic spin, where s=±\frac{1}{2}.

Each possible state of an electron is described by a wavefunction, which is a solution of the 
Schroedinger equation. The time-independent states of a hydrogenlike atom have wavefunctions:

$$\psi_{nlm} = R_{nl}(r)Y_l(\theta)Z_m(\phi)$$

which becomes:

$$\psi_{nilm} = N_{nilm} \exp \left( -\frac{Zr}{a_0} \right) L_{n+l}^{2l+1} \frac{Zr}{a_0} L_{l}^{m}(\cos \theta)e^{im\phi}$$

where n=1,2,3..., 0 \leq l < n; -l \leq m \leq l and l and m are integers. The electronic quantum states 
are filled in accordance with two laws: (i) thermodynamics requires that the lowest energy states 
are filled first, (ii) the Pauli exclusion principle requires that no electrons in an atom can have 
identical quantum numbers. In each subshell, m can take 2l+1 values, and spin 2 values, so 
the subshell can contain 2(2l+1) degenerate electrons (electrons with the same energy). This 
degeneracy is lifted in the presence of externally applied electric and magnetic fields.

When considering spin-orbit interaction, two more quantum numbers can be defined: j, the total 
angular momentum (l±n), and mj, which runs from +j to -j in integers. This interaction splits 
subshells further, for example the L shell now has three subshells, 2s\frac{1}{2}, where n=0, and 2p\frac{1}{2} 
and 2p\frac{3}{2}, where n=2, l=1 and j=\frac{1}{2} or \frac{3}{2}. If we consider spin-orbit interactions, the degeneracy 
within each subshell is removed, and states of different j have different energies, although the 
degeneracy due to mj remains, and is only lifted by an external magnetic field.
Transitions between states

Electrons can move between states in an atom, emitting or absorbing energy in the process. The transition probability is given by:

\[
W_{fi} = \frac{64\pi^4}{3c^2\hbar^2} \nu_{fi}^2 |(f|D(r)|i)|^2
\]

Here \( \nu_{fi} = \hbar (E_f - E_i) \), where \( E_f \) and \( E_i \) are the energies of the final and initial states, and \( D = er \) is the electric dipole moment. The matrix element of the transition probability determines whether the transition is possible: a transition between the initial state \( \psi_{n'i'm} \) and the final state \( \psi_{n'i'm'} \) will only occur if:

\[
\int \psi_{n'i'm'}^* D(r) \psi_{n'i'm} dr \neq 0
\]

Working through this equation, we find that there are certain electric dipole selection rules: \( \Delta l = \pm 1, \Delta m = \pm 1 \) or 0 and \( \Delta n \neq 0 \). Only transitions which obey these rules are allowed. Generally, in the simple cases considered here, quadrupole transitions make a negligible contribution to the transition probability.

1.6.2 X-ray absorption theory

Introduction

Consider an X-ray beam of intensity \( I_0 \) incident on an absorbing medium. After travelling a distance \( x \) through the material, the intensity of the transmitted beam, \( I \), is given by:

\[
I = I_0 e^{-\mu(E)x}
\]

where \( \mu(E) \) is the linear absorption coefficient, and has units of \( \text{cm}^{-1} \). \( \mu(E) \) is dependent upon the energy of the incident X-ray and the composition of the attenuating material. In some cases it is more convenient to use mass absorption coefficient, defined as

\[
\mu_m = \frac{\mu}{\rho}
\]
where $\rho$ is the density of the absorbing medium. The absorption coefficient increases as wavelength decreases, with $\mu \propto \lambda^3$, until the 'absorption edge' is reached. A wavelengths greater than this, the X-ray photon does not have enough energy to cause the ejection of an electron from a specified shell in the atom, and thus the absorption coefficient decreases. Absorption due to the ejection of an electron from a bound shell is called photoelectric absorption, and is typically followed by an outer electron falling into the newly created hole, and emitting an X-ray photon. The absorption edges are labelled $K, L_{\text{I}}, L_{\text{II}}, L_{\text{III}}$, continuing up the alphabet, after the atomic shell from which the primary photoelectron electron is ejected. The K shell corresponds to ejection from the inner, 1s, shell, which requires the greatest energy. The $L_1$ edge corresponds to the 2s shell, with the $L_{\text{II}}$ and $L_{\text{III}}$ edges corresponding to the $2p_{\frac{1}{2}}$ and $2p_{\frac{3}{2}}$ subshells respectively. Similarly, the 5 M edges correspond to the 3s, 3p and 3d subshells.

If an absorption edge is looked at in more detail, fine structure becomes apparent on the edge, for hundreds of electron volts on its high-energy side, and occasionally on the low-energy side of the edge. This structure is due to the electron, instead of being ejected completely out of the atom, being excited to unoccupied states in the atom. The allowed states are determined by the selection rules of quantum mechanics, which are discussed above 1.6.1. The fine structure is thus a measure of the allowed, unoccupied atomic states. These states are influenced by the atoms surrounding the absorbing atom, so fine structure can be used to tell us about the absorbing material.

**Photoionisation**

There are two modes of interaction between X-rays and matter: true absorption and scattering. This section will discuss true absorption. In order for true absorption to occur, an atom absorbs an X-ray photon and in the process is excited to a higher energy state. If the X-ray photon has enough energy an electron can be excited from one of the inner shells of the atom to the electron continuum: in that case, the atom has been ionised and a process of photoionisation has occurred. This is the X-ray equivalent of the UV photoelectric effect. The ejected electron is known as a photoelectron, and radiation emitted in the subsequent relaxation process of the atom is called fluorescence radiation. Conservation of energy during the process gives a
maximum kinetic energy for the emitted photoelectron of:

$$E_{\text{kin}} = \frac{1}{2} m v_{m,q}^2 = h\nu_0 - h\nu_q$$

(1.9)

where the binding energy of the shell is $E_q = h\nu_q$ and the energy of the incident X-ray is $E_0 = h\nu_0$. If $\nu_0 < \nu_q$, then there is not enough energy to eject an electron from the q shell. The number of photoelectrons from the q shell of an atom decreases as the incident X-ray energy increases beyond the shell energy, but the energy of each photoelectron increases. The photoelectron angular distribution is of the $\sin^2(\theta)$ form, where $\theta$ is angle between the direction of incidence of the X-ray photon and the direction taken by the photoelectron.

Relaxation processes

After absorbing an X-ray photon and ejecting a photoelectron, the atom must relax through some process. There are two mechanisms though which this can happen: emission of fluorescence radiation and Auger electrons.

Fluorescence Radiation

If an outer shell electron falls to fill the inner shell vacancy and fluorescence radiation is given off in a one-step process, the energy of the fluorescence radiation is simply the difference between the energies of the two shells. Fluorescence radiation is an important process for elements with high Z and hence high energy core electron levels (>10keV). Atoms from any of the higher energy shells can fall to the inner shell in the process of relaxation, with corresponding fluorescence radiation energies, and probability decreasing as fluorescence radiation energy increases. For example, electrons can fill a K shell vacancy by falling from the L, M or N shells, emitting $K_\alpha$, $K_\beta$ and $K_\gamma$ X-rays respectively, with $K_\alpha$ the most probable. This one stage relaxation process is most likely for K shell vacancies, with decreasing probability for L, M and N shells. As examples, fluorescence yield for the Cs K shell is ~0.9, and for the Br K shell is ~0.63 [58].
The Auger Effect

The other major relaxation process is the Auger effect. In this, as in the radiative process, the inner shell vacancy is filled by an electron falling from an outer shell. However, instead of the excess energy being emitted in the form of radiation, a second electron is ejected, most often from the same shell as the electron which filled the inner shell vacancy. These two electron transitions happen simultaneously, and no radiation is emitted. As a result, the atom is doubly ionised. An Auger process has notation of the form $K \rightarrow LM$, where the initial vacancy in the K shell is filled by an L shell electron and an M shell electron is simultaneously ejected. The energy of the M shell, or Auger, electron is given by:

$$E_A = E_K - E_L - E_M$$  \hspace{1cm} (1.10)

The Auger process can obviously only occur if $E_A > 0$, and selection rules determine that the final and initial states have the same symmetry and parity. The probability of an Auger process from initial bound states of $\psi_1^i$ and $\psi_2^i$ to a bound state $\psi_1^f$ and a non-bound state $\psi_2^f$ is given by:

$$P = \frac{2\pi}{\hbar} | < \psi_1^f \psi_2^f | \frac{e^2}{r_1 - r_2} | \psi_1^i \psi_2^i > |^2$$  \hspace{1cm} (1.11)

The probability of an Auger transition is highest at low energies and for atoms with low Z. An atom may also emit more than one Auger electron, and a series of Auger electrons can be emitted of decreasing energy in a vacancy cascade.

Coster-Kronig Transition

A Coster-Kronig transition is an Auger transition of the type $X_i \rightarrow X_f Y$, where the initial vacancy and the electron that fills the vacancy come from the same shell (same principal quantum number) but different subshells (different orbital quantum numbers). Because of the high overlap between the initial and final wavefunctions, this type of transition has a very high probability of occurring. Again, this process is radiationless.
Chapter 2

Calibration in the 50-350eV range

2.1 Introduction

This chapter considers the collection and analysis of quantum efficiency (QE) data taken on alkali-halide coated microchannel plates at the Daresbury Synchrotron Radiation Source in January 1995. Two MCP chevron detectors were used at that time; one on beamline 6.1 and one on beamline 4.2. The data taken on beamline 6.1 covered the energy range 50-350eV, and will be looked at here. The data taken on beamline 4.2 covered the energy range 2-6keV, and is analysed in Chapter 3.

Charge abstraction lifetests taken on beamline 6.1 during the same period are also discussed.

Measurements of QE as a function of energy for the MCP detector appear in Section 2.2.3. The ratio of QEs for CsI and KBr photocathodes is also discussed in Section 2.2.3 along with data illustrating the variation of QE as a function of incident X-ray angle. The charge abstraction life-tests are analysed in Section 2.3.
2.2 Quantum Efficiency measurements

All test detectors considered in this body of work were two stage ‘chevrons’ of 36mm diameter Philips Photonics low noise (radioisotope free [40]) lead oxide glass MCPs. The MCP bias angle was 6°. The MCP channels were 12.5μm diameter on a 15μm pitch, with open area fraction 63 percent. The channel length to diameter ratio was 120:1, and the MCP active area was 7.07cm². The front plate of each detector was coated through a semicircular mask over half its area with 14,000Å CsI, with an equivalent thickness of KBr on the remaining half (Fig. 2.1a). The MCPs were rotated during both depositions to ensure an even coating on the inside of the channel walls. The coating took place at normal incidence. Due to the bias angle of the MCPs, one side of the channel was coated while the other side was shadowed. This is illustrated in Figure 2.1b. The cone angle of X-rays emanating from the AXAF High Resolution Mirror Array (HRMA) is sufficiently small that, in the flight HRC, all interactions will be with the coated sides of the channels.

2.2.1 Beamline 6.1

Measurements in the 50-350eV range were made on beamline 6.1. Beamline 6.1 is generally used for solid state photoemission studies in surface science. The light is reflected off a pre-mirror, through an angle of 11.4° onto the monochromator. The monochromator is a Miyake plane grating with 1200 lines per mm. The light is then incident on one of two exit mirrors, and is focused vertically through exit slits. The exit mirrors are coated with 400Å of Au. There are two different focus positions for each mirror, hence four different angle settings and four energy ranges. For our experiment, energy range one was used, from 50-350eV. Finally, an ellipsoidal mirror deflects the light into the centre of the experimental chamber. Photon energy is selected by rotating the grating about its horizontal axis. The exit slit of the monochromator was set to 100μm, giving a resolution of 0.1eV at 80eV[59]. The MCP detector was mounted in the end-chamber on a manipulator which took the form of a vertical rod, allowing rotation in one axis and translation in two axes. The bias angle of the plates fell in the plane of rotation. The applied voltage was 1550V across each of the plates, with an electron accelerating potential difference of 200V between the MCPs. The potential difference between the resistive anode readout element
and the rear MCP was 300V. No beam monitor was available in low ring-current mode.

2.2.2 Initial Observations

At the start of the experimental campaign the SRS ring current was 0.6\(\mu\)A and the 1/e lifetime of the current was approximately 50 hours. The measuring sequence was of three days duration, with uninterrupted beamtime throughout that time. The flux through the monochromator varied significantly with energy; this had a corresponding effect on the count rate and pulse height distribution of the detector. The noise count rate above a lower level discriminator of 0.2pC was less than 20s\(^{-1}\), compared to a signal count rate of between 200s\(^{-1}\) (at an angle of incidence of 0° with respect to the channel axis, KBr photocathode, 70eV) and 22,000s\(^{-1}\) (9°, CsI, 150eV). Typical integration times, for this chapter and subsequent chapters, were between 1 and 10 seconds, so statistical errors are generally very small. Due to the high count rate at the peak of the monochromator response, gain suppression of the MCP occurred. In consequence, some of the pulse height distributions obtained were quasi-exponential. Figure 2.2 shows pulse height distributions obtained at the ‘peak’ and the ‘wings’ of the monochromator response for CsI. The consequences of this gain suppression will be discussed in Section 2.2.3 below.

Initially, measurements were made of the variation of count rate with angle, to determine the
Figure 2.2: Pulse height distributions obtained at 150eV (peak of the monochromator response: 22,000 counts s$^{-1}$) and 70eV (wing of the monochromator response: 800 counts s$^{-1}$). CsI photocathode. Channel number 157 corresponds to a signal gain of 1.0pC
Figure 2.3: Angle scan taken with KBr at 277eV (the energy of C-K characteristic X-rays). The channel axis lies at a manipulator scale angle of 156°, normal incidence to the MCP at 150°.

Angular scans were taken at a number of energies for both photocathodes, and all showed minima at a reading of 156° on the chamber angular scale, implying that this scale reading corresponds to the channel axis of the MCP (Figs. 2.1b, 2.3).

The height of the relative efficiency peak at 150° compared to that at 160° suggests that it is at 150° that the photons are interacting with the CsI coating on the inner channel walls, not with the bare glass. Thus, a chamber angular scale reading of 150° corresponds to normal incidence to the MCP surface. These angle scans will be discussed further in Section 2.2.3.

Quantum efficiency versus energy scans were taken at 1eV steps over the range 50-350eV for both CsI and KBr. These scans were repeated at 5° intervals for incident angles in the range -16° to +4° relative to the channel axis (140° to 160° on the chamber angular scale). Scans with higher resolution (0.5eV) were made on absorption edge related features hinted at on the initial scan. Scans were also taken at extreme angles of 170° and 195° (see Figure 2.1b) on the CsI-coated half of the detector, to search for any features associated with the lead oxide glass
Figure 2.4: Raw data from QE against energy scans on KBr and CsI, together with the monochromator response.

Raw data from sample scans are shown in Figure 2.4, along with the pre-calibrated monochromator response curve obtained using a tungsten grid reference counter [59].

2.2.3 Analysis

Quantum efficiency versus energy maps

In order to obtain the relative efficiency of the coated MCP detector, it was necessary to remove the monochromator response from the raw data. The monochromator response was measured at the start of the period at Daresbury using a tungsten grid reference counter. However, it was soon found that due to gain suppression and consequent event loss of the detector at high count rates, this procedure was not straightforward. In order to circumvent this problem, a data set from Siegmund et al. was used [24, 25]. Seven absolute QE values for a KBr-coated MCP detector in the range 50-300eV were interpolated to give a continuous data set (Fig. 2.5) and the corresponding Daresbury data (KBr photocathode, ~15° incidence with respect to the channel axis) was forced to fit the shape of the interpolated data by applying a correction factor (Fig. 2.6). This correction factor was then applied to the beam profile to give a modified 'gain
suppression corrected' profile. This modified profile was used to correct all other scans. This method does not allow for variations in gain suppression due to higher count rate at smaller angles of incidence with respect to the channel axis. However, it should give an approximate picture of the gain suppression.

Second order contamination from the monochromator was neglected. At 80eV the second order fraction is known to be 4.6 percent, dropping to less than 1 percent at 100eV. The count rate through the monochromator above an energy of 300eV was low, so gain suppression would not be expected. Therefore no gain suppression correction was applied to the data above this energy. These scans were corrected for exponential beam decay with time, with a period of 50 hours. The QE data was taken over a relatively short period of time, and count rates at the beginning and end of the experimental period were not significantly different. [59]

In order to finally obtain absolute values of QE, both photocathodes of both detectors were post-calibrated at Leicester at 0.28keV (C-K) using a proportional counter of known efficiency as a reference counter. This method is described in more detail in Section 3.6.2. The C-K calibration (at an X-ray incidence 6° to the channel axis - normal to the MCP front surface)
Figure 2.6: Gain suppression correction factor versus X-ray energy. Only the functional form of the correction factor is important: the absolute values obtained are simply a function of the reference point used to compare the Daresbury data set with the data set of Siegmund et al.

was then used as an benchmark to determine absolute QE values for all the data sets. The final results of this analysis are shown in Figures 2.7 and 2.8.

The general shape of the CsI QE curve, with peaks at 110 and 210eV, agrees with that of previous work by Saloman et al. [18] There are few absorption edge related features in any of the scans, except for a QE peak associated with the N_{III} absorption edge of Cs at 161eV. Figure 2.9 shows this feature in more detail, with enhanced energy resolution of 0.5eV. This feature has previously been observed, for example in the linear absorption coefficient survey of Cardona et al. [60] Lead glass features at 108 and 115eV can also be noted in the scan at 14°(see Figure 2.10). These have been previously associated by us with the Pb O_{II} edge. [4]

CsI/KBr quantum efficiency ratios

The ratio of CsI to KBr quantum efficiencies was found in three ways. First, linear scans were taken at Daresbury across the detector, and the count rates recorded on the CsI and KBr sides. This was done at a number of different energies at an angle of 9° from the channel axis. Second,
Figure 2.7: Absolute quantum efficiency variation with energy and angle of incidence with respect to the channel axis for CsI. The Daresbury angular scale reading is shown for each data set. Recall that a reading of 156° on the angular scale corresponds to 0° to the channel axis, and 150° corresponds to normal incidence to the front of the MCP.
Figure 2.8: Absolute quantum efficiency variation with energy and angle of incidence with respect to the channel axis for KBr. The Daresbury angular scale reading is shown for each data set. The data set at an angle of 140° obviously mirrors the shape of the Siegmund et al. data used to correct the beam profile.
Figure 2.9: Increased resolution scan across the CsI $N_{III}$ edge.

Figure 2.10: Increased resolution scan of the lead glass features at 108 and 115eV. Angle of incidence is 14° to the channel axis.
after the QE energy scans had been analysed, the ratio of CsI to KBr absolute QE was found at an angle of -16° from the channel axis for various energies. Finally, discrete values of QE were found by analysing post-Daresbury and pre-Daresbury calibration images, to obtain the ratio of the number of counts on either side of the plates. This data is shown together on Figure 2.11, along with data from Siegmund et al. [21] taken at 15° to the channel axis on MCPs with bias angle 13°.

Note that the ratio of CsI to KBr QE in the data of Siegmund et al. is rather lower than in the Daresbury data, although it follows the same functional form. Note also that the data taken from the QE-energy scans follows the shape and magnitude of the data taken directly from Daresbury count rates. The pre- and post- Daresbury calibration data are well within the range obtained by the other methods. From the Daresbury data, over most of the energy range considered, CsI is the more efficient photocathode. The HRC project has reconsidered the use of KBr as the HRC-S photocathode material, taking into account the sharper FUV cut off of KBr compared to CsI [23], and decided to use CsI as the photocathode on both MCPs, principally because of its higher quantum efficiency.

Quantum efficiency as a function of angle

Scans of count rate as a function of angle were carried out at Daresbury on both photocathodes, at energies of 70, 150 and 277eV (the ‘peak’ and ‘wings’ of the monochromator response). All scans showed the characteristic dip at an angle scale of 156° corresponding to the channel axis. Absolute QE as a function of angle was obtained from the QE-energy spectra, and examples of data sets from these two methods are shown in Figure 2.12. It can be seen that the data from the energy scans closely follows the directly taken count rate data.

2.3 Charge Abstraction Lifetests

Due to the small size of the beam spot on line 6.1, it was possible to extract a large amount of charge per unit area over a relatively short period of time, while the detector remained in photon counting mode. Both the CsI and the KBr sides of the plate were subjected to count rates of
Figure 2.11: Ratio of quantum efficiencies for CsI- and KBr- coated MCPs from a number of sources. All angles are relative to the channel axis.
Figure 2.12: QE as a function of angle for CsI at 70eV. Recall that the channel axis is at a manipulator setting of 156°. The Daresbury angle scans (derived from count rate measurements) are normalised to the QE-energy scan data at 150°.
Figure 2.13: Images from KBr- and CsI-coated halves of the MCP detector. Images linearised in software to remove resistive anode distortion. The linear 'drop out' features correspond to ‘preferred addresses’ in the digital portion of the amplitude ratio computation on the resistive anode output signals.

10,000s$^{-1}$ for 12 hours, at an X-ray energy of 100eV (near the peak of the monochromator response). Pulse height distributions were taken at 100eV throughout the test, and every hour at 70eV, where the count rate was low and the pulse height distribution was unaffected by count rate gain suppression. Throughout the tests, the number of counts accumulated at each energy was noted. It was therefore possible to determine the cumulative charge abstracted as the tests progressed. Images of the beam are shown in Figures 2.13a,b.

From the image on the CsI side of the plate (Fig. 2.13b), the beam spot size was found to be 0.0048cm$^2$ (FWHM). The beam spot size on the KBr photocathode appears larger, but this is due to very low gain and high count rate leading to position errors in the division algorithm of the electronics and artificially spreading the spot out. The resulting plot of gain against charge abstracted per cm$^2$ is shown in Figure 2.14. It was assumed that the total count rate fell within the beam spot size given above. Of course, the charge abstracted per cm$^2$ will vary across the beam spot as the incident X-ray intensity varies. The method used here gives an estimate of the maximum charge abstracted per cm$^2$. We note some salient features:
Figure 2.14: Plot of gain against charge abstracted per cm$^2$ for KBr and CsI lifetests. Note the 100V increase in plate voltage at an ordinate value of 0.04pC which restores the lost gain.

(a) the gain loss is easily recovered by increasing the plate voltages.

(b) the gain lifetime of the Philips low noise glass MCPs is comparable to that of standard glass MCPs (see Fig. 5b of Fraser et al. [61]). This is an extremely important result in qualifying such plates for use on the AXAF HRC.

Figure 2.15 is a companion plot of count rate against charge abstracted per cm$^2$. The fractional count rate decrease is much less than the fractional gain decrease over the same period, showing that the gain decrease is not due to a decrease in QE. The count rate decrease is simply due to events being lost below the lower level discriminator threshold as the gain decreases, and the count rate returns to its original value when the voltage (and gain) are increased.

2.4 Conclusions

The second MCP detector calibration campaign using the Daresbury SRS was generally successful even though the computation and removal of the appropriate monochromator response
on beamline 6.1 was seriously hampered by detector gain suppression. An attempt was made to correct for these problems by using an external data set. However, the method used does not allow for variations in the amount of gain suppression with angle. In later work (described in Chapter 4), emphasis was placed on reducing the count rate per unit area so that gain suppression did not result in the loss of counts and the monochromator response could be directly factored out from the raw data.

Despite these problems, this measurement series in the 50-350eV band has produced several significant results. The QE of CsI and KBr appears smooth within this range, apart from the line feature due to Cs \( N_{II} \) at 161eV. The lead features from the glass noted previously at 108 and 115eV [4] were also visible at high incidence angles. This data has also determined the superiority of CsI over KBr as a photocathode in the 50-350eV band. The lifetests on discussed here have demonstrated that Philips low noise glass is comparable with standard glass in terms of gain decay due to abstracted charge and that the gain depletion can be recovered by increasing the plate voltage.
Chapter 3

Calibration in the 2000-6000eV range

3.1 Beamline 4.2

The Interdisciplinary Research Centre in Surface Science (IRC) beamline 4.2 at the Daresbury Synchrotron Radiation Source (SRS) was used in January 1995 to measure microchannel plate relative QE as a function of energy in the energy range 2000-6000eV.

Beamline 4.2 is a double crystal monochromator beamline with a chromatic pre-mirror section which allows the high-energy cut off to be selected while maintaining a fixed angle of X-ray incidence on the pre-mirrors. The layout of the beamline is shown schematically in Figure 3.1 [62]. The pre-mirror system consists of a plane mirror followed by a sagittal cylindrical mirror. Selection of the photon energy is governed by rotation of the first crystal in the double crystal monochromator, while the beam direction is controlled by rotation and translation of the second crystal. The Bragg angular range of the monochromator is $14^\circ$ to $76^\circ$.

As set up originally for the January 1995 ‘low ring current’ campaign the beamline provided significant flux between 2000 and 4700eV with a peak at about 3500eV. High energy flux was suppressed by choice of the mirror materials: the X-rays were incident upon the uncoated (quartz) section of the first mirror, and on the Cr coating of the second mirror. The resolution
The low noise MCP detector used on beamline 4.2 was of the same configuration as that described in Chapter 2. Reference [63] also describes the low noise microchannel plate detector (Philips photonics low noise glass MCPs, half-coated with 14,000 Å KBr and CsI in an appropriate HRC geometry) and some initial analysis, of the 2-6keV data. This chapter presents a more exhaustive analysis of the data, including the results of post-Daresbury absolute QE measurement at Leicester.

The applied voltage was 1600V across each plate, with an inter-plate electron-accelerating voltage of 200V and a potential difference between the rear MCP and the resistive anode of 300V. The detector was mounted on a manipulator which could be translated in two axes (perpendicular to the direction of X-ray incidence) and rotated in one.
Figure 3.2: Pulse height distributions obtained at 2000eV (edge of the monochromator response: 13,600 counts s$^{-1}$), 3000eV (peak of the monochromator response: 12,200 counts s$^{-1}$) and 4000eV (edge of the monochromator response: 2000 counts s$^{-1}$). All taken at 17° to the channel axis. KBr photocathode. Quartz/Cr mirror coating.

3.3 Initial observations

The flux through the monochromator varied with energy. This led to a count rate of between 1100s$^{-1}$ (on KBr photocathode at 4000eV for an X-ray incidence angle of 29° with respect to the channel axis) and 43,000s$^{-1}$ (on CsI at 2000eV and at 8° with respect to the channel axis). The noise count rate above a lower level discriminator of 0.25pC was generally between 2 and 30s$^{-1}$. Pulse height distributions obtained at high and low count rates are shown in Figures 3.2 and 3.3. Noise pulse height distributions showed the expected exponential shape.

Unlike the pulse height distributions shown in Chapter 2, these PHDs show no high count rate gain suppression. Although the count rates over the detector active areas were comparable, the beam spot size on beamline 4.2 was greater than that for beamline 6.1 reported in Chapter 2. Images of the spot on beamline 4.2 are shown in Figure 3.4. The area of the beam spot is approximately 15.8mm$^2$. This implies that the counts were spread over a large number of
Figure 3.3: Pulse height distributions obtained at 2000eV (edge of the monochromator response: 18,000 counts s$^{-1}$), 3000eV (peak of the monochromator response: 15,600 counts s$^{-1}$) and 4000eV (edge of the monochromator response: 1800 counts s$^{-1}$). All taken at 17° to the channel axis. CsI photocathode. Quartz/Cr mirror coating.
Taking into account the non-uniformity of the beam spot, the maximum count rate per channel is 0.88 counts channel$^{-1}$ s$^{-1}$.

One would expect the modal gain to increase as X-ray energy increases, however inspection of Figures 3.2 and 3.3 shows that this is not the case: the PHDs at 4000eV have consistently lower modal gain than those at 2000eV. This could possibly be due to uneven gain decay of the detector, caused by high charge abstraction (see Chapter 2 for further discussion of gain decay in similar MCPs). Movement of the beam position with energy would thus result in lower modal gain than otherwise expected. The 5000eV PHD shown in Figure 3.5 seems to reinforce this hypothesis. Figure 3.6 shows a map of the MCP gain, with a contour map of the beam position at 5000eV superimposed. The light areas in the figure indicate gain decay. It can be seen that the beam straddles the gain decayed area, so that part of the PHD shows gain decay (the PHD peak with lower modal gain, corresponding to the left-hand side of the beam), and part does not (the PHD peak with higher modal gain, corresponding to the right-hand side of the beam). Fortunately, the modal gain is high enough for all the PHDs shown here that any the gain decay discussed has no effect on the MCP QE.
Figure 3.5: Pulse height distributions obtained at 5000eV (2400 counts s$^{-1}$) and 4500eV (4300 counts s$^{-1}$). Taken at 8° to the channel axis. KBr photocathode. Pt/Cr mirror coating.

Figure 3.6: Gain decay map taken on KBr at 5000eV at 8° to the channel axis. Superimposed is a contour map of the beam position.
3.4 Orientation of the detector

Measurements of the count rate variation with angle were made at an early stage in the experimental campaign. This was to establish the relationship between the chamber angular scale and the detector geometry. Initial examples of the variation of CsI and KBr count rates with angle are shown in Figure 3.7. It can be seen that both photocathodes give angular responses of the same functional form, with peaks at approximately 335°. There is no minimum in any curve, due to the orientation of the detector in the chamber. The detector was not positioned with the bias angle of the plates in the plane of rotation of the MCP, so there is no angle at which the incident X-rays can shine straight down the channels, and thus no minimum. It was therefore necessary to undertake further experimental determination of the detector geometry at Leicester.

Figure 3.8 shows the relationship between the plane of the front of the detector and the channel axis (see reference [64]). Normal incidence to the front of the detector was known to be 335° on the Daresbury chamber angular scale. For the application of the present data to the AXAF HRC, it was necessary to determine the azimuthal offset between the plane of the MCP rotation and the plane of the bias angle (angle $\psi$). Full-face images were taken at Daresbury, which enabled determination of the angle between the CsI/KBr interface on the MCP front surface and the resistive anode vertical. Analysis of the beam position on the CsI-coated MCP half relative to the KBr-coated MCP half gave the angle between the resistive anode vertical and the chamber vertical. Combination of these figures resulted in knowledge of the angle between the CsI/KBr interface and the chamber horizontal (see Figure 3.9). At Leicester, a laser was shone through the front MCP and the resulting interference pattern of spots in a hexagonal structure was observed. By manipulating the angle of incidence to equal the MCP bias angle, and then rotating the MCP, a position of maximum intensity could be observed. This corresponded to the radiation shining straight down the MCP channels. The angle of the CsI/KBr interface to the azimuthal offset was thus determined. This resulted, finally, in a value of 96° for the angle $\psi$ at Daresbury. The angle of X-ray incidence, $\theta$, with respect to the channel axis could then be calculated using Equation 3.1 [64], where $\theta_B$ is the bias angle of the channels and $\gamma$ the incident angle with respect to the normal to the front surface of the detector:

$$\cos \theta = \cos \theta_B \cos \gamma + \sin \theta_B \sin \gamma \cos \psi$$

(3.1)
Figure 3.7: Angle scans taken on KBr and CsI at 2500eV. The ordinate shows the angle as read off the chamber angular scale: related by an offset of 335° to the incidence angle with respect to the normal to the front surface of the MCP (γ). Normal incidence to the front of the MCP is therefore at 335°.

The large azimuthal offset means that the smallest possible angle of incidence with respect to the channel axis is 6°. Also, at ~90° azimuthal offset, the X-rays are not incident independently on the coated and shadowed sides of the channel wall (see reference [63]), so there should be little difference between +10° angle of incidence with respect to the channel axis and -10°. The variation of QE with angle will be considered further in Section 3.6.4.

3.5 Quantum Efficiency Data

Quantum efficiency versus energy data was first taken at 3eV intervals on both CsI- and KBr-coated detector halves over the range 2000-4000eV, using the quartz and Cr-coated mirrors to suppress higher order radiation. The scans were made at X-ray incident angles of 8° and 17° with respect to the channel axis (340° and 350° on the chamber angular manipulator scale). Higher resolution scans (1eV) were then taken across previously noted absorption edge features.
Figure 3.8: Geometrical construction for calculation of angle with respect to the channel axis. 
OB is the normal to the MCP surface, X-rays are incident along AO, where O is the centre of a channel. OC is the channel axis, with $\theta_B$ the bias angle of the plate. $\psi$ is the azimuthal offset, and $\gamma$ the incident angle with respect to the normal to the front surface of the detector.
Figure 3.9: MCP and resistive anode geometry for determining the angle between the CsI/KBr boundary and the true vertical.

Data was further taken at 3eV steps over the range 3400-6000eV using the Pt/Cr mirror. Scans were made at 8° on the KBr photocathode, and at 8°, 6° and -7° with respect to the channel axis on the CsI photocathode. Again, higher resolution scans (1eV) were taken across the edge features. Raw data from sample scans is shown in Figures 3.10 and 3.11, with relevant edges marked. Even without the removal of the monochromator response, edge features are clearly visible. Shifts in the position of the edges with respect to their tabulated values can be seen on the I_{Li} and Cs_{LII} edges. Similar edge shifts are discussed by Owen et al. [65] for gold, platinum and other X-ray mirror materials.

3.6 Analysis

3.6.1 Removing the monochromator response

Calibration curves for the monochromator/mirror combinations were provided by Daresbury SRS staff for both the quartz/Cr [62] and Pt/Cr mirror coatings. Figures 3.12 and 3.13 show
the monochromator/mirror responses with energy as measured in normal, high ring current SRS operation, using an Al foil. The quartz curve has been extrapolated as a straight line below 2400 eV. The Al efficiency response as a function of energy, measured by Day et al. [66], is shown in Figure 3.14. The true calibration curve for each mirror is thus the raw data divided by the Al efficiency. Relative quantum efficiency maps with energy are obtained by dividing the uncorrected MCP QE data by the appropriate mirror calibration curve and correcting for beam decay during the experimental period. The beam was assumed to decay exponentially, with a time period of 50 hours. The QE scans were not corrected for MCP noise. Over the whole energy range noise was less than 1\% of the count rate.

3.6.2 Absolute Quantum Efficiency Calibration

The MCP detector was post-calibrated at Leicester using a proportional counter in order to determine absolute QE values for the normalisation of the Daresbury relative QE data. This was necessary because the flux from the monochromator was not well known in absolute terms,
Figure 3.11: Plot of uncorrected relative QE against energy for KBr. Potassium K-edge indicated by broken vertical line. $8^\circ$ with respect to the channel axis.

Figure 3.12: Calibration curve for quartz/Cr mirror combination. Note the relatively smooth monochromator response.
Figure 3.13: Calibration curve for Pt/Cr mirror combination. Note the considerable structure in the beam flux. This calibration curve was taken several months after that for the quartz/Cr mirror combination, which may account for the structure present.
Figure 3.14: Current quantum yield of aluminium as a function of energy. Note that here, QE refers to current quantum yield (electrons per photon), while in general in this paper, QE refers to pulse quantum efficiency (counts per photon). Data from Day et al. [66]

especially at low ring current, and no reference counter was available at Daresbury. The experimental arrangement for this post-calibration is shown in Figure 3.15. The MCP was mounted in a vacuum chamber on a manipulator which allowed translation in two axes and rotation in one. An X-ray spot could be projected onto either the KBr or CsI side of the MCP, and observed using the MCP resistive anode readout. The procedure was relatively simple: the count rate of the MCP was noted at a given angle (with the proportional counter out of the X-ray beam). The proportional counter was then lowered into the beam and the count rate of the PC measured. This was repeated for a number of MCP angles on both photocathodes. Data was taken at three energies: C-K (277eV), Si-K (1740eV) and Ru-L (2558eV). The PC gas and filter used for each energy are shown in Table 3.1.

The absolute QE of the proportional counter ($Q_E_{PC}$) is calculable for a given gas composition and pressure [67], and thus the absolute QE of the MCP ($Q_E_{MCP}$) is given by:

$$Q_{EMCP} = Q_{E_{PC}} \frac{(N - noise)_{MCP} T_w}{(N - noise)_{PC} T_m}$$

(3.2)

($N - noise$)$_{MCP}$ and ($N - noise$)$_{PC}$ denote the count rate minus the noise count rate for the MCP and PC. The count rate on the PC is the mean of the count rates before and after
Figure 3.15: Absolute QE calibration set-up. There is no UV shield in front of the MCP detector.

Table 3.1: Filters, filling gases and PC window transmission used in MCP quantum efficiency measurements

<table>
<thead>
<tr>
<th>X-ray emission line</th>
<th>Energy (keV)</th>
<th>Filter</th>
<th>PC gas</th>
<th>$T_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-K</td>
<td>0.28</td>
<td>macrofol</td>
<td>P50</td>
<td>0.169</td>
</tr>
<tr>
<td>Si-K</td>
<td>1.74</td>
<td>1μm Ag</td>
<td>P10</td>
<td>0.399</td>
</tr>
<tr>
<td>Ru-L</td>
<td>2.56</td>
<td>1μm Ag</td>
<td>P10</td>
<td>0.427</td>
</tr>
</tbody>
</table>
the corresponding MCP measurement has been taken. \(T_w\) denotes the transmission of the PC window, which is measured independently as a function of energy, and \(T_m\) the transmission of the MCP mesh, which has a value of 0.9 at normal incidence (measured using a method described in Barstow et al. [68]). The mesh transmission as a function of X-ray incident angle \(\theta\) is given by the equation:

\[
T_\theta = T_0^{\frac{1}{2}}[1 + (T_0^{\frac{1}{2}} - 1) \sec \theta]
\]  

(3.3)

The values of the window transmission at the energies considered are given in Table 3.1.

Absolute quantum efficiency values obtained for this detector using the procedure outlined above are given in Table 3.2. The same method as described in Section 3.4 was used to determine the azimuthal offset of the MCP in the Leicester test chamber, which was found to be 90°. 0° on the chamber angular scale at Leicester is equivalent to 335° at Daresbury, so the scans taken at 340° at Daresbury (8° to the channel axis) can be directly compared with the absolute QE values at 5.6° on the Leicester scale (again, 8° to the channel axis). Ru-L is the only post-calibrated energy which was covered by beamline 4.2, so the values of absolute QE at 5.6°, Ru-L energy \((QE_{KB, n=0.106}, QE_{CS, n=0.206})\) were used as benchmarks.

However, when the ratio of CsI to KBr QE at the Ru-L energy was considered, a number of inconsistencies became apparent between the data taken at Daresbury and that taken at Leicester after the Daresbury run. The QE-energy scan at Daresbury (8° relative to the channel axis, 2558eV, on the quartz/Cr mirror combination) gave a CsI/KBr QE ratio of 1.68. Other data taken at Daresbury implied a ratio of less than 1.5: scans of count rate as a function of angle gave a ratio of 1.47 (at 2500eV and 8° with respect to the channel axis) and 1.40 (at 2500eV and 6°), and a linear scan across the detector gave a value of 1.27 at 3000eV and 6°.

In contrast, during absolute QE calibration at Leicester, after the Daresbury run, the CsI/KBr QE ratio was found to be 1.93. Analysis of the count rate on the two photocathodes from a post-calibration image gave the ratio to be 2.12.

Count rate data was also taken at C-K and Si-K energies in pre-Daresbury calibration. Comparison of this with similar post-Daresbury calibration showed a jump of approximately 30 percent in the ratio of the QEs of CsI- to KBr-coated MCP after Daresbury compared to before the SRS visit. This discrepancy seems to be a real effect. The X-ray source at Leicester is not as monochromatic as that at the SRS, however any spread in X-ray energy would not explain the
Unfortunately, comparable absolute QE data was available for two similar CsI and KBr coated MCPs at C-K and Si-K energies. This data was in good agreement with the absolute QE of the detector being discussed here for the CsI coating, but showed significantly higher KBr QE measurements than the present detector. Given this corroboration, the measured post-Daresbury absolute QE of CsI was assumed to be correct and was used to normalise the CsI relative QE measurements taken at Daresbury. The ratio of CsI to KBr relative QE at Daresbury was then used to determine absolute QE values for the KBr-coated detector. The results of these absolute QE calibrations on the quartz mirror are shown in Figures 3.16 and 3.17. Features marked with arrows are common to both cathodes and both angle settings and are therefore assumed to be artefacts of the monochromator/mirror combination not removed by the normalisation of Figure 3.12. These features are discussed further below.

No post-Daresbury absolute QE measurements were possible in the range covered by the Pt/Cr mirror, so in order to determine the absolute QE of the higher energy data the overlapping energy
Table 3.2: MCP QE measurements. The data was taken at 0° on the chamber angular scale, which corresponds to normal incidence to the front of the MCP.

<table>
<thead>
<tr>
<th>X-ray emission line</th>
<th>Energy (keV)</th>
<th>$Q_E_{CsI}$</th>
<th>$Q_E_{KBr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-K</td>
<td>0.28</td>
<td>0.411</td>
<td>0.258</td>
</tr>
<tr>
<td>Si-K</td>
<td>1.74</td>
<td>0.461</td>
<td>0.221</td>
</tr>
<tr>
<td>Ru-L</td>
<td>2.56</td>
<td>0.274</td>
<td>0.147</td>
</tr>
</tbody>
</table>

Figure 3.17: Absolute QE for the KBr-coated MCP using the quartz/Cr mirror combination.
The spurious features indicated by arrows in Figures 3.16-3.19 are thought to be instrumental in origin, but for some reason were not present in the calibration curve. The quartz calibration curve (Figure 3.12) is particularly smooth: considerably smoother than our data. A number of prominent features are seen in our data between 2000 and 3500 eV, below the energy of the K-K or I \( L_{III} \) edges, where the curve is expected to be smooth. There are a number of possible explanations for this discrepancy. The response of the monochromator is dependent on the quality of the crystals and the beam and beamline 4.2 is known to be particularly susceptible to any beam instability. Also, the calibration curve was measured with the ring in its normal operating mode, whereas our experiment was measured in low ring current mode. Finally, one of the double crystals is known to be slightly chipped in one corner, and this could produce...
fluctuations and noise in the monochromator response. Factors such as these are also thought to be responsible for anomalous features at 3300eV on all the scans (the energy of a known crystal glitch) and at 4360eV on the CsI/quartz mirror scan at 340°.

Examples of high resolution scans across edge features are shown in Figure 3.20.

An attempt has been made to remove the spurious monochromator/mirror features in some of the near-edge scans by comparison with similar scans on the other photocathode. So, for example, an exponential curve, $S(E)$, was fitted through CsI QE data taken at an incident angle of 17° (with respect to the channel axis) between 3550eV and 3800eV ($QE_{CsI}(E)$). $QE_{CsI}(E)$ was then divided by the exponential curve ($S(E)$), giving a measure of the deviations in $QE$ ($D(E)$) from the expected smooth curve. These deviations are assumed to be due to the monochromator response. KBr QE data at 17° across the K-K edge was then divided by $D(E)$, which, in principle, should remove the spurious features from the KBr data. Figure 3.21 shows the near-edge structures of Figure 3.20, with this procedure applied to remove the monochromator features.

Figures 3.22, 3.23 and 3.24 show the near edge structure of the Cs and I $L_{III}$ edges and the K-K
Figure 3.20: High resolution scans across (a) the K K edge at 17° (b) the Cs $L_{III}$ edge at 8°. Note the shift in the Cs $L_{III}$ edge from its tabulated position.

Figure 3.21: Corrected high resolution scans across (a) the K K edge at 17° (b) the Cs $L_{III}$ edge at 8°. Note the shift in the Cs $L_{III}$ edge from its tabulated position. Both scans have had spurious monochromator features removed.

80
Figure 3.22: (a) Data from Haelbich et al. showing the near-edge structure of the Cs $L_{III}$ edge. (b) CsI-coated MCP QE divided by X-ray energy across the Cs $L_{III}$ edge, for comparison with (a). Spurious monochromator features have been removed. $8^\circ$ with respect to the channel axis.

edge. In each case, the top section of the Figure, (a), shows data from Haelbich et al. [69], and the bottom section of the Figure, (b), shows our data. Our data has been corrected for residual monochromator features, as described above, and the plots show absolute QE divided by the incident X-ray energy. These should be directly comparable with the plots of linear absorption coefficient, $\mu(E)$, above them (since $\text{QE} \propto \mu E$). Large ($\sim 10\text{eV}$) edge shifts are clearly apparent on both $L_{III}$ edges, while the K-K edge shows no such shift. These shifts in edge energy are similar to those seen by Owens et al. [65] and Nelson et al. [70] in the M edges of high-Z metals, and are discussed further in Chapter 4.

3.6.3 CsI/KBr efficiency ratios

The ratio of the QE of CsI to that of KBr was be found in a number of ways in addition to the comparison of absolute QE discussed in the previous section.

(i) Linear count rate scans taken across the MCP at Daresbury provide the most direct way of
Figure 3.23: (a) Data from Haelbich et al. showing the near-edge structure of the I $L_{\text{III}}$ edge. (b) CsI-coated MCP QE divided by X-ray energy across the I $L_{\text{III}}$ edge, for comparison with (a). Spurious monochromator features have been removed. 8° with respect to the channel axis.
Figure 3.24: (a) Data from Haelbich *et al.* showing the near-edge structure of the K-K edge. (b) KBr-coated MCP QE divided by X-ray energy across the K-K edge, for comparison with (a). Spurious monochromator features have been removed. 17° with respect to the channel axis.
comparing the QE of the KBr- and CsI-coated MCP halves. These scans were taken using the Pt/Cr mirror, at an angle of 6° to the channel axis (335° on the manipulator scale).

(ii) Discrete values of QE were obtained by analysing post-Daresbury calibration images, taken at normal incidence to the MCP front surface (i.e. 6° with respect to the channel axis).

(iii) QE-Energy scans at Daresbury taken at 8° and 17° to the channel axis were analysed (340° and 350° on the chamber angular scale).

(iv) Finally, the absolute post-calibration QE of CsI and KBr gave discrete points at 6° to the channel axis. These are all plotted in Figure 3.25, along with data from Eliseenko et al. (pulse quantum yields taken on planar photocathodes at 20° grazing incidence [71]). It can be seen that the post-calibration ratio is considerably higher than that at Daresbury (see Section 3.6.2). The data from direct linear scans agrees closely with that found indirectly from the QE measurements at Daresbury, and with the data of Eliseenko et al. Over most of the energy range considered CsI is the more efficient photocathode, which agrees with the conclusions of Pearce et al. [63] (and Chapter 2) in the 50-350eV range.
3.6.4 Quantum efficiency as a function of angle

As introduced in Section 3.3, data was taken at Daresbury of the variation of count rate with angle. Both photocathodes were calibrated in this way. The results of this calibration are shown in Figures 3.26 and 3.27. The functional form of the response does not vary significantly either with energy or between the two photocathodes; the peak occurs for both photocathodes at 335°. An increase in QE at very low angles and high energy (4000 and 4500eV) on the CsI can be seen, but count rates are very low for these energies, and data points taken later at -30° show no such increase. This angular response data is important for the eventual construction of an AXAF HRC response matrix.

Figure 3.28 shows how the ratio of CsI to KBr count rate varies with angle. A similar increase in the ratio of CsI- to KBr-coated MCP QE at large grazing angles can be seen in the data of Rose et al. [22], although the very large ratios at 4000eV may be spurious. The data at 5° and 15° with respect to the MCP front surface normal (equivalent to 8° and 17° to the channel axis) generally agrees with that of Figure 3.25 across the energy range considered.
Figure 3.27: KBr-coated MCP normalised count rate as a function of incident angle.

Figure 3.28: Ratio of CsI- to KBr-coated MCP count rates
3.7 Conclusions

The use of beamline 4.2 at the Daresbury SRS was reasonably successful. Despite small fluctuations in the monochromator response, the MCP detector response over the 2000-6000eV range has been mapped, and a number of significant results obtained. The QE of CsI and KBr in this range follows the expected exponential shape, with discontinuities due to edge-related features at the caesium and iodine L edges and the potassium K edge. In particular, the large white line on the Cs L\textsubscript{III} is clearly visible. Shifts in the edge energy with respect to previously tabulated data are also noticeable on a number of lines.

As in other energy ranges described in Chapters 2 and 4, CsI was found to be the more efficient photocathode, justifying its use on both AXAF HRC detectors.

A further experimental campaign at the SRS took place in January 1996, where beamline 4.2 was again used, this time to span the energy range 1500-1800eV. Concurrently, beamline 1.1 covered the 250-1400eV range. Analysis of data taken over the lower energy range is considered in Chapter 4 and a preliminary analysis of the 15-1800eV data is shown in the concluding chapter.
Chapter 4

Calibration in the 250-1400eV range

4.1 Beamline 1.1

In January 1996, Beamline 1.1 at the Daresbury SRS was used to make quantum efficiency measurements on a microchannel plate detector which was half-coated with CsI and half-coated with KBr (see Chapter 2 for a full description of the detector geometry).

Beamline 1.1 at the Daresbury SRS contains a high energy spherical grating monochromator (HESGM). The beamline was designed to give high flux in the soft X-ray region 250-1000eV, which could be used to study surface X-ray absorption [72]. The beamline contains no entrance slit, which maximises the flux. Spherical gratings are used, which are relatively easy to fabricate to high precision, thus ensuring a high resolution monochromator. Figures 4.1 and 4.2 show the layout of the beamline. The X-rays are incident on the pre-mirror at an angle of 2° and are focused horizontally. The mirror is coated with Pt, which absorbs all radiation above 2keV. The X-rays are then incident on one of three spherical gratings, which diffract them vertically through a deviation angle of 172°, and focus on the movable exit slit. The gratings have ion etched line densities of 1050, 1500 and 1800 mm⁻¹. Rotating the grating selects the required photon energy, and the position of the exit slit can be varied. The light from the exit slit is finally incident on an ellipsoidal mirror, which focuses it onto the sample position. The beamline is kept under ultrahigh vacuum (pressure < $1 \times 10^{-9}$ mbar), which minimises contamination on
the optical surfaces. If the experimental chamber does not need to be run at ultra-high vacuum, as is the case here, a thin (1500Å) Al window is inserted into the beam path immediately before the sample, to separate the experimental chamber from the beamline.

The 1050 and 1500 mm\(^{-1}\) gratings have significant second order contamination (up to 20%), so the 1800 mm\(^{-1}\) grating was used for our studies. This grating has two sections, one coated with Ni and one with Au, and is translated to expose the desired coating. Both coatings give significant flux between 300 and 1400eV, but the nickel L edges cause calibration problems above 800eV, and second order contamination of the gold grating restricts its use below 800eV. The nickel coating was therefore used over the 250-850eV range, and the gold coating between 800 and 1400eV (see Figures 4.12 and 4.13 for the response of the gratings over these energy ranges).
The second and third order content of the two sections of the 1800 mm\(^{-1}\) grating is shown in Figures 4.3 and 4.4. At the energies considered here, the second and third order contamination is much less than 5\%, so can be neglected in further calculations. The resolving power of the monochromator is due mainly to errors in the figuring of the spherical gratings and the finite source size. The predicted energy resolution of the (1800 mm\(^{-1}\)) grating used here varies from 0.3eV at 500eV to 1.1eV at 1000eV.

4.1.1 Detector configuration

The detector configuration was described in detail in Chapter 2. The detector was set up similarly here, with an applied voltage of 1700V across each plate, an inter-plate accelerating voltage of 200V and a potential difference of 300V between the resistive anode and the rear MCP. The detector was mounted on a manipulator which could be rotated in one axis, which allowed variation of the angle of X-ray incidence with respect to the front of the plate, and translated in three axes.
4.2 Initial observations

The combination of MCP quantum efficiency and monochromator response (nickel grating) gave count rates of between $6.6 \text{ s}^{-1}$ (CsI photocathode at $330^\circ$ on the chamber angular scale, 300eV photon energy) and $3,700 \text{ s}^{-1}$ (CsI photocathode at $295^\circ$ on the chamber angular scale, 710eV). Using the Au grating, the count rate range was between $700 \text{ s}^{-1}$ (CsI; 800eV; $295^\circ$), and $24 \text{ s}^{-1}$ (CsI; 1400eV; $325^\circ$). The detector noise count rate above a lower level discriminator of 0.24pC was of order $2 \text{ s}^{-1}$, over the 30mm active diameter.

Sample pulse height distributions are shown in Figures 4.5 to 4.7. Noise PHDs showed the expected exponential shape. Early in the experimental period, it was noted that the modal gain of the MCP was dropping rapidly as charge was abstracted. For a further discussion of gain decay in similar MCPs, see Chapter 2. This gain decay is apparent in all the PHDs shown (figs 4.5 to 4.7), on both the CsI and KBr photocathodes and on the nickel and gold sections of the grating. It can be seen in Figure 4.5 that on the CsI-photocathode before gain decay, the MCP modal gain increased with increasing energy, as expected, while after gain decay the modal gain was constant with energy. The CsI photocathode shows greater gain decay than the KBr.
photocathode because of the larger amount of charge abstracted from it. Fortunately, the MCPs have a better modal gain than those used on beamline 6.1 (see Chapter 2), so the gain decay has no effect on the MCP count rate or quantum efficiency measurements. The gain was restored periodically during the experimental sequence by changing the position of the illuminated spot on the MCP.

Images of the beam spot were obtained at a variety of angles of incidence and energies, on both photocathodes and with both gratings: Sample images of the beam spot are shown in Figure 4.8. The beam spot size is approximately 0.75mm$^2$ FWHM, which results in a maximum count rate of 0.86 s$^{-1}$ channel$^{-1}$. The beam spot size is comparable to that of beamline 6.1, and considerably smaller than that of beamline 4.2. Despite the relatively high count rate per channel, we did not encounter any significant gain depression due to the count rate. However, the small spot size and therefore the considerable charge abstracted per channel does explain the gain decay discussed in the previous paragraph.

Figure 4.5: PHDs taken on CsI photocathode using the nickel grating. PHDs are shown for the 'wing' of the monochromator response (300eV, 215 counts s$^{-1}$) and the peak of the monochromator response (600eV, 3,000 counts s$^{-1}$) both before and after gain decay was noted. All data taken at 295° on the chamber angular scale.
Figure 4.6: PHDs taken on KBr photocathode using the nickel grating. PHDs are shown for the ‘wing’ of the monochromator response (300eV, 168 counts s$^{-1}$) and the peak of the monochromator response (600eV, 2,700 counts s$^{-1}$) both before and after gain decay was noted. All data taken at 295° on the chamber angular scale.

Figure 4.7: PHDs taken on CsI photocathode using the gold grating. PHDs are shown for the peak of the monochromator response at 800eV both before (687 counts s$^{-1}$) and after (653 counts s$^{-1}$) gain decay was noted. Gain-decayed PHDs are also shown at 1000eV (639 counts s$^{-1}$) and 1400eV (460 counts s$^{-1}$). All PHDs were taken at 295° on the chamber angular scale.
4.3 Beam Decay

During the experimental period, measurements were taken of count rate at a pre-determined energy and angle of incidence, which enabled us to estimate the decay of the beam over the three days of our experiment. On beamline 1.1, the MCP count rate was measured on the CsI-coated detector half at an angle of 295° on the chamber angular scale, and at an energy of 600eV for the nickel grating and 800eV for the gold grating. Measurements were also taken using a similar detector on beamline 4.2, where we were running a parallel experiment. This resulted in four sets of decay measurements: the gold and the nickel gratings on beamline 1.1, and two monochromator/mirror combinations on beamline 4.2. Exponential curves were fit to each data set using linear regression, and extrapolated, where necessary, back to the start of the experimental period, $t=0$. The count rate of each data set was then normalised to 1 at $t=0$. Figure 4.9 shows all the data after this procedure was applied. A single exponential curve was then fitted through all the data, again using linear regression (the solid line in Figure 4.9). This exponential curve gave a decay constant for the beam of 23459 minutes, or 16.3 days, with an error of $\pm 1.4$ days, which was then used in the subsequent analysis of all the quantum efficiency.
Figure 4.9: Decay of the beam intensity with time. Count rate normalised to 1 at t=0. The line shows an exponential decay with a time constant of 23,459 minutes.

4.4 Detector orientation

The angular response of the detector was determined near the beginning of the experiment, so that QE data could be taken at angles appropriate to the AXAF HRC detectors. Unfortunately, the scale on the chamber angular manipulator was rather coarse, being graduated in 5° steps. We estimate an angular scale accuracy of ±1°. For most of the angular range, data was taken at 2.5° intervals: only at the peak of the detector angular response was any attempt made at a finer angular resolution. Figures 4.10 and 4.11 show the relative quantum efficiency on the CsI-coated MCP-half at a variety of energies and angles using the nickel and gold gratings. Normal incidence to the front of the plate corresponded to 296° on the manipulator angular scale. The peak in the MCP response was at an angular setting approximately 1° greater than this.
The lack of a dip in the angular response indicates that, as on beamline 4.2 previously (see Chapter 3) the detector was not oriented such that X-rays could shine directly down the MCP channels. Further measurements were therefore required at Leicester in order to accurately determine the MCP orientation in azimuth. The detector angular response is not symmetric about the peak, but is greater when the angle on the manipulator scale is less than 297°. This indicates that the azimuthal angle (see Section 3.4) is less than 90°, so that the X-rays are incident on the coated (below 297°) and shadowed (above 297°) sides of the channels (see Figure 2.1). Determination of the azimuth is described in Section 3.4, and the same method was used for this detector. Orientation in the Daresbury chamber was also confirmed by vertical scans at varying positions across the detector, which determined the angle of the CsI/KBr boundary to the vertical. The channels were found to be oriented at 18.6° with respect to the CsI/KBr boundary, which implied an azimuthal angle of 20.5° at Daresbury. The minimum possible angle of incidence with respect to the channel axis was thus 2°. Every 10° increase in azimuthal angle corresponds to approximately a 1° increase in the minimum angle of incidence with respect to the channel axis. Further angles in this chapter will be stated with respect to the channel axis, with a negative angle denoting X-rays incident on the coated side of the channel, and a positive angle denoting X-rays incident on the shadowed side of the channel.

4.5 Quantum Efficiency Measurements

Initial quantum efficiency measurements were made in the 250-850eV region, using the nickel grating, in 2eV steps and at -7° with respect to the channel axis. Higher energy resolution scans on the CsI photocathode were then made over the 250-850eV energy range, with the energy increment of 0.2, 0.3 or 0.4eV reflecting the resolution of the monochromator. Further high energy scans were then taken across absorption edge features, with the 0.25eV or 0.2eV energy increment oversampling the monochromator resolution. High resolution (0.1, 0.3 or 1eV steps) scans were also completed on the KBr photocathode between 250 and 850eV. The KBr response was found to be without significant features, and was therefore not studied in detail. In contrast, a number of noticeable features were present in the response of the CsI-coated detector half, associated with the $M_\text{IV}$ and $M_V$ edges of Cs and I. The CsI response was therefore studied at a range of angles with respect to the channel axis, between 7° on the coated side of the channel.
Figure 4.10: Angular response of CsI-coated detector on the nickel grating and 38° on the shadowed side, at resolutions ranging from 2 to 0.2eV.

Using the gold grating, scans were first made on the CsI and KBr photocathodes between 800 and 1400eV, with an energy increment of 5eV between points and at an incident angle of -7° with respect to the channel axis. Neither of these scans showed any significant features, despite the presence of the Cs and I M_{I}, M_{II} and M_{III} edges in this energy range. The CsI response was studied at higher resolution, with energy increments of 1 and 0.3eV, but again no significant features were found. Further scans were made on CsI at a range of incident angles between 12° on the coated side and 9° on the shadowed side of the channel. Angles are with respect to the channel axis, and the energy increment for these scans was 5eV. Only one further data set was taken of the KBr response, at 8° with respect to the channel axis, over the 800-1400eV range and at 5eV energy steps.
Figure 4.11: Angular response of CsI-coated detector on the gold grating
4.6 Quantum Efficiency Analysis

4.6.1 Removal of the beamline response

The response of the beamline monochromator with energy was measured using a gold foil for both the nickel and gold gratings. However, calibration of the beamline took place after the low ring current experimental period was over. Calibration of the beamline was not possible during the low ring current period because the signal current from the beam monitor would have been too low. During our experimental period an aluminium foil was in the path of the beam (see Section 4.1); this foil was left in for the calibration of the monochromator. The efficiency response of the gold foil with energy was removed by fitting a cubic spline to the gold quantum efficiency data of Day et al. [66]. Calibration curves for the monochromator, corrected for the gold response, are shown in Figures 4.12 and 4.13 [73, 72]. A number of features can be seen in the Ni grating response, which were useful in determining if there was any offset in energy of the X-rays delivered by the monochromator, either in low or normal ring current. In particular, the O-K edge at 543eV enabled us to eliminate any possibility of an offset, in either current mode. The relative QE response of the MCP with energy was then found by dividing the raw data from the QE scans described above by the appropriate monochromator calibration curve, and correcting for beam decay. Beam decay was considered both between scans, and during the period of a single scan.

4.6.2 Absolute Quantum Efficiency Calibration

Detector Orientation

Absolute quantum efficiency calibration took place at Leicester, as for the data from beamlines 6.1 and 4.2. Due to the orientation of the angular manipulator at Leicester, the azimuth for this absolute calibration was approximately 90° greater than that at Daresbury. A similar procedure to that described previously was undertaken (see Section 3.4), and the azimuth was found to be 110.5°. Figure 4.14 shows the correspondence between angle of incidence with respect to the channel axis and angle of incidence with respect to the MCP front surface normal at Daresbury.
Figure 4.12: Calibration curve for the monochromator nickel grating [73].

Figure 4.13: Calibration curve for the monochromator gold grating [73].
Because the MCP channels are biased, the amount of the photocathode coating ‘seen’ by the X-rays depends not only on the angle of incidence to the channel, but also on the azimuthal angle. Thus, the QE of the MCP at Daresbury for X-rays incident at 10° with respect to the channel axis would not be the same as the QE at Leicester for X-rays incident at 10° with respect to the channel axis. However, at normal incidence to the plate (6° with respect to the channel axis), the X-rays are incident on the same photocathode thickness, and the Leicester and Daresbury results are comparable. No data was actually taken at normal incidence at Daresbury, so results 1° below normal incidence were used: 295° on the Daresbury chamber angular scale, or -7° with respect to the channel axis.

A computer aided design package [75] was used to model the orientation of the MCP. An image of this three dimensional model is shown in Figure 4.15. The model could be rotated in three dimensions and shaded as desired. Figures 4.16 to 4.19 show the view down the channel at various
azimuthal angles and X-ray angles of incidence with respect to the normal to the front plate (\(\gamma\)). In each figure the dark grey colour represents CsI coating on the inside of the channel and the black represents uncoated channel wall. Any white on the inside of the channel indicates that the X-rays are shining straight down the channel. On each set of diagrams a line indicates the orientation of the CsI/KBr boundary on the MCP front surface. This shows the relationship between the orientation of the MCP and the plane of rotation in the vacuum chambers at Daresbury and Leicester. The coated section of wall was determined by the intersection of two cylinders: one normal to the MCP front surface, representing the coating, and one at 6° to the front surface, representing the channel. Although the model does not perfectly represent the channel (having a length:diameter ratio of considerably less than 120:1), it is good enough to gain an overview of how the variation of azimuthal angle affects the part of the channel ‘seen’ by the incident X-rays. The main effect of the shorter channel is to exaggerate the range of angles at which the X-rays can shine straight down the channel. In a 120:1 channel, this will not happen at angles greater than 0.5° to the channel axis.

It can be seen that at small azimuthal angles (0° and 20°), there is a definite transition from viewing the coated side of the channel to the uncoated channel wall as \(\gamma\) increases. At larger azimuthal angles (90° and 110°), some part of both the coated and uncoated channel wall is visible, and there is no such transition. The clear view possible down the channel at 0° azimuthal angle is apparent, as is the impossibility of seeing straight down the channels at a 90° azimuthal angle.

**Absolute QE Data**

Calibration data was initially taken at two energies: 277eV (C-K) and 1740eV (Si-K). Absolute quantum efficiency measurements were made on both photocathodes at a range of angles both before and after the Daresbury run. Figures 4.20 and 4.21 compare these measurements. There was a 4° difference in azimuthal angle between pre- and post-calibration at Leicester, but this will not make a measurable difference to the QE values. On both photocathodes, it can be seen that the Si-K quantum efficiency remained constant before and after Daresbury, whereas the C-K QE decreased significantly. The quantum efficiency of the CsI is higher than KBr at all angles and both energies, as expected. However, on the CsI-coated half, the QE at Si-K is higher.
Figure 4.15: Image of the model used to create Figures 4.16, 4.18, 4.17 and 4.19. The model is a solid block, with a channel cut though it at a bias angle of six degrees. The inside of the channel is shaded to represent coated and shadowed areas of the channel wall. The perpendicular lines on the front surface of the block represent the orientation of the CsI/KBr coating interface, and the normal to that interface.
Figure 4.16: Views down the channel at an azimuthal angle of 0°. Dark grey: CsI coating. Black: uncoated channel wall.
Figure 4.17: Views down the channel at an azimuthal angle of 20°. Dark grey: CsI coating. Black: uncoated channel wall.
Figure 4.18: Views down the channel at an azimuthal angle of $90^\circ$. Dark grey: CsI coating. Black: uncoated channel wall.
Figure 4.19: Views down the channel at an azimuthal angle of 110°. Dark grey: CsI coating. Black: uncoated channel wall.
than at C-K, whereas the opposite is true for KBr. These measurements confirm the conclusion of Section 3.6.2 that the MCP absolute QE can change at some point between before the SRS experimental run and after it.

Unfortunately, the monochromator on Beamline 1.1 showed a large feature at the energy of the C-K edge which was not so noticeable in Figure 4.12. We assume this was due to contamination of the optics which was not fully removed by the normalisation of Section 4.6.1. The relative QE measured at Daresbury was, therefore, a sharply varying function of energy at 284eV (see Figure 4.22) which seemed spurious in comparison with previous results (Chapter 2). Hence it was deemed unreliable to calibrate the Daresbury data for absolute efficiency solely at the C-K energy, as had been previously hoped. The Si-K energy of 1740eV was out of range of this data set (250-1400eV), so it was necessary to find the absolute QE of the MCP at a third energy. Absolute QE measurements were made using Cu-L X-rays (930eV). The filter used was 4μm of aluminium, and P50 gas was used in the proportional counter. The transmission of the PC window was measured as 18.5% at 930eV, and the PC efficiency calculated to be ~100% [67]. The absolute values of QE measured using this method were 52% for CsI and 27% for KBr at
Figure 4.21: Comparison of absolute QE on the KBr-coated MCP half before and after Daresbury.

-7° to the channel axis.

The absolute QE at C-K was then used to normalise the data taken on the Ni grating, whereas the absolute QE at Cu-L normalised the Au grating. These two normalisations could therefore be compared, and the reliability of the C-K normalisation determined.

### 4.6.3 Absolute QE Results (250-850eV)

Figures 4.23 to 4.26 summarise the absolute QE of the MCP obtained using the Ni grating. The monochromator contamination artefact due to C-K is obvious at 284eV, as are the known, imperfectly removed, monochromator glitches at the O-K edge (543eV) and the Ni-L\textsubscript{III} edge (853eV). The Ni-L\textsubscript{III} edge is thought to be responsible for the large increase in apparent QE seen above 800eV. Figures 4.23, 4.24 and 4.26 show the MCP QE over the full range of the Ni grating, whilst Figure 4.25 concentrates on the high resolution scans across the Cs and I M\textsubscript{IV} and M\textsubscript{V} edges. The two scans at +9° on Figure 4.25 were taken 25 hours apart, and show the
Figure 4.22: Relative QE of the CsI-coated detector half across the C-K edge. The edge-related feature is clearly visible. Data taken at -7° to the channel axis.

The decrease in QE as incident angle to the channel axis increases is clear in Figures 4.23 to 4.26, as is the higher QE on the coated side of the channel. The Cs $M_{1\nu}$ and $M_{\nu}$ edge features can be clearly seen in all the CsI scans, at all angles. The features become stronger as the incident angle increases on the shadowed side of the channel. This is thought to be an artefact of the very low absolute QE on either side of the edge, so that the increase in QE due to the edge is more noticeable.

Of note is the slow onset of the $I_{M_{1\nu}}$ and $M_{\nu}$ edge features (Figure 4.25). Similar features have been observed in the M edges of gold, Pt, Pb and Ir by Owens et al. [65] and by Nelson et al. [70], and are thought to be due to the slow onset of the 3d→f transitions.
However, the 13eV discrepancy between the Cs $M_{I/V}$ and $M_V$ edge related features (also Figure 4.25) and the tabulated values of the edges [76] cannot be explained by reference to the slow onset of the edge, as the features are very sharp and cover an energy range of only a few eV. This energy shift can also be seen for the $I_{M_{I/V}}$ and $M_V$ edges. These energy shifts and their impact upon the AXAF HRC calibration are considered further in the Chapter 8.

4.6.4 Absolute QE Results (800-1400eV)

Unfortunately, the procedures described in Sections 4.6.1 and 4.6.2 did not give entirely satisfactory results when applied to data taken using the gold grating. Figure 4.27 shows the results obtained for a range of angles of incidence to the CsI-coated MCP half. The large, physically impossible, QE is immediately apparent at higher energies and small angles of incidence with respect to the channel axis. Possible reasons for this related to the MCP have been discounted, so this problem is felt to lie with the beamline itself. The most likely explanation is a discrepancy between the response of the monochromator when it was calibrated, in normal, multi-bunch
Figure 4.24: Absolute QE of CsI-coated MCP as a function of energy and incidence angle with respect to the channel axis. The energies of relevant atomic edges are indicated.

In an attempt to compensate for these problems, CsI data taken by Pearson at a number of spot energies on a 0° bias CsI coated MCP was compared to the data here [67]. A cubic spline was fitted to Pearson's data, and the result is shown in Figure 4.28. Corresponding QE data derived from the Daresbury measurements (7° to the channel axis, CsI photocathode) was then divided by the Pearson data, to obtain a 'correction factor', quantifying the difference between the two. This correction factor was then normalised to 1 at 929eV, the energy of the Cu-L emission line, so that the one definitely known absolute QE value for this detector in the 800-1400eV range was retained (QE=0.52 on CsI at -7° to the channel axis). The normalised 'correction factor' is shown in Figure 4.29. The rest of the data taken on the gold grating was then divided by the
Figure 4.25: Absolute QE of CsI-coated MCP at a range of angles to the channel axis. High resolution scans showing edge-related features. The energies of relevant atomic edges are indicated.

Figure 4.26: Absolute QE of KBr-coated MCP at -7° to the channel axis. The energies of relevant atomic edges are indicated. Essentially, the true photocathode response is 'featureless'.
Figure 4.27: Absolute QE of CsI-coated MCP on taken on the Au grating at a variety of angles to the channel axis. Note the impossibly large values of QE.

normalised correction factor, to give absolute QE-energy maps in the 800-1400eV range.

The results of this process are shown in Figures 4.30 and 4.31. The lack of edge-related features is apparent in both the data sets. In particular the Cs and I $M_I - M_{III}$ do not appear in the detector response.

4.6.5 Comparison between the two gratings

As discussed previously 4.6.2, the absolute QE calibration of the Ni grating was somewhat unreliable, due to the rapid variation of the detector response around the C-K edge energy. Three further checks on these values are possible:

(i) the absolute QE values can be compared with values from Pearson [67] and Lees et al. [74].
(ii) data from the two gratings can be compared where the energy ranges overlapped: 800-850eV.
(iii) absolute QE data can be compared to those obtained from the detector run on beamline 6.1 and described in Chapter 2. This comparison covers the 250-300eV energy range and is shown in Chapter 8.
Figure 4.28: Absolute QE of CsI-coated MCP at 7° to the channel axis taken by Pearson et al. [67]

Figure 4.29: Dividing factor applied to data taken on the Au grating to correct for anomalies in the grating response.
Figure 4.30: Absolute QE of CsI-coated MCP at a range of angles to the channel axis. The energies of relevant atomic edges are indicated.

Figure 4.31: Absolute QE of KBr-coated MCP at -7° and 9° to the channel axis.
Figure 4.32 shows a comparison of the absolute quantum efficiencies for the different gratings. This data has been through the normalisation procedure described in Sections 4.6.1 to 4.6.4, and is thus corrected for the response of the monochromator/grating combinations. It can be seen that, neglecting data taken between above 800eV on the Ni grating (which is contaminated by features related to the Ni-L\_III edge), the Ni- and Au-grating data sets fit together well. This suggests that both the absolute calibration of the Ni grating at C-K and the procedure used to correct the monochromator response for the Au grating have some merit. It also implies that, whatever the problem with the Au grating, it is not present in the Ni grating.

Figure 4.33 shows absolute QE data taken on the Ni grating along with the spline fitted to Pearson’s data. The single data point from Pearson in this range is shown as a cross. The absolute values of QE match up fairly well, although the spline does not reflect any of the structure in the Daresbury data, which is to be expected given the small number of points from which it was interpolated. Data from Lees et al. gives a QE of 38% at 7 degs to the channel axis for an azimuthal angle of 20°, and 36% for an azimuthal angle of 90°. This ties in well with our value of 36% at an azimuthal angle of 20°.

4.7 CsI : KBr Quantum Efficiency ratio

The ratio of CsI to KBr in quantum efficiency was most easily found by simply scanning the X-ray spot across the MCP and measuring the relative count rates. Figures 4.34 and 4.35 show the results of this method at various energies on the nickel and gold gratings. It can be seen that the CsI-coated half of the detector has the greater QE at all energies, as expected.

Figure 4.36 compares data on the CsI:KBr-coated MCP QE ratio from various sources:
(i) linear scans across the MCP at Daresbury (-7° to the channel axis)
(ii) The QE-energy maps of Sections 4.6.3 and 4.6.4 (-7° to the channel axis).
(iii) Absolute QE data taken at Leicester as part of pre- and post-calibration (-6° to the channel axis).

We note particularly that the ratios from linear scans across the plate and from QE-energy maps compare well, having the same general shape and, for the Ni grating especially, the same absolute values. This gives some confidence in the QE-energy maps obtained.
Figure 4.32: Comparison of relative QE data taken Ni and Au gratings. Filled circles: Ni, CsI-coated detector half. Crosses: Au, CsI-coated detector half. Open circles: Ni, KBr-coated detector half. Stars: Au, KBr-coated detector half. Data taken at -7° to the channel axis.
Figure 4.33: Comparison of relative QE data taken on the Ni grating with the spline fit to Pearson's data (smooth curve). The cross represents Pearson's actual data. Data taken at -7° to the channel axis.

Figure 4.34: Linear scans across the MCP detector taken using the nickel grating. At -7° with respect to the channel axis.
Figure 4.35: Linear scans across the MCP detector taken using the gold grating. At -7° with respect to the channel axis.

Figure 4.36: Ratio of CsI to KBr QE by various methods.
4.8 Conclusions and further work

The data taken on beamline 1.1 has revealed a number of important and interesting edge-related features, which will be particularly significant in the calibration of the AXAF MCP detectors.

Despite a number of features associated with contamination in the beamline, the data taken on the Ni grating produced some well defined edge-related features, particularly for the Cs $M_{IV}$ and $M_Y$ edges. These features are $\sim$13eV above the tabulated values of the edge energy. Also of note is the slow onset of the features due to the $I_{M_{IV}}$ and $M_Y$ edges, and their offset. There were no features due to the MCP on the KBr-coated half of the detector.

Problems with calibrating the data taken using the Au-coated half of the grating were more severe, but the lack of features was still apparent on both photocathodes.

As in other energy ranges described in Chapters 2 and 3, CsI was found to be the more efficient photocathode, justifying its use on both AXAF HRC detectors.

However, later measurements described in Chapter 8 casts doubt on some of the results reported here. It seems likely that the monochromator response in high ring current mode cannot be linearly mapped to low ring currents.

Further work in this region will concentrate on determining the actual energy response of the grating monochromator in low ring current mode, using a beam monitor in tandem with an MCP detector. This should eventually enable a more accurate calibration of the data described here, and is discussed further in Chapter 8.
Chapter 5

Modelling of MCP Quantum Efficiency

5.1 Introduction

The modelling described in this chapter was based on a FORTRAN program (MCP4) written in 1981 by GW Fraser. The program models the quantum efficiencies (QE) of both MCPs and planar photocathodes. The MCP can be modelled with an electrode coating, a photocathode coating or as bare lead silicate glass. If a repeller grid is used in front of the MCP to focus electrons produced on the web between the channels, the front surface contribution to the QE becomes important [77]. This contribution can also be modelled, but as a repeller grid was not used in the Daresbury experiments the facility was not required for this particular body of work. Results from the program have been cited in a number of publications [6, 7, 8, 9].

5.2 Theoretical Model of MCP Quantum Efficiency

The soft X-ray QE of an MCP (Q) can be written $Q = Q_c + Q_s$ where $Q_c$ is the MCP open area response and $Q_s$ is the response of the front surface web. For modelling the data from Daresbury, due to the absence of a front surface repeller grid, only the open area channel response $Q_c(\lambda, \theta)$
is applicable. I will not, therefore, describe the theory of the front surface response [9]. The model considers straight channel MCPs with channels perpendicular to the front surface (bias angle $\theta_B=0$) and length to diameter ratio $L/D$. For hexagonally packed channels of radius $r$ and pitch $p$, (Figure 5.1) the open area fraction is $A_{\text{open}} = 2\pi(r/p)^2/\sqrt{3}$ [6].

5.2.1 **Primary electron contribution to $Q_c$ for a homogenous channel wall**

We assume an incident beam of parallel monochromatic X-rays of intensity $\Gamma_0$ photons cm$^{-2}$ s$^{-1}$. If we consider a strip of an MCP channel wall, parallel to the channel axis, between azimuthal angles $\psi$ and $\psi + d\psi$, then the grazing angle of the X-ray beam with respect to the channel wall $\alpha(\psi)$ is given by [78]

$$\sin \alpha = \cos \psi \sin \theta$$

Resolving the beam parallel and normal to the surface, the flux incident upon this strip is $\Gamma_0 \sin \alpha$ photons cm$^{-2}$ s$^{-1}$. Of this incident flux, a fraction $R(\alpha)$ will be reflected. The grazing angle is preserved on each reflection, thus multiple reflections from the channel wall lead to a geometric
Consider the $n$th reflection. If $nD \cos \psi \cot \theta < L$, where $L$ is the length of the channel, then reflection will occur. If, however, $nD \cos \psi \cot \theta > L$ then there will be no reflection.

We can set $t = \cos \psi \cot \theta$. Multiple reflections can then be accounted for by considering an 'equivalent strip'. The area of the strip is given by $Dtrd\psi$. If we then include the geometrical reflection, the area of the equivalent strip becomes [6]:

$$dA = 2rt^2 \left( \sum_{n=1}^{n_{\text{max}}} R(\alpha)^{n-1} B_n \right) d\psi$$  \hspace{1cm} (5.2)

where $B_n$ is a coefficient which takes account of the channel length such that

- $B_n = 1$ if $nt < \frac{L}{2r}$
- $B_n = \frac{L}{2rt} - (n-1)$ if $(n-1)t \leq \frac{L}{2r} \leq nt$
- $B_n = 0$ if $(n-1)t > \frac{L}{2r}$

and $R(\alpha)$ is the reflection coefficient, a function of the X-ray energy and the channel wall composition as well as the X-ray incident angle. So, the number of photons incident upon an equivalent strip is $dA \Gamma_0 \sin \alpha$ photons s$^{-1}$, and the number entering the strip is the number of photons incident upon it, minus the number reflected:

$$dN_c(\psi) = (1 - R(\alpha)) \Gamma_0 \sin \alpha dA \text{ photons s}^{-1}$$  \hspace{1cm} (5.3)
For a photon incident upon the channel wall at grazing angle $\alpha$, the refraction angle $\alpha'$ can be calculated using the method described by Henke [79]. The decrements in the real and imaginary part of the complex index of refraction ($n$) are denoted $\delta$ and $\beta$, such that $n = 1 - \delta - i\beta$. Similarly the complex dielectric constant ($K$) can be written in terms of its unit decrements: $K = 1 - \alpha_K - i\gamma_K$. The relationship between dielectric constant and refractive index is $n = K^{1/2}$, which implies:

$$\alpha_K = 2\delta - \delta^2 + \beta^2$$  \hspace{1cm} (5.4)

and

$$\gamma_K = 2(1 - \delta)\beta$$  \hspace{1cm} (5.5)

Assuming the unit decrements in the refractive index are small, so that second order terms can be neglected, $\alpha_K = 2\delta$ and $\gamma_K = 2\beta$. The critical angle, above which there is no reflection, occurs at $\alpha = (2\delta)^{1/2}$. We then define an intermediate function $\alpha$, where [79]:

$$a^2 = \frac{1}{2} \left[ \sin^2 \alpha - \alpha_K \left( (\sin^2 \alpha - \alpha_K)^2 + \gamma_K^2 \right)^{1/2} \right]$$  \hspace{1cm} (5.6)

In an exact calculation, two refraction angles for energy flow result: $\alpha_1'$ where the incident beam is polarised with its electric vector perpendicular to the plane of incidence, and $\alpha_2'$ parallel to the plane of incidence. They are given by:

$$\sin \alpha_1' = \frac{a}{(\cos^2 \alpha + a^2)^{1/2}}$$  \hspace{1cm} (5.7)

and

$$\tan \alpha_2' = \frac{2a^2(1 - \alpha_K) + \gamma_K^2}{2a^2(1 - \alpha_K) \cos \alpha}$$  \hspace{1cm} (5.8)

For this model a single value for the refraction angle is used, $\alpha'$, which is the mean of $\alpha_1'$ and $\alpha_2'$. The linear absorption coefficient, $\mu$, can be calculated using the equation below:

$$\mu = \frac{4\pi}{\lambda} \frac{\gamma}{\left( 2 \left[ (1 - \alpha) + ((1 - \alpha)^2 + \gamma^2)^{1/2} \right] \right)^{1/2}}$$  \hspace{1cm} (5.9)

We assume the channel wall is homogenous within the region of X-ray interaction. The interaction region thickness, $d$, is given by the maximum photoelectron range for a photon of energy $E_x$ (see Section 5.3 for further discussion of the interaction region).

If we consider a photon incident upon the channel wall, the probability of it being absorbed in the distance $l \rightarrow l+dl$ along the refracted path of the photon is given by $\mu e^{-\mu dl}$. This interaction
at a distance 1 along the refracted path occurs at a distance \( r_1 \) from the centre of the nearest channel, where, by simple geometry [6]:

\[
r_1^2 = (l \sin \alpha' + r)^2 + (l \cos \alpha' \sin \gamma)^2
\]  

(5.10)

and

\[
\gamma = \frac{\cos \alpha - \cos \theta}{\sin \theta \sin \psi}
\]  

(5.11)

This interaction has probability \( p_{i,j} \) of giving off a primary photoelectron from the jth orbital of the ith atomic type constituting the channel wall, if the X-ray energy is greater than the binding energy of the shell \( E_{i,j} \). The probability \( p_{i,j} \) is found by a sum of atomic absorption cross-sections over all atomic types:

\[
p_{i,j} = \frac{a_i \sigma_{i,j}}{\sum a_n \sigma_{n,m}}
\]  

(5.12)

where \( a_i \) is the atomic fraction by weight, and \( \sigma_{i,j} \) is the atomic absorption cross-section for the orbital under consideration. The energy of the photoelectron, \( T_{i,j} \), is given by \( E_x - E_{i,j} \), and the photoelectron has a range \( R_e(T_{i,j}) \). The geometric probability of the electron escaping into the channel is obtained by considering the intersection of a sphere of radius \( R_e \) with the channel wall, and is given by [6]:

\[
P = \frac{1}{\pi} \int_0^{\omega_0} \left[ 1 - \left( \frac{r_1}{R_e} \cos \omega - \left( \frac{r}{R_e} \right)^2 - \left( \frac{r_1}{R_e} \right)^2 \sin^2 \omega \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} d\omega
\]  

(5.13)

where:

\[
\omega_0 = \cos^{-1} \left[ \frac{1}{2} \left( \frac{r_1}{R_e} + \frac{R_e}{r_1} - \frac{r^2}{R_er_1} \right) \right]
\]  

(5.14)

This assumes both that the emission process is isotropic and that, if the electron reaches the surface of a channel then it enters that channel.

The probability of a photoelectron being emitted is augmented by the possible creation of an Auger electron. However, Auger electron production is only important if a photoelectron has not created an avalanche from the interaction under consideration: this is the 'dependent Auger yield'. If we take the K shell as an example, the total electron yield is given by the probability that a K shell photoelectron will escape into the channel, plus the probability that a K shell Auger electron will enter the channel, minus the probability that both enter the channel. Mathematically, if \( P(T_{i,1}) \) is the probability of a K-shell photoelectron from atomic
type $i$ entering the channel, $(\omega_k)_i$ is the K shell fluorescence yield of atomic type $i$ and $P(T_{i,i}^A)$ is the probability of a K-shell Auger electron from atomic type $i$ entering the channel, we can write:

$$S_{i,1} = P(T_{i,1}) + (1 - (\omega_k)_i)P(T_{i,1}^A) - (1 - (\omega_k)_i)P(T_{i,1}^A)P(T_{i,1})$$  \hspace{1cm} (5.15)

where $S_{i,1}$ is the probability of a batch of photoelectrons entering the channel, initiated by an interaction involving a K shell electron from an atom of type $i$. In this case, $T_{i,1}^A$ is the average energy of all possible Auger K shell transitions, weighted according to probability. This analysis neglects the effect of fluorescence upon the pulse yield. Therefore, the total probability of a batch of electrons entering the channel for a given photon ($E$) is the multiple of $p_{i,j}$ and $S_{i,j}$ summed over all energy levels and all atomic types, integrated along the refracted path of the photon in the channel wall. If $l_{\text{max}}$ is the maximum distance of the path (when $r_1 = r + d$), and we set $y = \mu l$ then $E$ is given by:

$$E = \int_0^{l_{\text{max}}} \exp^{-y} \left( \sum_i \sum_j p_{i,j} S_{i,j} \right) dy$$  \hspace{1cm} (5.16)

We are now in a position to amalgamate these equations, and thus obtain an expression for the pulse quantum yield produced by the primary electrons in the channel. The number of electron batches leaving each strip on the channel is given by the number of photons incident upon the strip, multiplied by the probability of a batch being created per incident photon: in the notation used previously, $dN_c(\psi)E$. For the present we will assume that the probability that an electron batch fails to initiate a detectable pulse is independent of energy and angle, and is given by $1 - p_a$. The number of counts coming from the strip of channel wall per second due to primary electrons is thus:

$$dN_0 = p_a dN_c E$$  \hspace{1cm} (5.17)

which, integrated over $\psi$ in the range $\frac{\pi}{2}$ to $-\frac{\pi}{2}$, gives $N_0$, the total number of counts from the channel per second. The number of photons incident upon the channel is $\Gamma_0 \cos \theta$ multiplied by the surface area taken up by the channel ($\frac{\pi r^2}{A_{\text{open}}}$), thus the open area contribution to the quantum yield is $\frac{A_{\text{open}} N_0}{\Gamma_0 \pi r^2}$ counts photon$^{-1}$. Hence the total pulse quantum yield due to primary electrons is [6]:

$$\chi_\rho = (\theta, \lambda) = \frac{4A_{\text{open}} p_a \csc \theta}{\pi} \int_0^\theta \frac{(1 - R(\alpha)) \sin^2 \alpha \cos \alpha}{(\sin^2 \theta - \sin^2 \alpha)^{\frac{1}{2}}} \left[ \sum_{n=1}^{n_{\text{max}}} R(\alpha)^{n-1} B_n \right] E d\alpha$$  \hspace{1cm} (5.18)
5.2.2 Primary avalanche initiation

If we consider a photoelectron emitted perpendicular to the channel wall with energy $eV$, it will travel a distance $D$ perpendicular to the wall in a time $\frac{D}{2eV}$. Parallel to the channel wall the electron will be accelerated through a voltage $\frac{V_0^2}{2s}$ where $s$ is the distance travelled parallel to the wall, and $s = \frac{V_0 D^2}{4VL}$. Thus the total energy when it hits the opposite wall will be [9]:

$$E_e = e \left( V + \frac{V_0^2}{2} \left( \frac{L}{D} \right)^2 \frac{4V}{4V} \right)$$

(5.19)

Assuming the secondary electron yield obeys poissonian statistics with a mean of $\delta_e$, then the probability that this collision of the primary produces no secondary electrons (and hence the avalanche dies out) is given by $1 - p_a = \exp(-\delta_e)$. $\delta_e$ varies with the collision energy $E_e$, so $p_a$ must also be a function of the photoelectron emission energy, and therefore of incident X-ray energy and position. The value of $p_a$ can be calculated separately for each primary photoelectron using measured values of $\delta_e$ as $E_e$ varies, and the probability of primary photoelectron emission into the channel and of avalanche initiation combine to produce $E_p$, which replaces $p_a$ and $E$ in equation 5.18.

5.2.3 Secondary pulse quantum yield

When photoelectrons and Auger electrons are created but do not escape into the channel, their energy is used to create low energy secondary electrons. If we consider a layer of the channel wall a perpendicular distance $z$ from the surface of the channel between $z$ and $z+dz$, the probability of a photon being absorbed is $\mu \csc \alpha' e^{-\mu z \csc \alpha'} dz$. The energy absorbed from the X-ray beam in that layer, $dE(z)$, is thus [7]:

$$dE(z) = \Gamma_0 E_e (1 - R(\alpha)) \mu \csc \alpha' e^{-\mu z \csc \alpha'} dz \text{ keV cm}^{-2} \text{ s}^{-1}$$

(5.20)

A fraction ($f$) of this energy will be used to create secondary electrons, where $f$ is given by $f(z) = 1 - \phi_f - \phi_z$. $\phi_f$ is the fraction of energy lost through fluorescence, and $\phi_z$ is the fraction which is lost through primary electrons escaping through the surface of the channel. Through most of this analysis we assume that the fluorescence loss is zero. If we assume that all primary
electrons escape into the channel with negligible energy loss, then the upper limit on $\phi_z$ is [7]:

$$\phi_z = E_z^{-1} \sum_i \sum_j p_{i,j} \left[ T_{i,j} P(T_{i,j}, z) + (1 - \omega) T_{i,j}^A P(T_{i,j}^A, z) \right]$$  \hspace{1cm} (5.21)

where $j$ indicates the shell, $i$ the atomic type and $\omega$ is the average fluorescence yield. Recall that $p_{i,j}$ is the probability of an interaction, $P(T_{i,j}, z)$ the probability of a primary photoelectron electron at depth $z$ escaping and $T_{i,j}$ the energy of the photoelectron. The superscript $A$ indicates the corresponding values for Auger electrons. So, knowing $f(z)$ and assuming that all secondaries are created at the point of photon interaction, the number of secondary electrons created at a depth $z$ is:

$$dN(z) = \frac{f(z)}{\epsilon} dE(z)$$  \hspace{1cm} (5.22)

where $\epsilon$ is the energy in eV required to create a single secondary electron, which will be regarded as a material constant.

The secondary electron escape probability at a depth $z$ can be written:

$$P_s(z) = P_s(0) e^{-z/L_s}$$  \hspace{1cm} (5.23)

where $L_s$ is the secondary electron escape length. Although $L_s$ and $P_s(0)$ are actually functions of the energy of the secondary electron, we assume that they are material constants, taking an average value over the energy range under consideration.

The probability that a batch of secondary electrons escapes into the channel is equivalent to $1 - p_s(z)$ (the probability that no secondary electrons escape).

For a batch of size $dN(z)$, the probability of one of the electrons not escaping is $1 - P_s(0) e^{-\beta_y}$, where we have substituted $\beta = (\mu c s c o L_s)^{-1}$ and $y = \mu z c s c o'$. The probability of all $dN$ electrons failing to escape into the channel is simply $\left(1 - P_s(0) e^{-\beta_y}\right)^{dN(y)}$, so the probability of a batch of any number $(1,2,...,dN)$ of electrons escaping is $1 - \left(1 - P_s(0) e^{-\beta_y}\right)^{dN(y)}$. Thus, the secondary pulse yield $(X_p)_s$ is the integral of this over the path of the secondary electron through material of thickness $T$ [7]:

$$(X_p)_s = (1 - R(\alpha)) \int_0^{\mu T c s c o'} e^{-\gamma} \left[ 1 - \left(1 - P_s(0) e^{-\beta_y}\right)^{dN(y)} \right] dy \text{ counts photon}^{-1}$$  \hspace{1cm} (5.24)

Assuming the pulse yields from primary and secondary electrons are independent, the total pulse yield is then:

$$(X_p)_T = (X_p)_s + (X_p)_s - (X_p)_s (X_p)_s \text{ counts photon}^{-1}$$  \hspace{1cm} (5.25)

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5.2.4 QE for a channel with two wall compositions

This calculation assumes a base channel wall composition (usually glass), with a surface coating of thickness \( d \), which extends (at constant thickness) a distance \( H_0 \) down the channel. If \( d < 500 \text{Å} \) (true in this case), then the MCP open area fraction and the X-ray interaction geometry remain essentially the same as for a single wall composition. We can write the channel QE as [15]:

\[
Q_c = f_p(Q_c)_p + (1 - f_p)(Q_c)_g
\]

(5.26)

where \((Q_c)_p\) is the channel QE for a wall composed entirely of photocathode, and \((Q_c)_g\) for a wall entirely composed of glass. \( f_p \) is the fraction of the flux absorbed in the length \( H_0 \), calculated from equation 5.18 by setting the electron escape and avalanche probability \((E_a)\) to 1, and calculating \( B_n \) first using the true channel length to diameter ration, \( L/D \), and then \( H_0/D \). The first value gives the fraction of the total input flux absorbed down the whole length of the channel, \( f_L \) (which tends towards the open area fraction at small grazing angles), and the second the fraction absorbed in length \( H_0 \) \((f_H)\). \( f_p \) is then simply \( f_H/f_L \).

5.2.5 Channel Coating

The analysis of channel coating depth as presented in [15] is valid for an MCP with zero bias angle. It will be considered here, but an extension of the analysis for biased plates is discussed in Section 5.6.

Consider an unbiased MCP placed a vertical distance \( h_m \) above a coating source \( S \), and with its centre \((O)\) offset horizontally a distance \( d_m \) from \( S \). We assume that the coating material is radiated in a hemisphere centered upon \( S \). We now consider a channel, a distance \( r_m \) from the centre of the plate, \( O \). The centre of the channel is labelled \( C \) (see Figure 5.3), and is at an angle \( \phi \) to the line \( S'O \). In order that the coating material not pass straight through any channel, we impose the condition \( d_m > R_m \). We now define the central coating angle, \( \alpha_0 \) as \( \tan^{-1} \frac{R_m}{h_m} \). Whilst the plate is stationary, only half of any one channel can be coated, so in order to increase the uniformity of coating the plate is rotated about \( O \) a number of times. However, this introduces a variation in the coating angle, \( \alpha \), with the rotation of the plate, and hence a variation in the coating depth down the channel, \( H \), as the angular position around the channel, \( \gamma \), is varied.
Figure 5.3 shows how the greatest values of $H$ for angular position $\gamma$ are obtained when $C$ lies along the line $S'T$. It can then be shown that the coating penetrates to a depth $H$, where $H$ is given by [15]:

$$H(r_m, \gamma) = D \cot \alpha_0 \left[ 1 + \left( \frac{r_m}{d_m} \right)^2 - 2 \left( \frac{r_m}{d_m} \right) \cos \phi \right]^{\frac{1}{2}}$$  \hspace{1cm} (5.27)

where the value of $\phi$ is given by:

$$\sin(\pi - \gamma) = \sin \phi \left[ 1 + \left( \frac{r_m}{d_m} \right)^2 - 2 \left( \frac{r_m}{d_m} \right) \cos \phi \right]^{\frac{1}{2}}$$  \hspace{1cm} (5.28)

In the centre of the plate, rotational symmetry ensures that the coating depth is constant as $\gamma$ varies, and

$$H = D \cot \alpha_0 = H_0$$ \hspace{1cm} (5.29)

At this centre point, the thickness of the coating $G_0$ varies as [15]:

$$G_0(l_c) = \frac{\cos^2 \alpha_0}{\pi} \sin \alpha_0 \sin \left[ \arccos \left( \frac{l_c}{D} \tan \alpha_0 \right) \right]$$ \hspace{1cm} (5.30)

This coating profile will be discussed further in Section 5.5.1.
Figure 5.4: Channel geometry during coating. C is the centre of a channel and rotates along the line marked by an arrow.

5.3 Program structure

A flow chart of the overall structure of the program is shown in Figure 5.5. The program is constructed in sections which can be accessed using a number of flags. The most important of these are the flags NPART1 and NPART2, which determine whether the program calculates the QE of an MCP (NPART1=1) or of a planar photocathode (NPART2=1). Only the part of the code used for the QE of an MCP will be discussed here (although many of the sections of the program are used in both parts). The code was also used at one time to calculate the effect of a postulated two-layer glass composition in the channel (the ‘channel base layer’ and ‘channel surface layer’ in 5.5). This two-layer composition has not been considered here. In order to calculate the QE of a coated MCP, the program must be run three times: once for the MCP glass, once for the coating and finally to find the fraction of X-rays absorbed by the coating. The MCP QE is then found by combination of these results as described above in Equation 5.26.

Table 5.1 shows some of the main variables used in the code.

The initial inputs to the code are the dimensions of the MCP, the bias voltage on the front plate, the distance and thickness of coating down the channels, the wavelength of the X-ray light and the angle of incidence to the front surface of the MCP. In addition, material constants such as atomic number, weight and secondary electron parameters are required. For a material consisting of more than one element, the atomic number and weight are replaced by effective atomic number
READ IN INITIAL INPUTS AND CALCULATE OPTICAL CHARACTERISTICS FOR THE CHANNEL SURFACE LAYER

SET NPASS-0 AND NSURF-0

READ IN CHARACTERISTICS OF CHANNEL BASE LAYER AND CALCULATE REFRACTIVE INDEX

Determine refractive index of the material interface

READ IN AND CALCULATE THE OPTICAL CHARACTERISTICS OF THE MCP FRONT SURFACE OR THE PLANAR PHOTOCATHODE

INTEGRATE TO FIND THE QE OF THE MCP FRONT SURFACE OR THE PLANAR PHOTOCATHODE AT EACH ANGLE

ADD THE SURFACE AND CHANNEL QE TO GET THE TOTAL QE

END

Figure 5.5: Flow chart showing overall structure of MCP4.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>absorption length cm$^{-1}$</td>
</tr>
<tr>
<td>AF(J)</td>
<td>atomic fraction of jth element</td>
</tr>
<tr>
<td>ATOMN</td>
<td>atomic number</td>
</tr>
<tr>
<td>ATOMW</td>
<td>atomic mass</td>
</tr>
<tr>
<td>AOPEN</td>
<td>open area fraction of MCP</td>
</tr>
<tr>
<td>ALPHA</td>
<td>unit decrement in the real part of the dielectric constant</td>
</tr>
<tr>
<td>BETA</td>
<td>unit decrement in the imaginary part of the refractive index</td>
</tr>
<tr>
<td>DELTA</td>
<td>unit decrement in the real part of the refractive index</td>
</tr>
<tr>
<td>D1</td>
<td>thickness of photocathode coating</td>
</tr>
<tr>
<td>DC</td>
<td>channel diameter</td>
</tr>
<tr>
<td>GAMMA</td>
<td>unit decrement in the imaginary part of the dielectric constant</td>
</tr>
<tr>
<td>EP(I,J)</td>
<td>probability of X-ray interaction releasing a photoelectron from ith orbital of jth atomic type</td>
</tr>
<tr>
<td>EX</td>
<td>incident X-ray energy</td>
</tr>
<tr>
<td>FPP(I,J)</td>
<td>partial photoelectric cross-section of ith orbital of jth atomic type</td>
</tr>
<tr>
<td>LAMBDA</td>
<td>incident X-ray wavelength</td>
</tr>
<tr>
<td>LDC</td>
<td>channel length to diameter ratio</td>
</tr>
<tr>
<td>NLEV(J)</td>
<td>no. of atomic levels in element j</td>
</tr>
<tr>
<td>OW</td>
<td>critical angle</td>
</tr>
<tr>
<td>P</td>
<td>hexagonal packing dimension</td>
</tr>
<tr>
<td>RANGE</td>
<td>electron range in given material</td>
</tr>
<tr>
<td>RHO</td>
<td>density of channel wall/coating material</td>
</tr>
<tr>
<td>RK</td>
<td>range of K shell electron (similarly for L,M,N)</td>
</tr>
<tr>
<td>SIGMA</td>
<td>cross-section normalisation (sum of all atomic fractions x cross-sections)</td>
</tr>
<tr>
<td>TE</td>
<td>KE of free electron</td>
</tr>
<tr>
<td>THETA</td>
<td>angle of incidence</td>
</tr>
<tr>
<td>VOLT</td>
<td>MCP bias voltage</td>
</tr>
<tr>
<td>V0</td>
<td>mean secondary electron escape energy</td>
</tr>
</tbody>
</table>
The code begins by calculating the probability of a secondary electron with initial energy $V_0$ (the mean energy of the secondary electrons upon escape into the channel), starting an avalanche after being accelerated in the MCP bias field. This calculation uses measured values of $\delta_e$ (the secondary electron yield coefficient) as function of collision energy to predict the probability of the avalanche dying out. If the calculation is being carried out for the channel glass, rather than a photocathode coating, the maximum range of electrons in the glass is calculated using the formulae of Tabata [80] and Burke [81]. The surface layer thickness is then set equal to this maximum range. For a photocathode, the thickness of the layer is simply the photocathode thickness.

The channel composition is then used with a library routine developed by Cromer and Liberman [82] to calculate the real and imaginary unit decrements in the dielectric constant and the linear absorption probability at the energy under consideration. It also returns absorption cross-sections for each atomic type. At this stage values of measured linear absorption coefficients can be inserted if required. The unit decrements in the refractive index and the critical angle can then be calculated. The next stage is the calculation of atomic fractions and weighted cross-sections, followed by the interaction probability and photoelectron kinetic energy for each energy level. A calculation of the electron range and avalanche probability is then undertaken for each primary photoelectron kinetic energy. A similar exercise then takes place for the Auger electrons, with the mean energy of the Auger electrons for each of the K, L, M and N shells being considered. A summary of these results is then printed for each energy level of each atomic type.

With the preliminary calculations complete, the total primary and secondary electron yield is calculated by integrating contributions from strips parallel to the channel axis. This procedure can be undertaken for a variety of energies, incident angles and effective channel lengths. The final output lists the energy, incident angle, effective channel length, MCP QE, calculation error
and linear absorption coefficient.

5.3.1 Updates to the program

The main updates to the program were concerned with adapting the original code to run on a current computer (a Sparcstation 10). This involved deleting a number of calls to no-longer existing library routines and replacing them with up-to-date, working routines. A number of the variable definitions and I/O calls also had to be changed to correspond with the current implementation of FORTRAN 77. The I/O was updated to make it slightly more ‘user-friendly’, and a loop was added so that the QE could be calculated for a range of energies in one running of the program. The program now takes approximately two seconds to calculate the QE at one energy and angle.

5.4 Reproductions of previous data

The model considered here was originally used to produce many of the figures in Fraser et al. [9]. Therefore, a crucial step in confirming the functionality of the new code was to reproduce these figures.

Secondary electron coefficients are as described in Fraser et al. [9] and shown in Table 5.2. Of particular note are the extremely poor (for our purposes) secondary electron coefficients of nichrome compared to either glass or CsI. Plots of the mean secondary electron yield as a function of primary electron energy for glass and CsI are shown in Figure 5.6. For CsI, the range-energy formulae of Tabata were used above 0.2keV, and those of Burke below 0.2keV. For glass modelling, the equivalent partition came at 1.0keV.

Figure 11 of Fraser et al. shows the open area contribution to the QE for an uncoated MCP (see Figure 5.7) at an X-ray wavelength of 8.3Å. The curves show calculated values, whilst the filled circles indicate measured values at positive incidence angles and the open circles measured values at negative incidence angles. The unbroken curve assumes zero angular beam divergence, and the broken curve an X-ray beam width of ±0.5°. It is the former of these which has been
Table 5.2: Variables used in MCP4

<table>
<thead>
<tr>
<th>Material</th>
<th>$\epsilon$ (eV)</th>
<th>$L_s$ (Å)</th>
<th>$P_s(0)$</th>
<th>Energy range for $P_s(0)$</th>
<th>$\epsilon V_s$(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI</td>
<td>7</td>
<td>215</td>
<td>0.35</td>
<td>$&lt;$180eV</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>180-5700eV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.15</td>
<td>$&gt;$5700eV</td>
<td></td>
</tr>
<tr>
<td>Lead Glass</td>
<td>10</td>
<td>33</td>
<td>0.15</td>
<td>all</td>
<td>6</td>
</tr>
<tr>
<td>Nichrome</td>
<td>100</td>
<td>2</td>
<td>0.01</td>
<td>all</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 5.6: Mean secondary electron yield as a function of primary electron energy.
reproduced (Figure 5.8). The L:D ratio of the MCP is 80:1, its diameter 25µm (and pitch 30µm). The bias voltage across the MCP is 1.3kV. Figure 5.8 shows the total open area QE (solid line), the QE due to glass (dashed line), and the QE due to nichrome (dot-dash line). The nichrome coating was assumed to be 1000Å thick, and to penetrate one channel diameter. The results from the current model and that of Fraser et al. compare well.

Figures 12a and b of Fraser et al. (Figure 5.9) show the measured and calculated open area efficiency of a CsI coated MCP at X-ray wavelengths of 8.3Å (Figure 12a) and 44.7Å (Figure 12b). The MCP L:D ratio is 80:1, its diameter 25µm (and pitch 30µm). The bias voltage across the MCP is 1.3kV. The filled circles indicate measured values at positive incidence angles and the open circles measured values at negative incidence angles, whilst the squares are data from a plate of L:D=120 and bias voltage 1.9kV. The broken curve represents the CsI contribution to the QE, the hatched curve the glass contribution and the full curve the total QE (the sum of the broken and hatched curves). The QE is shown for three channel wall coating thicknesses: 310Å,
450Å and 550Å. The maximum penetration depth of the coating is 3.73 channel diameters. The vertical lines indicate the critical angles of the CsI and the glass, and the coating angle at 15°.

The calculated curves are reproduced in Figures 5.10 and 5.11 using the current code and the parameters above. There is an excellent correlation between the two figures, indicating that the adapted program gives very similar results to the original program. The small differences between the two are thought to be due to improvements in integration routines and increased precision in floating point calculation in the updated program.

Figures 17 of Fraser et al. shows the calculated open area efficiency of a CsI coated MCP with a L:D ratio of 120:1, 12.5μm channel diameter (on a 15μm pitch) and a bias voltage of 1.625kV. The open area efficiency is shown as a function of wavelength over the region 50-250Å for incident angles of 20° and 30°. The coating thickness on the channel wall is 400Å and the angle of incidence is assumed to be large enough that the glass contribution to the QE is negligible. In this energy range the calculated values of μ become unreliable, showing a large discontinuity at the energy of the CsI 4d→4f resonance between 150 and 160Å. Figure 17 was therefore produced using measured values of μ, and our model imitates this. Figure 5.12 shows
Figure 5.9: Figure 12 from Fraser et al. [9]
Figure 5.10: Reproduction of Figure 12a from Fraser et al. [9]

Figure 5.11: Reproduction of Figure 12b from Fraser et al. [9]
Figure 5.12: Reproduction of Figure 17 from Fraser et al. [9]. Measured values of $\mu$ for CsI from Brown [83]

a reproduction of the Fraser et al. data using values of $\mu$ measured by Brown [83]. The full curves show results from our current model, and the broken curves data taken from Figure 17 of Fraser et al. In each case the higher curve corresponds to the incidence angle of 20° and the lower curve to 30°. Figure 5.13 is similar to Figure 5.12, but uses values of $\mu$ measured by Cardona [60]. It can be seen that both sets of results fit well with Fraser et al. although neither are exact. Despite extensive efforts, it was not possible to obtain a more exact fit to the Fraser figures. However, the ability of the updated program to reproduce the shape and magnitude of the original figures was thought to be enough to justify faith in the new model.

5.5 Modelling the Daresbury data

Given the success in reproducing the figures from reference [9], an attempt was made to model the Daresbury data of QE as a function of energy and angle for a CsI coated MCP (see Chapters 2-4). However, the code assumes the MCP has a zero degree bias angle, whereas the MCPs used
Figure 5.13: Reproduction of Figure 17 from Fraser et al. [9]. Measured values of $\mu$ for CsI from Cardona [60]

at Daresbury had a six degree bias angle. This discrepancy results in a poor model of the depth of coating down the channel. The non-biased plates are assumed to have symmetric coating around the central channel, down to a depth $H_0$. As described in Section 2.2, the bias angle of the channels implies that one side of the channel is coated and the other side shadowed: an extremely non-symmetric coating distribution around the channel. Thus the Daresbury results were modelled in two parts: firstly with a symmetric coating distribution, and secondly with a coating depth which varied with azimuthal angle. The results for a symmetric coating distribution will be discussed first.

5.5.1 First effort: CsI

The secondary electron coefficients for CsI had already been determined by Fraser et al. in reference [8], so the CsI results were modelled first. These were, in any case, the more important results for the AXAF project. The diameter of the MCP channels was $12.5\mu m$ with a $15\mu m$ pitch, which resulted in a open area of 63%. The L:D ratio was 120:1.
The secondary electron coefficients for CsI were as described in Table 5.2 and the effective atomic number (54.02), weight (130.1) and density (4.51 g cm⁻³) were as determined by Fraser. The variation in MCP coating thickness with depth down the central channel was modelled using equation 5.30 assuming a coating angle of 6°, and with a front surface coating thickness of 14,000 Å. The results can be seen in Figure 5.14. The coating thickness on the channel wall at the top of the channel is 460 Å, and the maximum coating depth is 9.51 channel diameters. This model therefore assumed a constant coating thickness of 460 Å down to a depth \( h_0 = 9.51D \).

**Coefficients used: glass**

The glass used in the MCPs was a newly developed low noise glass (Philips Type DA4073) [40]. After neglecting atomic constituents which were present in amounts less then 5%, and amalgamating those with similar properties, a pseudo-molecule of \( \text{Si}_{11}\text{O}_{28}\text{Pb}_{2}\text{Cs} \) was obtained. Using the method described in Section 5.3, the pseudo-molecule was calculated to have an
effective atomic number of 37.72 and an effective atomic weight of 82.41. The density was assumed to be that of Philips 3502 lead glass (3.3 g cm$^{-2}$), and the secondary electron coefficients were as in Table 5.2.

The 50-350eV range

Figure 5.15 shows the results of the model in the 50-350eV range, along with the corresponding experimental data from Chapter 2. They were produced using $P_s(0)=0.2$, an MCP bias voltage of 1550V and using calculated values of linear absorption coefficient. Although none of the measured data sets are reproduced exactly, the absolute values of QE are reasonably accurately modelled at 6 and 11°. The experimental data sets at angles 4°, 14° and 29° to the channel axis were taken on the shadowed side of the MCP, so we do not expect them to be accurately modelled here. Despite this, the shapes of the response at 14° and 16° are close to the measured values, although the absolute QE of the peak is factor of 2 too large. The measured QE at 29° is much lower than the calculated value, due to the coating variation round the channel and the model does not reconstruct the QE at 1° well. At small angles, the QE changes very rapidly with angle, so an error in the measured value of theta could explain this discrepancy.

Figure 5.16 shows how the contributions of glass and CsI change with angle, the CsI contribution becoming much more significant as the X-ray incidence angle is increased.

The discontinuity at ~80eV due to calculated values of $\mu$ noted in Figures 5.12 and 5.13 is obvious in Figure 5.15 at higher angles. Measured values of $\mu$ from Cardona [60] and Brown [83] between 50 and 180eV have been used in Figure 5.17 at 11°, 14° and 16° to the channel axis. Although the absolute QE remains the approximately the same as when using calculated values of $\mu$, the sharp discontinuities in QE have been reduced, and the shapes of the model and data look very similar. Figure 5.18 shows the measured and calculated values of $\mu$ over this energy range.

Finally in this energy range, the experimental data was modelled between 50 and 180eV using $P_s(0)=0.35$, as suggested by Fraser et al. [9] for energies below 180eV. The results of this are shown in Figure 5.19 for angles 6° and 14° to the channel axis. Calculated values of $\mu$ have been used. The model seems to reproduce the data marginally more accurately at 6° to the
Figure 5.15: Model and data between 50 and 350eV with $P_s(0)=0.2$ and calculated $\mu$. Unbroken line: calculated values. Dots: measured values. Angles with respect to the channel axis: a: 1°, b: 4°, c: 6°, d: 11°, e: 14°, f: 16°, g: 29°.
Figure 5.16: Model between 50 and 350eV with $P_s(0)=0.2$ and calculated $\mu$. Unbroken line: total QE. Dashed line: glass contribution. Dot-dash: CsI contribution. a: 4° to channel axis, b: 11° to channel axis.

Figure 5.17: Model and data with $P_s(0)=0.2$ and measured values of $\mu$. Unbroken lines: model with Cardona values of $\mu$. Dashed lines: model with Brown values of $\mu$. Dots: measured values of QE a: 11° to channel axis, b: 14° to channel axis, c: 16° to channel axis.
channel axis between 50 and 80eV than the model using $P_s(0)=0.2$, but otherwise there is no improvement.

**The 250-1400eV range**

The results from beamline 1.1 (see Chapter 4) were modelled assuming $P_s(0)=0.2$ for all energies within the range 250-1400eV. The MCP bias voltage was 1700V, and calculated values of $\mu$ were used.

Figure 5.20 shows data and results from the model at a range of angles. The angle of the data with respect to the channel axis is marked on the figures, with the side of the channel onto which the X-rays are incident indicated (coated or shadowed). The difference between the coated and shadowed side of the channel is immediately apparent: the coated side has a higher QE, the difference between the two increasing with increasing angle. The model reproduces the absolute QE of the coated side of the channel above the $I_{M_V}$ edge (620eV) accurately at all angles. Below the $I_{M_V}$ edge the correlation is less clear, although at lower angles (2 and 4°), some of the general shape of the data appears to be reproduced.
Figure 5.19: Model and data using calculated values of \( \mu \). Unbroken lines: \( P_s(0)=0.35 \). Dashed lines: \( P_s(0)=0.2 \). Dots: measured values of QE. a: 6° to the channel axis. b: 14° to the channel axis.

A large feature can be seen at the energy of the O-K edge at low angles in the model, which is only evident at higher angles in the data. This is likely to be a problem with the data rather than the model, as the beamline optics were thought to be contaminated in some way at this energy. Similarly the large increase in QE in the data at C-K is thought to be due to contamination of the optics, and therefore we would not expect it to be reproduced by the model. The increase in QE at the I \( M_V \) and \( M_{IV} \) edges is visible both in the model and the data. However, the data increases much more slowly than the model, due to the slow onset of the 3d→f transition (which is not included in the linear absorption coefficient data set): see Section 4.6.3. The sharp peaks related to the Cs \( M_V \) and \( M_{IV} \) edges are also not seen in the model, although there is a discontinuity at the edge energies. Chapter 6 deals with a more accurate model of the QE near atomic edges using Shah and Gurman’s ‘Simple method for calculating X-ray absorption coefficients’ [10].

Figure 5.21 shows how the relative fraction of the QE contributed by the CsI and the glass changes with incidence angle. Above \( \sim5^\circ \) angle of incidence with respect to the channel axis the glass contribution is negligible.
Figure 5.20: Model and data between 250 and 1400eV with $P_s(0)=0.2$ and calculated $\mu$. Unbroken line: calculated values. Dots: measured values. Angles of data with respect to the channel axis are marked on each figure. Angle of model with respect to the channel axis: a - 2°, b - 4°, c - 7°, d - 12°.

Figure 5.21: Model between 250 and 1400eV with $P_s(0)=0.2$ and calculated $\mu$. Unbroken line: total QE. Dashed line: glass contribution. Dot-dash: CsI contribution. a: 2° to channel axis. b: 4° to channel axis.
Figure 5.22: Model and data between 2000 and 6000eV with \( P_5(0)=0.2 \) and calculated \( \mu \). Unbroken line: calculated values. Dots: measured values. Angles of data with respect to the channel axis are marked on each figure. Angle of model with respect to the channel axis: a - 6°, b - 8°, c - 17°. 

The 2000-6000eV range 

The results from beamline 4.2 (see Chapter 3) were modelled as described above, with \( P_5(0)=0.2 \), calculated values of linear absorption coefficient and MCP bias voltage of 1600V. The results from the model are shown in Figure 5.22, with corresponding data. Because the azimuthal angle when the data was taken was \( \sim 90° \), the X-rays interact with both the ‘coated’ and ‘shadowed’ sides of the channel, so data sets taken at -10° and +10° are approximately the same. 

Although the general shape of the model is similar to the data, the gradient of the data is considerably steeper than that of the model. This leads to a much greater modelled QE around
the Cs and I L edges (above 4.5keV) than expected. However, the edges appear in the expected position. The difference between the data and the model may be due to the azimuthal angle of 90°, which implies that the X-rays are hitting the channel wall at an area where the coating depth down the channel is less the 9.51D. The angle of incidence and high energy result in no contribution to the QE from the MCP glass; the entire QE is a results of the CsI-coated fraction of the channel length. Note that the single point of absolute QE known directly from measurement at Leicester (at an energy of 2.56keV) has a somewhat higher value than the corresponding modelled figure (measured QE=27% at 6° to the channel axis).

5.6 Coating depth for a biased channel

Coating for the plates used at Daresbury took place in the coating rig at Leicester (see Figure 5.23). The MCP coating source was 762mm below the plane of the MCP front surface, with the MCP centre offset by 10cm, which gives a coating angle of 7.5° to the centre channel. As a first order approximation, we will assume the coating angle is 0°: for a biased MCP, the variation in coating depth due to the bias angle will be far more significant than the variation due to a non-zero coating angle. The MCP was rotated about its centre, but for coating at normal incidence the rotation make no difference to the coating depth, so a static plate can be considered. The coating depth will vary slightly with \( r_m \), the distance of the channel from the centre, but, as earlier for a non-biased plate, we will consider only the centre channel in our model.

It is assumed that the diameter of the MCP is small, such that the coating cannot travel straight down the channels. The coating can be considered as a cylinder of incident material, with radius \( r' \) and zero degree bias angle. The line of interception between this cylinder and another at a bias angle \( \theta_B \), with a radius of projection on the x-y axis of \( r' \) (representing the channel) delineates the coating depth down the channel (see also Section 4.6.2). The cylinder representing the coating has equation \( x^2 + y^2 = r'^2 \), whilst the equation of the channel is:

\[
(x - z \tan \theta_B)^2 + y^2 = r'^2
\]  

(5.31)

The line of interception thus has equations:

\[
z = \frac{2x}{\tan \theta_B}
\]  

(5.32)

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$$y^2 = r'^2 - \frac{z^2 \tan^2 \theta_B}{4}$$  \hspace{1cm} (5.33)

The maximum height along the z axis occurs at $x = r'$ and has value $\frac{2r'}{\tan \theta_B}$. This converts to a maximum coating depth along the channel of $H_0 = \frac{2r'}{\sin \theta_B}$. The relationship between $r'$ (the radius of the channel projected onto the x-y plane) and $r$ (the actual radius of the channel) is $r' \cos \theta_B = r$, which makes $H_0 = \frac{2r}{\sin \theta_B \cos \theta_B}$: similar to, but not exactly the same as the maximum coating depth as for a zero bias plate with a coating angle of $\theta_B$ (equation 5.29). Figure 5.24 shows a representation of these results.

The coating depth down the channel will vary with $y$, and can be found by calculating the distance between the circle in the xy plane and the line of intersection of the cylinders for each value of $y$. This results in a coating depth of

$$H = \frac{2(r^2 - y^2 \cos \theta_B)^{\frac{1}{2}}}{\sin \theta_B \cos \theta_B}$$  \hspace{1cm} (5.34)

which is shown in Figure 5.25 for a bias angle of $6^\circ$. Note that the maximum coating depth ($H_0$) is 9.62D (where D is the channel diameter = 2r), compared to 9.51D for the zero biased bias.
Figure 5.24: Representation of the coating (vertical cylinder) and channel (oblique cylinder). Dark line: intersection of the two cylinders.

MCP with 6° coating angle (Figure 5.14). Of prime importance is the complete lack of coating for values of x greater than 0. As we deduced earlier, one half of the channel is shaded from the coating by the bias of the channel.

5.7 QE model for a biased channel: CsI

The model of coating depth described above was then used to determine an approximate coating depth for each azimuthal angle used at Daresbury.

5.7.1 50-350ev

With an azimuthal angle of zero degrees, the data from Beamline 6.1 can be clearly split into that taken on the coated and the uncoated channel sides. Figure 5.26 show data and model results for glass only (a coating depth of 0D); the uncoated side of the channel. The magnitude
of the absolute QE on the uncoated channel side is reasonably well modelled, although the peak at 0.1keV is not reproduced. Comparison with Figure 5.15 shows that using just the glass response results in a much more accurate model of the absolute QE than if the CsI response is included, especially at high angles.

Figure 5.27 shows the results when the model using a CsI coating (9.51D coating depth) and the model with glass only are combined. The CsI model uses measured values of $\mu$ (from Cardona et al. [60]) up to an energy of 100eV, and calculated values above 100eV. The results in Figure 5.27 are produced by taking the mean of the model results for the coated and uncoated halves of the channel, and as can be seen, a good fit to the data is produced. There is some justification for this approach: even on the coated side of the channel, the coating depth decreases around the channel (see Figure 5.24), so it is to be expected that the actual QE of the MCP be some combination of the uncoated QE and the coated QE. Unfortunately, the least successful model (at 6° to the channel axis) is the one which considers the angle which is most relevant for AXAF.
Figure 5.26: Data from the uncoated channel side and model results using glass surface only. 
(a: 4° to the channel axis b: 14° c: 29°

Figure 5.27: Data from both sides of the channel. Model using half CsI-coated channel and half glass channel. 
(a: 6°, coated side of channel b: 11°, coated side c: 14°, uncoated side of channel d: 16°, coated side.
Figure 5.28 shows data from beamline 1.1 (250-1400eV), along with model results using various coating depths. The coating depth of 9.51D is the depth expected for an unbiased channel, and close to the maximum coating depth for a bias channel (9.62D). The data in this energy range was taken at an azimuthal angle of 20°, which implies that the X-rays incident upon the coated side of the channel 'see' a coating depth of 6.33D, so this is also modelled. Finally, the QE for glass only is given, to illustrate the model results for the uncoated channel side. It can be seen that a coating depth of 6.33D does not seem to produce a significantly more accurate model than a coating depth of 9.51D, indeed at most angles there is little or no difference between the two. However, data taken on the uncoated side of the channel is reproduced much more accurately using the glass only model than using the CsI, as would be expected. This is particularly true at large angles and high energies: at small angles and lower energies, the model still seems to overestimate the QE somewhat.

5.7.3 2000-4000keV

A similar process to that described in Section 5.7.2 was undertaken to produce Figure 5.29. Again, the 9.51D coating depth represents the maximum depth for a non-biased MCP. The dashed line is the result of running the model with a coating depth of 4.81D, a balance between no coating and the maximum depth of 9.62D for a biased channel. The data was taken at a 90° azimuthal angle, and so some fraction of the X-rays would be incident upon coating and some not. This is reflected by the third line on the graphs, which shows the result when the mean is taken of zero coating depth and a coating depth of 4.81D. This is similar to the procedure used in Figure 5.27. In the present case, the X-rays see both the 'coated' and 'uncoated' side of the channel. It should be noted that the model using half CsI and half glass successfully reproduces the QE of the MCP above 4keV, but below 4keV the QE gradient of the data is much steeper than that of the model.
Figure 5.28: Model with various coating depths and corresponding data for a range of angles. Solid line: coating depth 9.51D. Dashed line: coating depth 6.33D. Dots and dashes: glass only. Dots: data. Angles used for the model were: a:2° to the channel axis. b:4° c:7° d:9° e:12° f:18°. The angle of the data to the channel axis, and the side of the channel the data was taken on are shown on each plot.
Figure 5.29: Model with various coating depths and corresponding data for a range of angles. Solid line: coating depth 9.51D. Dashed line: coating depth 4.81D. Dots and dashes: half glass and half 4.81D coating. Dots: data. Angles used for the model were: a:6° to the channel axis. b:8° c:17°.

5.8 Modelling the Daresbury results for the KBr-coated MCP

5.8.1 KBr Coefficients

Unlike the CsI coefficients, the secondary electron coefficients for KBr have not been previously optimised using this model. However, there have been a number of attempts to estimate them. Grais and Bastawros [84] use experimental data of the electron-induced secondary electron yield from KBr to estimate $L_s = 51 \text{Å}$ and $P_s(0) = 0.28$. They also give values of 7.8eV for the band gap and 0.9eV for the electron affinity, which implies $\epsilon = 8.7$eV. Siegmund et al. [21] derive their values of the band gap (7.4eV) and electron affinity (0.8eV) from Henke et al. [85], which leads to $\epsilon = 8.2$eV. They use the same source to estimate $L_s$, which they believe lies in the 100-150Å range.
range. Kanaya et al. [86] give a value of $L_s = 111\,\text{Å}$, which is obtained from a theoretical study of the electron-induced secondary electron yield. Finally, Brohnstein and Protsenko [87] estimate a slightly different parameter, the maximum secondary electron escape depth. They give this for both KBr (500Å) and CsI (900Å). If we assume, perhaps simplistically, that the maximum secondary electron escape depth is proportional to $L_s$, then using $L_s = 215\,\text{Å}$ for CsI we obtain as value of KBr of $L_s = 120\,\text{Å}$.

We have only one value of $P_s(0)$, 0.28, so we accept that as the starting point for the model. Apart from the Grais value, all the other estimates point to an $L_s$ of between 100 and 120Å, so we have assumed a value of $110\,\text{Å}$. The two values of $\epsilon$ are close enough that the model will not be unduly affected whichever we choose. Given the disagreement between the Grais values for $L_s$ and all the other $L_s$ values, we have chosen the Siegmund value for $\epsilon$ of 8.2eV. The KBr secondary electron coefficients used to begin the modelling are thus:

$$P_s(0) = 0.28, \quad L_s = 110\,\text{Å}, \quad \epsilon = 8.2\text{eV}.$$  

Henke shows the secondary electron emission energy distribution, which appears similar to that for CsI. We thus assume the same mean secondary electron energy as CsI: 1.4eV. A curve of secondary electron yield versus energy is given by Gomoyunova and Letunov, and is shown in Figure 5.30 over the energy range considered here. An additional point at a secondary electron yield of 1 and an energy of 12eV is given by Afansyev and Bronshtein and also shown in Figure 5.30. The KBr effective atomic mass is 66.5, its effective charge 30.105, and from Kaye and Laby [88] its density at 25°C is 2.75g cm$^{-3}$.

Figure 5.31 shows the first-pass results from the model using the coefficients above and an MCP voltage of 1600V. It is compared on the plot with data taken at Daresbury over the whole energy range, with an incident angle as close to the normal to the front of the plate as possible (6° to the channel axis over 50-350eV, 7° to the channel axis for 250-1400eV and 8° to the channel axis for 2-6keV). It can be seen that the model seriously overestimates the experimental results, by a factor of $\sim 3$ at $\sim 400$eV.

Figure 5.32 is similar to Figure 5.31, but the values of $L_s$ and $P_s(0)$ have been halved to 55Å and 0.14 respectively. The value of $L_s$ used is thus similar to that of Grais, although we have no a priori justification for changing $P_s(0)$. Note that the overestimation by the model is now...
Figure 5.30: Secondary electron yield for KBr as a function of energy from Gomoyunova et al. and Afansyev et al.

Figure 5.31: Model and experimental data for a KBr-coated MCP with $L_s=110\text{Å}$, $P_s(0)=0.28$ and $\epsilon=8.2\text{eV}$. 
Figure 5.32: Model and experimental data for a KBr-coated MCP with $L_s=55\,\text{Å}$, $P_s(0)=0.14$ and $\epsilon=8.2\text{eV}$.

reduced considerably, as expected, but the model still fits the data very poorly below 1keV. Figure 5.33 compares the model (using $L_s=55\,\text{Å}$ and $P_s(0)=0.14$), data and calculated values of linear absorption coefficient multiplied by X-ray energy ($\mu(E)xE$). The model follows the general shape of $\mu(E)xE$, as expected, so the dip in the experimental data at 400eV is unlikely to be replicated by any minor changes to the model. There is some doubt as to the validity of the low energy data: data taken between 200 and 350eV was in a region of very low count rate, and therefore high relative noise. There were also problems calibrating data from beamline 1.1, which covered the 250-1400eV range, which must cast doubt onto those results. Given these uncertainties, it was decided to continue the modelling using the original secondary electron parameters of $P_s(0)=0.28$, $L_s=110\,\text{Å}$ and $\epsilon=8.2\text{eV}$. 

![Graph showing modelled and experimental data for KBr-coated MCP](image)
Figure 5.33: Model, experimental data and $\mu(E)xE$ for a KBr-coated MCP with $L_s=55\text{Å}$, $P_s(0)=0.14$ and $\epsilon=8.2\text{eV}$.

5.8.2 Modelling KBr QE for a biased channel

50-350eV

Figure 5.34 shows data from beamline 6.1 (the 50-350eV energy range) along with the results of modelling the KBr-coated MCP response using the secondary electron parameters above. In this case a coating depth of 9.51D was assumed (with a constant coating thickness down to that depth of 460Å, as for the previous CsI models). This coating depth implies a non-biased channel. Calculated values of $\mu$ were used, with a MCP bias voltage of 1550V. Recall that the azimuthal angle was 0°, implying a sharp division in the data between that taken on the coated and uncoated sides of the channel. The figure shows both the total modelled QE and the contributions from glass and CsI. As expected, the glass contribution is only significant below an angle of 6° to the channel axis. As with the corresponding CsI data, this model overestimates the experimental results significantly at higher angles, although it does model the general shape reasonably well. Again, the model seems to be more accurate at higher angles.

Figure 5.35 shows the data of Figure 5.34, but in this case some attempt has been made to
compensate for the bias angle of the channel and the consequent variation in coating. The total modelled QE with a coating depth of 9.51D is shown, along with the modelled results when the mean of the coated and non-coated channel sides are shown. All the data was taken on the coated side of the channel, except for that at 4° (shown in part b of Figure 5.35, which was taken on the shadowed side. For that reason Figure 5.35(b) also includes the modelled QE from the non-coated channel side (glass only). It can be seen that, particularly at higher angles, inclusion of some non-coated component significantly improves the fit of the model. It is particularly edifying to note the successful reproduction of the rise at ~0.1keV. Above 0.3keV, the count rate was particularly low, and it is perhaps not surprising that the rise seen in the model at 0.3keV is not echoed in the data. For the data taken on the shadowed side of the channel, including only the glass response in the QE model does not improve the fit to the data at all. This suggests that the partition between coated and non-coated channel sides is not as clear as originally thought, and that even data taken on the 'non-coated' channel side includes some component of QE due to the coating. These conclusions are all similar to those found over the same energy range for the CsI-coated MCP-half (see Section 5.7.1).

250-1400eV

Figure 5.36 shows both data and model results for the 250-1400eV energy range on the KBr-coated MCP half. The secondary electron coefficients were as previously, and the MCP bias voltage was 1700V. As the azimuthal angle for this data set was 20°, the data was modelled with coating depths of 9.51D and 6.33D, although the coating thickness was constant at 460Å. The figure shows the QE modelled using these coating depths, and the QE when the mean is taken of the part-coated-channel QE and the non-coated channel QE (see Section 5.7.2). Figure b also includes the QE of a glass-only channel, as the 9° data was taken on the uncoated side of the channel.

The magnitude of the data taken on the uncoated side of the channel (b) is reasonably well reproduced by the glass-only model, and the difference between the coated and uncoated channel sides is obvious. On the coated side of the channel (a), it is useful to note that the one point of absolute QE reliably measured at Leicester (QE = 27%, 7° to the channel axis, 930eV) is not far in magnitude from the model (using a coating depth of 9.51D). However, apart from the
Figure 5.34: Model and experimental data for a coating depth of 9.51D. Dots - experimental data. Solid line - total QE from model. Dashed line - glass QE fraction. Dot-dash line - KBr QE fraction. a: 1° b: 4° c: 6° d: 11° e: 16°. All angles with respect to the channel axis. Data taken on coated side of channel except for 4° data which was taken on the shadowed side.
Figure 5.35: Model and experimental data for a coating depth of 9.51D. Dots - experimental data. Solid line - total QE from model (KBr coated). Dashed line - half KBr-coated channel QE and half uncoated-channel QE. Dot-dash line (graph b)- QE for uncoated channel. a: 1° b:4° c: 6° d:11° e:16°. All angles with respect to the channel axis. Data taken on coated side of channel except for 4° data which was taken on the shadowed side.
Figure 5.36: Model and experimental data for coating depths of 9.51D and 6.33D. Dots - experimental data. Solid lines - total QE from model (KBr coated). Dashed lines - half KBr-coated channel QE and half uncoated-channel QE. Dot-dash line (graph b) - QE for uncoated channel. On graph a, the model result for a coating depth of 9.51D is the higher of the two lines. On graph b the model results for a coating depth of 9.51D and 6.33D are indistinguishable. a: 7° on coated channel side b: 9° on uncoated channel side. All angles are with respect to the channel axis.

noticeable features at the energies of C-K and O-K, there appears to be little correspondence between the model and the data. Doubt can legitimately be cast upon the validity of the data in this energy range (see Section 4.6.3), and until further data is taken it will be difficult to judge whether the model or the data is the more reliable indicator of the actual MCP QE for KBr between 250 and 1400eV.

2000-6000eV

Experimental data and the results of modelling in the 2-6keV energy range are shown in Figure 5.37. The secondary electron coefficients were as previously, and the MCP bias voltage was 1600V. As in Section 5.7.3, the azimuthal angle of 90° implied no clear distinction between the coated and uncoated sides of the channel, so the data was modelled using coating depths of 9.51D and 4.81D. The QEs for a glass-only channel and for a half-coated and half-glass are also shown. Again (see Section 5.7.3) the gradient of the data is much steeper than that of the model, so the different parameters either overestimate the QE above ~3.5keV or underestimate the QE.
below ~3.5keV. However the step in the QE at the energy of the K-K edge is well modelled, particularly by the model which uses the 4.81D coating depth and includes the half-glass QE (the lower dashed line in Figure (a)).

5.9 Conclusions

The model used here has proved to be generally good at reproducing the data shown in previous chapters. The results for CsI were particularly encouraging, especially at larger angles. The model fits both the shape and absolute value of the QE as a function of energy once some account has been taken of the bias angle of the channels.

The model developed of coating for a biased channel was only a first attempt. In further work, a more detailed model of the coating depth down the channel should be produced, and the variation in coating thickness down the channel should be incorporated into the model. With the use of the improved model, the fit to the data should be significantly improved, particularly at low angles where the partition between the glass and coating contributions to the QE is, at present, uncertain.

On the whole, the modelling has been reasonably successful, although there are some major differences between the model and the data. These are most apparent in the 250-1400eV energy range, particularly on the KBr-coated MCP-half. However, give the uncertainties in the data in this energy range, it would be a mistake to draw conclusions concerning the validity of the model from these discrepancies.
Figure 5.37: Model and experimental data for coating depths of 9.51D and 4.81D. Dots - experimental data. Solid lines - total QE from model (KBr coated). Dashed lines - half KBr-coated channel QE and half uncoated-channel QE. Dot-dash line - QE for uncoated channel. On graph a, the model result for a coating depth of 9.51D is the higher of the two lines in each case. On graph b the model results for a coating depth of 9.51D and 4.81D are indistinguishable. a: 8° b: 17° All angles are with respect to the channel axis.
Chapter 6

Modelling of atomic edge-related structure

6.1 Introduction

Previous chapters (2, 3 and 4) have given described the synchrotron calibration of photocathode-coated MCPs, in particular the measurement of MCP QE as a function of incident X-ray energy. Chapter 5 introduced and developed a model of the MCP response, concentrating on the general shape of the QE-versus-energy curve. The values of linear absorption coefficient used in this model were from a tabulation by Cromer and Liberman [82], which gives absorption coefficient only at a discrete number of energies and does not attempt to show the detailed features present near the atomic absorption edges. There are a number of such features in the photocathode materials under consideration here, the most prominent of which are the 'white lines': spikes on the absorption edge due to promotion of electrons to a resonant, loosely bound state. The modelling of these white lines is vital if the MCP response is to be accurately calibrated for astronomical use. An uncalibrated white line feature in the CsI-coated HRC-S response would mimic an emission line in the spectra of sources observed with the AXAF HRC-S. This chapter describes an attempt to model these features, based upon the method for calculating linear absorption coefficients developed in [10] and [11].
6.2 Atomic theory

A brief discussion of the relevant atomic theory is given here (for more details see the original papers by Shah and Gurman [10, 11]). This model considers contributions to the linear absorption coefficients from each atomic energy level separately, and then adds the contributions together as appropriate. Combination of Fermi's Golden Rule and the dipole approximation gives a contribution from each atomic energy level of [89]:

\[ \mu(\omega) = \frac{4\pi^2 e^2}{\hbar c} \omega |<i|\epsilon_r|f>|^2 \]  

(6.1)

where \( \mu \) is the linear absorption coefficient and \( \omega \) the frequency of the X-rays. \( i \) and \( f \) symbolise the wavefunctions of the initial and final states of the electron, and \( \epsilon \) is the vector of polarisation. All other symbols have their usual meanings.

If the initial state has angular momentum quantum number \( l_0 \), then the dipole selection rules allow two possible angular momenta for the final state: \( l_0 \pm 1 \). Both of these final states must be considered in the calculation, along with all the sublevels of both initial and final states (with the same values of principal quantum number \( n \), and \( l \) but differing values of \( m \)). Gurman [11] gives the results of this calculation as:

\[ \mu(\omega) = \sum_l \frac{8\pi^2 e^2}{9\hbar c} \omega |R(l_0,l)|^2 A(l_0,l) \]  

(6.2)

In the expression above, the matrix element is split into two parts: the radial part \( (R(l_0,l)) \) and the angular part \( (A(l_0,l)) \). If we let \( k \) represent the momentum of the photoelectron \( (k^2 = \frac{2m\hbar^2}{\omega^2}(\hbar \omega - E_b)) \) where \( E_b \) is the initial state binding energy) part of the matrix element becomes:

\[ R(l_0,l) = \frac{2mk^{\frac{1}{2}}}{\pi \hbar^2} \frac{1}{m\omega^2} \int r^2 R_{l_0}(r) \frac{\delta V(r)}{\delta r} R_l(r) dr \]  

(6.3)

where \( V \) is the atomic potential. The angular momentum part of the matrix element has its usual form:

\[ A(l_0,l) = \begin{cases} l_0 + 1 & \text{if } l = l_0 + 1 \\ l_0 & \text{if } l = l_0 - 1 \end{cases} \]

This treatment does not take into account spin-orbit splitting: this will be discussed further in Section 6.3.1.
Thus, in order to calculate the linear absorption coefficient we require a calculation of the initial and final state wavefunctions and the atomic potential. The simplest solution is to assume a simple Coulomb potential for the atomic potential, which results in analytical forms for the initial and final state wavefunctions. However, such a solution leads to the prediction that there is no edge structure present at all. Shah et al. [90] consider the Hulthen potential, but the model employed here uses the Tietz potential:

\[ V(r) = -\frac{Z}{r}(1 + \alpha r)^{-2} \]

\( \alpha \) varies with the atomic charge, and has been found analytically to equal 0.6057 \( Z^{\frac{1}{3}} \) [91]. To take account of surrounding atoms in a solid, this potential is truncated to a muffin-tin form at the radius of the atom or ion. The potential at this radius is then taken as the energy zero. The initial state wavefunctions are a combination of Slater orbitals and hydrogenic wavefunctions. The normal hydrogenic wavefunctions are used, but screening of the nucleus is included by using Slater's rules to determine a screened value of the nuclear charge. Gurman [11] gives the Slater screening constants, and the hydrogenic wavefunctions are given by [92].

The Schrodinger equation is solved numerically to give the final state wavefunctions, as described by Shah and Gurman [10], and normalised at the muffin tin radius to the final state wavefunction outside the muffin tin. We take the binding energy of the initial state to be equal to the edge energy, neglecting the minimal energy difference between the muffin tin zero and the Fermi level. We are now able to evaluate equation 6.2 for each atomic energy level under consideration.

### 6.3 Edge shapes for alkali halide atoms

To model the alkali halide linear absorption coefficients, the absorption coefficients are first calculated for the atomic constituents separately and then combined to give the final result. Thus, reproducing the Daresbury results initially required modelling absorption coefficients for K, Br Cs and I. The major inputs for the model are the atomic charge, radius and energy levels. The maximum principal quantum number \( n \) to be considered in the model is input, along with the energy of each of the atomic levels under consideration (a total of \( 2n+1 \) energy levels). As mentioned previously, spin-orbit splitting is not taken into account initially, so the mean energy for split levels is used (e.g. for the \( L_{II} \) and \( L_{III} \) levels). The energy levels employed in this
Table 6.1: Energy (in eV) used for each atomic energy level in the model discussed here

<table>
<thead>
<tr>
<th></th>
<th>1s</th>
<th>2s</th>
<th>2p</th>
<th>3s</th>
<th>3p</th>
<th>3d</th>
<th>4s</th>
<th>4p</th>
<th>4d</th>
<th>4f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>35985</td>
<td>5714</td>
<td>5186</td>
<td>1211</td>
<td>1037</td>
<td>734</td>
<td>232</td>
<td>167</td>
<td>79</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>33169</td>
<td>5188</td>
<td>4705</td>
<td>1072</td>
<td>903</td>
<td>625</td>
<td>186</td>
<td>123</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>3608</td>
<td>379</td>
<td>296</td>
<td>35</td>
<td>18</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Br</td>
<td>13474</td>
<td>1782</td>
<td>1573</td>
<td>257</td>
<td>185</td>
<td>69</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

model are those given by Vaughan et al. [76], and are shown in Table 6.3. The muffin-tin radius used was the ionic radius of the element, taken from and Kaye and Laby [88] and assuming co-ordination numbers of 8 for Cs\(^+\) and 6 for K\(^+\). The ionic radii for I and Br are independent of co-ordination number. The model gives values for \(\mu\) in barns/atom, beginning at energy \(E\) above the absorption edge and continuing in steps of \(\Delta E\). To obtain the total atomic absorption coefficient the responses from each atomic level are then summed over the appropriate energy ranges.

The ionic charge is also required for each constituent. The actual charge felt by each ion is a matter of some uncertainty. Classically, the Cs and K atoms each have a charge of +1 and the I and Br ions have a charge of -1. Quantum mechanically, the charge appears less obviously distributed, and in many cases zero charge on each atom produces accurate results. In the model considered here, each element is modelled separately. This implies that we must use zero charge on each atom, because an array of all positive or all negative ions makes little sense physically. The shapes of the K and Br edges were modelled with +1 and -1 charge respectively, to compare the results to the zero charge model. Figures 6.1 and 6.2 show the results of this comparison. Consideration of the K-K edge is particularly interesting. Experiment shows a significant white line on the K-K edge, which is much more obvious on the zero charge model than on the +1 charge model (as would be expected). For both Cs and I modelling with zero charge results in white lines which are not so obvious when the classical charge of ±1 is used, but which are present in experimental data. Therefore, for our modelling, no charge was used on any atom.
Figure 6.1: Comparison of modelled K edges with charge +1 (solid line) and charge 0 (dashed line). a-K edge b-L₁ edge c-L_{II,III} edge.

Figure 6.2: Comparison of modelled Br edges with charge -1 (solid line) and charge 0 (dashed line). a-L₁ edge b-L_{II,III} edge.
Modelled linear absorption coefficients for the Cs edges in the energy range under consideration are shown in Figure 6.3. These assume an ionic charge of 0 and a muffin-tin radius of 1.82 Å. White lines can be clearly seen on the L_{I}, M_{I} and M_{IV,V} edges. These are transitions from initial states with quantum numbers \((l=0, j=\frac{1}{2}), (l=0, j=\frac{3}{2})\) and \((l=2, j=\frac{3}{2}, \frac{5}{2})\) respectively. Given the selection rules \((\Delta l = \pm 1, \Delta j = 0, \pm 1)\), these suggest transitions to a state with \((l=1, j=\frac{3}{2})\).

Although the M and L edges appear as expected in Figure 6.3, there are large oscillations in the linear absorption contribution from the N edges. These suggest that the approximations used to estimate the initial state wavefunction break down at high principal quantum numbers. The N-edge responses obviously cannot be used as they stand (changing the ionic charge makes little difference to the result), but for our purposes the linear absorption coefficient does not need to be well modelled close to the N edges. Therefore, when the edge responses are combined the produce the total \(\mu \) for Cs, the N edge contribution is obtained by extrapolating the tabulated linear absorption coefficient below the M edge (assuming an exponential shape: \(\mu = ae^{bE}\) where \(E\) is the X-ray energy and \(a\) and \(b\) are constants). Tabulated values of \(\mu\) from Cromer and Liberman were used for this purpose [82], after being converted from cm\(^{-1}\) to barns atom\(^{-1}\). Figure 6.4 shows the Cromer and Liberman data near the M edges, with the extrapolated N edge response superimposed. It can be seen that the N-shell response is only a small fraction of the total linear absorption coefficient above the M edges.

In addition to adding the N edge response, spin-orbit splitting can also be introduced to obtain the final Cs linear absorption coefficient. This is done by assuming that the modelled edge response can be split according to the statistical weights of the split edges (where the statistical weight is \(2j+1\)). This gives us the ratios \(\mu L_{II} : \mu L_{III} = \mu M_{II} \) : \(\mu M_{III} = 1 : 2\) and \(\mu M_{IV} : \mu M_{V} = 2 : 3\).

The Fermi energy of CsI should also be taken into account: if the final states for the white line transitions lie below the Fermi level then they will not contribute to the absorption, and the absorption coefficient should be truncated at the appropriate energy. Fortunately, band structure calculations for both CsI and KBr [93, 94, 95] show that the Fermi level lies below the final states, and therefore it is safe to assume a Fermi energy of zero.
Figure 6.3: Model results for Cs edges.
Figure 6.4: Cromer and Liberman linear absorption coefficient in the vicinity of the Cs M edges (dashed line), with the extrapolated N edge response (solid line).

Figure 6.5 shows the finally-estimated total absorption coefficient for Cs, including the Cromer and Liberman N edge contribution, spin-orbit splitting and the M and L edge modelled contributions.

Similar figures to those described above are shown in Figures 6.6 - 6.8 for the modelled iodine absorption coefficient. The model again used zero ionic charge, and has a muffin-tin radius of 2.2 Å. Figure 6.6 displays the edge responses for I. Note the oscillations in the N edge responses, as for Cs. Once more there are white lines on the L_I, M_I and M_{IV, V} edges, suggesting transitions to a hybrid s-p state. Figure 6.7 shows the exponential fit to Cromer and Liberman data below the M edges, while Figure 6.8 gives the total absorption coefficient for iodine, including spin-orbit splitting and the N edge response.

The absorption coefficients of Cs and I must then be combined to produce the absorption coefficient for CsI. According to Hubbell and Seltzer [96], this can be done by assuming that:

$$\frac{\mu}{\rho} = \Sigma_i \omega_i \frac{\mu_i}{\rho_i}$$

(6.5)
where $\omega_i$ is the atomic fraction by weight of the constituent element and $\rho$ is the elemental density. This was done for Cs and I, after conversion to units of cm$^{-1}$, and using densities of 1.87 and 4.92 g cm$^{-2}$ respectively [76]. The density of CsI was taken as 4.51 g cm$^{-2}$. The results of this combination are shown in Figure 6.9. Note that the linear absorption of the compound is greater than for either of the constituent elements. The linear absorption coefficient from Cromer and Liberman is also displayed. It can be seen that the modelled result overestimates the Cromer and Liberman calculation by approximately a factor of 2. This is because of a higher than expected M shell contribution to the model, probably again due to the inaccuracy of the screening approximation. A similar problem was noted by Gurman [11] and Slater [97]. Gurman suggests that agreement with experiment could be improved by reducing the screening constant, if this was thought necessary.
Figure 6.6: Model results for I edges.
Figure 6.7: Cromer and Liberman linear absorption coefficient near the I M edges (dashed line), with the extrapolated N edge response (solid line).

Figure 6.8: Total absorption coefficient for I, including spin-orbit splitting.
Figure 6.9: Comparison between the CsI linear absorption coefficient for the current model (solid line) and Cromer and Liberman data (dashed line).
6.3.2 KBr

The same procedure was carried out for K and Br as described for Cs and I in Section 6.3.1. The modelled contribution to the absorption coefficient from each level in the K and Br atoms is shown in Figures 6.10 and 6.11. In both cases the ionic charge was zero and the muffin-tin radius was 138 Å for K and 196 Å for Br [88]. There were no significant white line structures in the Br absorption coefficient, but white lines appear on the K, L_I, and M_I edges of K. These are all edges produced by transitions from an initial state with l=0 and j=\( \frac{1}{2} \). The selection rules imply the white lines are caused by transitions to a state with l=1 and j=\( \frac{1}{2} \) or \( \frac{3}{2} \).

Similar oscillations to those seen on the N edges of Cs and I can be seen on the M edges of Br and, particularly, K. Fortunately, the energies at which we are interested are higher than the M edge energies, so the M edge contribution to the absorption coefficient can be extrapolated from Cromer and Liberman data below the L edges, in an analogous manner to the N edge.

Figure 6.10: Model results for K edges.
contribution for Cs and I. Figures 6.12 and 6.13 show the Cromer and Liberman absorption coefficients close to the K and Br L edges, with the exponential extrapolation of the absorption from the M edges indicated.

Figures 6.14 and 6.15 show the total modelled absorption coefficient for K and Br respectively, including spin-orbit splitting and the contribution of the M edges, extrapolated from Cromer and Liberman data.

The K and Br absorption coefficients were combined in the manner described above (Section 6.3.1); the result is shown in Figure 6.16. The corresponding results from Cromer and Liberman's tabulation are also shown. As for CsI, we see that the current model overestimates the absorption coefficient compared to Cromer and Liberman, by a factor of slightly less than 2. The model for KBr is somewhat closer to the Cromer and Liberman results than that of CsI.

6.4 Quantum efficiency model

The modelled linear absorption coefficients for CsI and KBr shown in Figures 6.9 and 6.16 were incorporated into the model of MCP quantum efficiency developed in Chapter 5. The QE model could then be compared to data obtained at Daresbury, giving an indication of the accuracy of our model of the linear absorption coefficients of these photocathode materials.
Figure 6.12: Cromer and Liberman linear absorption coefficient near the K L edges (dashed line), with the extrapolated M edge response (solid line).

Figure 6.13: Cromer and Liberman linear absorption coefficient near the Br L edges (dashed line), with the extrapolated M edge response (solid line).
Figure 6.14: Total absorption coefficient for K, including spin-orbit splitting.

Figure 6.15: Total absorption coefficient for Br, including spin-orbit splitting.
Figure 6.16: Comparison between the KBr linear absorption coefficient for the current model (solid line) and Cromer and Liberman data (dashed line).

6.4.1 CsI

There were two energy ranges of interest: 600-800eV, which includes the Cs and I M_{IV} and M_{V} edges, and 4000-6000eV, which includes the Cs and I L edges. There were edges with white lines in both these energy ranges, which should now be reproduced by the model.

The M_{IV} and M_{V} edges

The MCP QE in the 600-800eV energy range was modelled using an MCP accelerating voltage of 1700V, and with secondary electron parameters for CsI of P_{s}(0)=0.2, L_{s}=215Å and ε=7eV. A coating thickness of 460Å was assumed. Two coating depths down the channel were modelled: 9.51D (the coating depth for a channel of zero bias) and 6.33D (the coating depth for a channel of 6° bias angle and azimuthal angle of 20°). All these figures are as used in Section 5.7.2. However, in this case the linear absorption coefficient employed was that derived in this chapter, rather than the Cromer and Liberman values used previously.
Figure 6.17 shows the results of this modelling for a range of photon incidence angles between 2° and 18°, along with the corresponding data from Daresbury. The Daresbury data is labelled with the exact angle to the channel axis at which it was taken, and the side of the channel the X-rays were expected to impact. The modelled QE is shown for coating depths of 9.51D, 6.33D, and for an uncoated channel (glass only).

Figure 6.17 can be compared to Figure 5.28, which used the Cromer and Liberman values of linear absorption coefficient for CsI. It can be seen that, over the limited energy range considered here, the absolute QEs obtained are similar to those using Cromer and Liberman values of linear absorption coefficient, but the model developed in this chapter introduces large ‘white line related features’ at the Cs and I M_{IV} and M_{V} edges and causes the onset of the increase in QE due to the I edges to occur much less rapidly. The slow increase in QE is seen in the experimental data, and is due to the slow onset of 3d shell transitions. However, although the experimental data shows large white line features on the Cs M_{IV} and M_{V} edges, no such features are visible on the corresponding I edges. Note also that the model does not reproduce the shift of approximately 13eV between the Cs M_{IV} and M_{V} edge features and the tabulated energies of the edges. This is expected, as the energy shift is a function of the binding between Cs and I, and is therefore not considered in the model.

The L edges

The energy range between 2 and 6keV contains the Cs and I L edges. Experimental data (Section 3.6.2) showed significant structure in the CsI-coated MCP QE related to these edges. The QE was modelled with the same secondary electron parameters as above (Section 6.4.1), but with an MCP accelerating voltage of 1600V. The coating thickness was 460Å, and two coating depths were modelled: 9.51D (as above) and 4.81D, representative coating depth for a channel viewed at a 90° azimuthal angle (see Section 5.7.3).

Figure 6.18 shows the results of this modelling for both coating depths in comparison to experimental data. Model results are also shown for a combination of 4.81D coating and zero coating (\(Q_{E_{comb}}=\frac{1}{2}(fQE_{CsI}+(1-f)QE_{glass})+\frac{1}{2}QE_{glass}\), where \(QE_{CsI}\) is the QE expected from a fully coated channel, \(QE_{glass}\) is the QE from an uncoated channel, and \(f\) is the fraction of X-rays
Figure 6.17: Modelled and experimental QE for a CsI-coated MCP. Modelled values of linear absorption coefficient have been used. Solid line: 9.51D coating depth. Dashed line: 6.33D coating depth. Dot-dash line: glass only. Dots: experimental data. The model uses the following angles to the channel axis: a: 2° b: 4° c: 7° d: 9° e: 12° f: 18°. Experimental incidence angles are given on the figures.
Figure 6.18: Modelled and experimental QE for a CsI-coated MCP. Modelled values of linear absorption coefficient have been used. Solid line: 9.51D coating depth. Dashed line: 4.81D coating depth. Dot-dash line: half 4.81D coating and half glass. Dots: experimental data. a: 6° to the channel axis. b: 8° c: 17°.

absorbed in the coating depth of 4.81D (see Section 5.2.4). All the models overestimate the experimental data, although the half-glass half-coated model reproduces the QE at the lowest angle accurately. The main points to notice are the large white line features on the Cs and I L₁ edge of the model, which are definitely not seen in the experimental data. Figure 6.19 gives a closer view of the half-glass half-coated model and the experimental data at 6°. Apart from the anomalous white line at 5.2 keV, the edge features appear to have been well modelled.

6.4.2 KBr: the K-K edge

Our experimental data show only one feature edge of interest in the KBr-coated MCP QE: the K-K edge. The absorption coefficient model shows a large white line on this edge, which should produce a significant feature in the QE near the edge. The KBr-coated MCP QE was modelled as described in Section 5.8.1, with secondary electron parameters for KBr of Lₛ=110Å, Pₛ(0)=0.28 and ε=8.2eV. The MCP accelerating voltage was 1600V, with an X-ray energy range of 3500
to 3800eV. The coating thickness of 460Å was modelled to two depths: 9.51D and 4.81D, as described for CsI in the previous section. The results of this modelling, and the corresponding experimental data are shown in Figure 6.20. As expected from previous results, the experimental data is best modelled by the half-glass half-coated combination, and at an angle of 8° to the channel axis this combination reproduces the absolute values of QE below and above the K edge particularly accurately. Unfortunately, although not surprisingly, the white line seen on the experimental data is considerably smaller than that produced by the model, as has been the case with most of the edges considered here. Indeed, a white line of the size predicted by the model would cause a great deal of concern had it been seen in the data.

### 6.5 Conclusions

This method of modelling linear absorption coefficients, whilst currently having some significant problems, does seem to promise a useful and interesting addition to the suite of models currently available for modelling near-edge structure in MCP QE. In general the absolute value and shape
Figure 6.20: Modelled and experimental QE for a KBr-coated MCP. Modelled values of linear absorption coefficient have been used. Solid line: 9.51D coating depth. Dashed line: 4.81D coating depth. Dot-dash line: half 4.81D coating and half glass. Dots: experimental data. The model uses the following angles to the channel axis: a-8° b-17°
of the QE modelled here, both for CsI and KBr, ties in well with that produced using Cromer and Liberman data, with the advantage of showing some near-edge structure. The shielding approximation does appear to break down at high quantum numbers, leading to oscillations in the low energy edge responses, but for the energies considered here the method of extrapolating the low energy edge contribution from Cromer and Liberman data works well. Of course, if it were necessary to model the near edge structure of the low energy edges, then this approach would not be appropriate.

The main difficulty with this model lies in its inability to take into account the difference between an array of CsI and arrays of Cs and I combined. This problem is evident in the uncertainty about which charge should be applied to each atom, and the wide difference between results when ±1 charge is applied as opposed to 0 charge. The extremely (implausibly) large white lines seen on some edges are, perhaps, a symptom of this problem.

These inconsistencies could be solved by using a different model for linear absorption coefficient currently under development at Leicester by Roy and Gurman [98]. This model modifies the muffin tin potential using a Madelung potential (a 1/r potential superimposed on each muffin tin), and also enables the ionic charges to be varied between 0 and ±1. The model can consider both elements in the lattice at once. A further option is to use Cs+ and I- wavefunctions as the initial wavefunctions, rather than using the Madelung potential.

Using one of the modified models available, this technique could be very useful in modelling the near edge structure in MCP quantum efficiency.
Chapter 7

Thermally Annealed Soft X-ray Photocathodes

7.1 Introduction

During the research described in this thesis, and in a considerable body of work by previous authors [15] - [22], the advantages of coating the front plate of an MCP detector with CsI have become apparent. Coating MCPs with alkali halide photocathodes to increase quantum efficiency is now standard practice [99, 100, 101]. Importantly, CsI coating can also endow an MCP X-ray detector with modest energy resolution [99, 26].

Recent papers in this field have reported a VUV (1500-2200Å) quantum efficiency enhancement obtained by heat annealing photocathodes after deposition [102] - [107]. Although, according to Breskin [107], the exact reasons for this enhancement are not yet fully understood, these reports were sufficient to stimulate the present investigation of heat-treated X-ray photocathodes both on planar substrates (Section 7.2 below) and on microchannel plates (Section 7.3). The effects of thermal treatments on coated MCP gain are also investigated in Section 7.3.3.
7.2 Planar photocathodes

7.2.1 Experimental procedure

The current quantum yield of thermally annealed planar CsI photocathodes, \( \chi_0 \), was investigated by colleagues in St. Petersburg in the 5–10 keV X-ray energy range.

An X-ray tube and Bragg crystal spectrometer were used to produce K\( \alpha_1 \) or K\( \beta_1 \) line radiation from Cr, Co and Cu targets. A proportional counter was used as an absolute flux monitor. \textit{In situ} deposition, thermal annealing of the photocathodes and electrometer measurement of photocurrent could be carried out inside a common, Be-windowed, vacuum chamber.

A number of (5000Å thick) CsI photocathodes were evaporated onto polished stainless steel substrates both \textit{in situ} and outside the measurement chamber. The latter cathodes were stored for some hours in air before installation in the measurement chamber.

Samples were heated from room temperature to 270±30°C over a 7-10 minute period. To prevent the CsI subliming (the sublimation temperature of CsI is estimated to be \( \sim 270°C \)) the thermoelectric furnace was switched off and the photocathode allowed to cool to room temperature over a period of approximately 50 minutes. This annealing cycle was repeated up to 10–13 times for each sample. The current quantum yield (electrons per photon) was measured using an electrometer, prior to annealing and then after each cycle when the photocathode had cooled to room temperature.

7.2.2 Results

Figure 7.1 shows the St Petersburg measurements (averaged over three identically treated CsI photocathodes) of room-temperature current yield after ten thermal cycles. Also shown are comparable data from Day \textit{et al.} \cite{66} and Eliseenko \textit{et al.} \cite{71}. Note that Eliseenko’s data, obtained at a grazing angle of 20°, has been rescaled to normal incidence using the well known cosec (grazing angle) dependence of the current quantum yield \cite{8}. The linear absorption coefficient \( \mu(E) \) was calculated from the atomic database of Cromer and Liberman \cite{82}. 

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Figure 7.1: X-ray energy dependence of normal incidence photocurrent for standard and annealed CsI cathodes. Crosses - data from Eliseenko et al. (see text). Open circles - Day et al., also unannealed. Filled circles - annealed CsI, present study. Named atomic absorption edges indicated by broken vertical lines. Solid lines - photocurrents calculated from eq.7.4, using indicated values of the surface escape probability, $P_s(0)$ (see text for values of $L_s$, $\varepsilon$). Linear absorption coefficient $\mu(E)$ calculated from the atomic database of Cromer and Liberman.
Thermally annealed CsI is seen to be substantially more efficient than the "standard", untreated material. The photoyield increased by a factor of 2 after just one annealing cycle and reached full enhancement (up to 4–5 times improvement in yield) after 8–10 cycles. Keeping some of the CsI photocathodes in air led to a loss, as expected, of 40-60% of the “fresh” photocathode yield. However, after 3–4 annealing cycles such photocathodes had recovered to the level of an in situ prepared sample. During any heat annealing cycle the photoyield increased as the photocathode cooled. For one sample the photoyield was measured at 5 minute intervals as the photocathode temperature decreased from 270°C to 17±1°C (see Figure 7.2).
Table 7.1: Microchannel plate detector operating characteristics, measured using 0.28 keV X-rays at 1600V bias per plate. Electron accelerating inter-plate voltage 400V. Rear MCP - resistive anode potential difference 300V. *Measured above a lower level threshold equal to 10% of the modal gain.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance of front plate (MΩ)</td>
<td>160</td>
</tr>
<tr>
<td>Resistance of rear plate (MΩ)</td>
<td>160</td>
</tr>
<tr>
<td>Modal gain (pC)</td>
<td>2.27</td>
</tr>
<tr>
<td>Pulse height FWHM (%)</td>
<td>65</td>
</tr>
<tr>
<td>Dark noise* (cm⁻²s⁻¹)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

7.3 Coated microchannel plates

7.3.1 Detector configuration

Studies at Leicester involved a chevron microchannel plate detector incorporating 36mm diameter MCPs of the type used for previously described quantum efficiency measurements (see Chapters 2, 3 and 4). The MCPs had channel length-to-diameter ratios of 120:1, 12.5μm channels, a 6 degree bias angle and were manufactured by Philips Photonics [111] from a proprietary radioisotope free “low noise” glass. The bias voltages across the MCPs could be individually adjusted. A resistive anode readout was used for charge collection and imaging [100].

The operating characteristics of the detector were measured before photocathode deposition and are recorded in Table 7.1.
7.3.2 MCP coating and photocathode annealing

Coating

The front plate of the detector was half coated with CsI and KBr as shown in Figure 2.1. As described earlier (see Chapter 1), CsI and KBr are the commonest deposition photocathodes used in open-window MCP detectors for astronomy. Before coating, the MCP was vacuum baked (for 48 hours at 250°C) to remove any absorbed water. During transfer from the vacuum furnace to the evaporator the MCP was kept in a dry nitrogen filled container. Before deposition the MCP was heated to approximately 90°C then underwent a 10 minute plasma discharge clean. The MCP temperature was also maintained at 90 degrees during coating.

CsI and KBr layers were produced in turn by evaporation through a suitable mask, from a resistively-heated molybdenum boat perpendicularly below the microchannel plate. The deposition rates, as measured by a quartz crystal thin-film monitor co-located with the MCP, were $\sim 20 \text{Å s}^{-1}$ and the thickness on the front surface was 14000Å. The MCP was rotated at $\sim 1 \text{ Hz}$ during evaporation in order to maximise coating uniformity.

Annealing

Siddiqui [112] has shown that MCPs subjected to vacuum bakeout can undergo irreversible changes in their electrical characteristics. The temperature above which any change in the MCP resistance will be irreversible was found by Siddiqui [112] to be 250°C. We therefore selected 250°C, twenty degrees below the sublimation temperature of CsI, as the temperature likely to give full yield enhancement without compromising the MCP multiplier operation. The vapour pressure of KBr is much lower, at a given temperature, than that of CsI [113]. Conversely, the temperature required to produce a given vapour pressure is some 60°C greater for KBr. By comparison with the cyclic annealing procedure adopted for planar photocathodes in St. Petersburg (Section 7.2.1), the annealing of the MCP photocathodes at Leicester was a single-pass procedure for a longer time at a lower temperature.

The detector was initially taken, after coating, to the Daresbury Synchrotron Radiation Source
(SRS) as part of the calibration programme for the AXAF HRC (see Chapter 2). On return from Daresbury the absolute detector quantum efficiency was measured in the Leicester laboratory test facility (see Chapter 3), after which the coated front MCP was removed from the detector for annealing.

Annealing was carried out in the vacuum furnace used for pre-coating MCP bake-out. This chamber is evacuated by a turbomolecular pump maintaining pressure less than $10^{-6}$ mbar. Heating is controlled by a thermocouple/power monitoring system which keeps the temperature within set limits ($\pm 2^\circ$C).

The MCP was mounted in a dedicated coating holder and the temperature slowly increased over an 8 hour period. The coated plate was annealed for 18 hours at $250^\circ$C before the heaters were switched off. The plate was then allowed to cool slowly over a period of $\sim 24$ hours.

### 7.3.3 Results

Quantum efficiency measurements were made in the test facility described in reference [9] and in Chapter 3 using a single wire Ar-CH$_4$ proportional counter (PC) as the reference detector. X-rays were generated using an electron bombardment source with a (SiC or RuO) coated anode and complementary filters used to reduce UV and bremsstrahlung radiation [16] (see Table 3.1).

The PC was preceded by a 1.0mm diameter collimation hole which ensured that the full X-ray beam reaching the MCP detector was captured by the reference counter.

Figures 7.3(a)-(d) show results for both CsI and KBr coated plate halves before and after annealing. The single-peaked efficiency-versus-angle curve is expected from biased channel plates where the azimuthal angle (the angle between the plane of X-ray incidence and the plane containing the MCP normal and the channel axis) is close to 90 degrees [114].

Small but significant improvements in the quantum efficiency can be seen for both annealed cathodes at large incidence angles (see Figures 7.3(b),(d)). These increases in pulse yield are of a much lesser order than those observed in current yield (Figure 7.1).

Figure 7.4(a) shows the pulse height distributions (PHDs) obtained for 1.74 keV illumination.
Figure 7.3: Comparison of detector quantum efficiencies for CsI and KBr photocathodes, before and after thermal annealing. Relative errors in QE are of order 1%. Crosses - C-K X-rays. Stars - Si-K. Open circles - Ru-L. Figure (a) CsI, before annealing, (b) Ratio of annealed and unannealed quantum efficiencies, CsI photocathode, (c) KBr before annealing, (d) Ratio of annealed and unannealed quantum efficiencies, KBr photocathode.
of the CsI-coated detector half, before and after annealing. A much-increased population of high-charge events is observed, for the same bias conditions (1600V per plate), for the annealed case. Figure 7.4(b) is the corresponding plot for the KBr-coated half and shows a smaller change in Si-K PHD shape after annealing. In order to quantify the improvement in energy resolution which follows from annealing the CsI coating we may introduce the parameter $S(n)$:

$$S(n) = \frac{1}{N} \sum_{m=1}^{n} C(m)$$

(7.1)

where $C(m)$ is the number of counts in PHD channel $m$ and $N$ the total number of counts. Figure 7.5(a) shows that, before annealing, the 1.74 and 2.56 keV PHDs are essentially indistinguishable. That is, the $S(n)$ curves for these energies practically coincide. After annealing, the corresponding curves have clearly separated. As to the separation of C-K and Si-K X-rays, choosing a discriminator setting to reject 99% of the lower energy photons implies acceptance of 29% of the higher energy flux before annealing ($n=360$; see Figure 7.5(a)) rising to 35% ($n=435$; see Figure 7.5(b)) after thermal treatment.

### 7.4 Discussion

#### 7.4.1 Temperature dependence of $\chi_c$

Figure 7.2 indicates that the X-ray photocurrent from CsI decreases with increasing temperature, in agreement with the findings of recent UV studies. Figure 7.6 plots the 20-100°C photocurrent data of Lu et al. [115], normalised to the photocurrent value at 31°C. These measurements refer to in vacuo deuterium lamp illumination of a fresh 520Å-thick CsI layer on an aluminium substrate. The full curve of Fig. 7.6 is the result of a naive calculation which assumes that the relative temperature dependence of the photoyield $\chi_c$ from an ionic dielectric is the same as that of its secondary electron yield, $\delta_e$. Certainly, both quantities can be expressed in terms of the same semi-empirical electron escape parameters $P_5(0)$, $L_5$ and $\epsilon$ [8] (see below). The ratio of secondary electron yields corresponding to temperatures $T_1$ and $T_2$ may be written in the form originated by Dekker [116]:

$$\frac{\delta_e(T_1)}{\delta_e(T_2)} = \left(\frac{2n(T_2) + 1}{2n(T_1) + 1}\right)^{\frac{1}{2}}$$

(7.2)
Figure 7.4: (a) Si-K PHDs, CsI-coated MCP half, (b) Si-K PHDs from KBr-coated MCP half. Crosses - before photocathode annealing. Stars - after photocathode annealing. Angle of incidence with respect to the channel axes - 6°.
Figure 7.5: (a) Integrated events fractions $S(n)$ for 0.28, 1.74, 2.56 keV X-rays. CsI photocathode, before annealing. $1pC = 77.625$ channels. (b) As Figure 7.5(a), after annealing. $1pC = 80.5$ channels
where \( n(T_i) \) is the average number of longitudinal optical phonons per mode at temperature \( T_i \):

\[
\begin{align*}
n(T_i) &= \frac{\hbar \omega}{kT_i} - 1
\end{align*}
\] (7.3)

The phonon energy, \( \hbar \omega \), for CsI is variously estimated to be 0.0105 eV [117, 118] or 0.00962 eV [110]. The choice of \( \hbar \omega \) makes no significant difference to the form of the curve in Fig. 7.6 (which is calculated, in fact, for the lower of the two \( \hbar \omega \) values). We see that the phonon-dominated electron transport calculation gives rather good agreement with the Lu et al. data over its limited range of temperatures.

Applying the same model to the X-ray data of Figure 7.2, which encompasses the much wider temperature range ~ 17-270°C, give less satisfactory agreement. Eq. 7.2 predicts the ratio of yields 1.36:1 for these temperature endpoints, while the observed ratio after the first annealing cycle is 1.77:1 and after the eighth, 2.53:1.

### 7.4.2 SEM studies

Buzulutskov et al. [106] have recently studied the effects of thermal treatment (temperatures up to 165°C, durations ~ 15 hours) on the VUV efficiency of caesium, sodium and copper iodides. These authors consider a number of mechanisms to explain the thermally-induced increases in near-threshold \( \chi_c \) observed in all three materials: lattice modification, elimination of residual water vapour and changes in cation:iodine ratio. This list is not, however, necessarily exhaustive.

In the case of CsI (thallium-doped), it is well known that post-evaporation annealing at high temperatures (500°C for 30 minutes [119]) causes an increase in crystalline regularity in the columnar structures typical of thick scintillator layers. Indeed, Almeida et al. [120] speculate that VUV efficiency increases are due to the annealing of dislocations produced by the original evaporation process.

We therefore prepared a number of CsI and KBr layers on glass microscope slides and subjected half to the annealing schedule of Section 7.3.2. Both ‘standard’ and annealed photocathodes were then studied using a scanning electron microscope, with the results for CsI shown in Figures 7.7 and 7.8. For both 150 Å and 1500 Å thick CsI layers, the effect of post-evaporative heating is to increase grain size. In the case of the thinner layer, the cathode material agglomerated
Figure 7.6: CsI photocurrent vs temperature of ref [115] (circles), compared with model of equations (7.2,7.3) (full curve). The error bars were computed by the present authors from the symbol sizes of Figure 5 of ref. [115] which imply an uncertainty ±1pA in the measured photocurrents I.
into discrete islands, exposing the substrate. The characteristic wall coating thickness [9] for
the MCP of Section 7.3.2 was 460Å. No increase in grain size was observed for KBr.

Examination of Figures 7.7 and 7.8 gave weight to the hypothesis that post-annealing changes in
both \( \chi_c \) (Section 7.2.2) and in MCP quantum efficiency and PHD shape (Section 7.3.3) might be
explicable in terms of an increase in secondary electron escape length, following from a reduction
in defect scattering. This hypothesis was tested using the semi-empirical model of refs. [8, 82],
as described in the next section.

### 7.4.3 Photoyield calculations

The X-ray photocathode model described in refs [26, 8] allows us to rapidly calculate current and
pulse quantum yields and electron emission number distributions for any material for which the
parameters \( P_s(0), L_s \) and \( \epsilon \) are known. \( P_s(0) \) is the probability of a low energy (~ eV) secondary
electron escaping from the surface into vacuum. \( L_s \) is the secondary electron escape length
and \( \epsilon \) is the average energy required to create an internal secondary. While this model lacks
the physical rigour of the microscopically-based electron transport calculations of Akkerman et al.
[118], it is ideal for present purposes in that surface properties and intra-cathode transport
are separately embodied in the parameters \( P_s(0) \) and \( L_s \).

The secondary photocurrent \((\chi_c)_s\) or X-rays of energy \( E \) incident at grazing angle \( \alpha \) may be
written, for an asymptotically thick (thickness \( T \gg L_s \)) cathode layer, in the form:

\[
(\chi_c)_s = (1 - R(\alpha)) f P_s(0) E \epsilon^{-1} (1 + \beta)^{-1} \text{ electrons photon}^{-1}
\]

(7.4)

where

\[
\beta = (\mu \csc(\alpha') L_s)^{-1}
\]

(7.5)

Here, \( R(\alpha) \) is the X-ray reflection coefficient (negligible at normal incidence for \( \sim \) keV energies),
\( f \) is the fraction of deposited energy available for secondary electron creation (\( \sim \) unity for CsI,
where secondary electron emission dominates over primary (photo-Auger) yield [16]) and \( \mu(E) \)
is the linear absorption coefficient. \( \alpha' \) is the refraction angle.

Figure 7.1 shows that \((\chi_c)_s\), calculated for ‘standard’ CsI photocathodes on the basis of the
previously-determined [8] parameter set:
Figure 7.7: SEM images of 150Å thick CsI layers deposited on microscope slides. (a) layer before annealing, (b) layer after annealing; note the exposed substrate areas.
Figure 7.8: SEM images of 1500Å thick CsI layers deposited on microscope slides. (a) layer before annealing, (b) layer after annealing; note the increased size of the CsI grains after thermal treatment.
\[ P_s(0) = 0.15 : L_s = 215\,\text{Å} : \epsilon = 7\text{eV} \]

is in rather good agreement with the measurements of Day et al. [66] and Eliseenko et al. [71]. Maintaining \( \epsilon \) fixed, the present St. Petersburg annealed photocathode data is equally well-fit by the parameter combinations:

(a) \( P_s(0) = 0.15 : L_s = 755\,\text{Å} \) (not shown)

(b) \( P_s(0) = 0.52 : L_s = 215\,\text{Å} \)

To discriminate between these physically-distinct solutions, we attempted to model our CsI-coated MCP pulse height distributions. The output charge from a two-stage MCP detector with 12.5\,\mu m diameter channels has been found to be proportional to the number of photoelectrons initiating the avalanche, raised to the power 0.4 [26]. The probability of \( n \) electrons being emitted per absorbed photon, from a planar photocathode of thickness \( T \) is [26]:

\[
p(n) = \mu \csc \alpha' \int_0^T C_N^n \exp(-\mu x \csc \alpha') \left( \left[ P_s(0) \exp(-\frac{z}{L_s}) \right]^{n} \left[ 1 - P_s(0) \exp(-\frac{z}{L_s}) \right]^{N-n} \right) \, dz
\]

\[
C_N^n = \frac{N!}{(N-n)!n!}
\]

\[
N = \frac{E}{\epsilon}
\]

Number distributions were calculated for 1.74keV X-rays incident on CsI and are plotted, with \( n^{0.4} \) as ordinate, in Figures 7.9(a) and (b) - which are to be compared with the measured MCP PHDs of Figure 7.4(a). Parameter combination (a) above \(^1\) - representing a post-annealing increase in electron escape length - fails to account for the PHD shape observed from the thermally-treated detector. Combination (b) - representing a post-annealing increase in surface escape probability - much better represents the observed change in gain characteristics.

Figure 7.10 models the effect of this increase in \( P_s(0) \) from 0.2 to 0.6 at 0.277keV (C-K) and 2.558keV (Ru-L) on the CsI-coated half. This model can then be compared with Figures 7.11 and 7.12, which show PHDs, before and after coating, at these two energies. We note that the C-K model seems to recreate, if only crudely, the increase in high charge events after annealing. At the Ru-L energy, the increase in modal gain after annealing is accurately modelled, but we...

\(^1\)For X-ray energies below the Cs and I L edges, \( P_s(0) \) has the higher value 0.2 [8] for ‘standard’ cathodes. For our Si-K PHD calculations, the parameter combinations (a) and (b) appropriate to the annealed planar cathode data were therefore modified appropriately.
Figure 7.9: Normalised electron number probability distributions calculated for CsI, Si-K, 1.74 keV X-rays. Grazing angle of incidence - 6°. Cathode thickness - 460Å. Electron creation energy $\varepsilon=7$eV. Linear absorption coefficient $\mu=1.30\mu$m$^{-1}$. (a) Surface escape probability fixed ($P_s(0)=0.2$), $L_s=215\AA$ (open circles) and 755Å (crosses) (b) escape length fixed ($L_s=215\AA$), $P_s(0)=0.2$ (filled circles) and 0.6 (open circles).
Figure 7.10: Normalised electron number probability distributions calculated for CsI. $P_4(0)=0.2$ (filled circles) $P_4(0)=0.6$ (crosses) (a) C-K, 0.277 keV X-rays. (b) Ru-L 2.558 keV X-rays. Grazing angle of incidence=6°. Cathode thickness - 460Å. Electron creation energy $\varepsilon=7$eV. $L_5=215$Å. Linear absorption coefficient $\mu=1.30\mu m^{-1}$. 

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also note that the model does not convincingly represent the two-peak structure of the PHDs seen at all energies after annealing, despite the well-modelled high charge tail.

We note, finally, that the probability of no electron being emitted ($\sim 0.11$ for C-K, $\sim 0.56$ for Si-K and $\sim 0.80$ for Ru-L) is essentially unchanged by the three-fold increase in $P_s(0)$. Thus the large increases in $\chi_c$ observed after annealing in St. Petersburg (Figure 7.1) are entirely consistent with the limited increases in (pulse yield) QE observed in Leicester (Figure 7.3(a)). Annealing promotes an increase in the proportion of electron batches containing very large numbers of electrons, but does not affect the proportion of absorption events which fail to excite any electrons.

7.5 Conclusions

We have shown that the enhanced X-ray properties of thermally-treated CsI photocathodes can be accounted for by changes in the surface escape probability. This finding supports the
conclusion of Buzulutskov et al. [106], that increases in VUV efficiency after annealing are due to changes in surface stoichiometry following liberation of I$_2$. Although the grain sizes of polycrystalline CsI films increase after annealing, a substantial increase in secondary electron escape length does not appear to result.

The fivefold increase in planar CsI X-ray photocurrent is of immediate interest in fields such as fusion plasma diagnostics [66]. Further investigations into the soft X-ray response of CsI-coated MCPs will concentrate on larger angles of incidence and longer wavelengths, where, as the number of electrons per emitted bunch decreases larger increases in pulse quantum yield may be expected.
Chapter 8

Update and Conclusions

8.1 SRS Calibration of MCPs

8.1.1 Comparison of experimental data and model

The synchrotron calibration considered here took place on three different beamlines at the Daresbury SRS. It is useful to combine the various energy ranges and compare the overlapping sections of data. Unfortunately, because data on the different beamlines was taken at different azimuthal angles, it is not possible to compare data for a range of angles. Indeed, there is no one single angle to the channel axis at which data was taken over the whole energy range. However, it is possible to consider measurements taken at incident angles close to the normal to the front surface of the plate (approximately \(6^\circ\) to the channel axis). Figures 8.1 and 8.2 show combinations of data from beamlines 6.1, 1.1 and 4.2 for the CsI- and KBr-coated MCP halves. The measurements used to plot Figures 8.1 and 8.2 are summarised in Table 8.1. The angle to the channel axis in each energy range is the same for KBr and CsI.

Figures 8.1 and 8.2 also include a simple model, for comparison to the experimental data. The model uses the secondary electron parameters given in Chapter 5 and assumes an X-ray incidence angle of \(6^\circ\) to the channel axis. No account of the azimuthal angle is taken by the model, because at close to normal incidence all azimuths are the same. Therefore, a single coating depth down
Figure 8.1: Composite of CsI QE over the whole energy range considered. Data taken at Daresbury is shown (dots), along with a model response with coating depth 9.51D and absolute values of QE from various sources.

The channel of 9.51D (the coating depth for non-biased channel) is assumed. This probably leads to the model overestimating the QE slightly at higher energies, where the azimuthal angle was 96° and the data was not taken at exactly normal to the MCP front surface. However, this will be a small effect.

The third component of Figures 8.1 and 8.2 are single data points of absolute QE for CsI- and KBr-coated MCPs taken from various sources. There are two sets of recent data taken at Leicester: the stars denote data which was used to convert the Daresbury relative QE to absolute QE and the crosses show other efficiency measurements taken at 6° to the channel axis. Additional data points are taken from Fraser and Pearson [26], Chappell et al. [19], Murray et al. [121] and Rose et al. [22], all at 6° to the channel axis.

It can be seen that the synchrotron experimental data sets exhibit a reasonable degree of continuity, both on the CsI- and KBr-coated MCP halves. The two data sets which cover the 250-350eV energy range (from beamlines 1.1 and 6.1) do not have exactly the same shape, but this is to be expected, given the large amount of carbon contamination observed at C-K on beamline 1.1.
Figure 8.2: Composite of KBr QE over the whole energy range considered. Data taken at Daresbury is shown (dots), along with a model response with coating depth 9.51D and absolute values of QE from various sources.

Table 8.1: Angle with respect to the channel axis for the data used in Figures 8.1 and 8.2

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Energy Range</th>
<th>Azimuthal angle</th>
<th>angle wrt channel axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>50-350eV</td>
<td>0°</td>
<td>6°</td>
</tr>
<tr>
<td>1.1</td>
<td>250-1400eV</td>
<td>20.5°</td>
<td>7°</td>
</tr>
<tr>
<td>4.2</td>
<td>2-6keV</td>
<td>96°</td>
<td>8°</td>
</tr>
</tbody>
</table>
The general shape of the model is similar to the Daresbury data, particularly for the CsI curve. There seem to be two particular difficulties. The first is the dip in the experimental QE for both CsI and KBr at approximately 300eV, which is not reflected in the model. This problem is alleviated somewhat if a combination of bare and coated channel QE is used. However, the model still overestimates the experimental data. The validity of the experimental data is in some doubt, but the absolute QE at C-K (277eV) is known to be approximately 40% for CsI and approximately 30% for KBr (as opposed to >50% for the model). The second area of concern is the steepness of the Daresbury QE curve between 2 and 4keV (particularly for CsI). Given that this data was taken at an azimuthal angle of ~90°, it should be somewhat lower than the model. However, between 2 and 2.6keV, the Daresbury CsI QE is greater than the model QE. The problem seems likely to be with the experimental data, rather than the model.

Agreement between the Daresbury measurements and the single points of QE is generally good, although the Daresbury data seems to have anomalously high QE between 800 and 1600eV. Within this energy range there are known problems with the Daresbury data (discussed in Section 8.1.2). The model and Daresbury CsI values compare particularly well with those of Fraser and Pearson [26].

There are considerable problems with calibration of the monochromator responses for all the beamlines used here (see Section 8.3). Given the uncertainty in this calibration, and therefore in the shape of the QE-energy curve, there is some doubt as to the validity of the experimental data discussed above. However, the ratio of CsI to KBr QE as measured at Daresbury should not be affected by the monochromator responses. Figure 8.3 shows that ratio as a function of energy, along with the ratio for the model discussed above and individual data points from Rose et al. [22].

The general shape of the Daresbury CsI:KBr QE ratio with energy is exceptionally consistent with that of the model, apart from between 1 and 1.5keV. However, the experimental data seems likely to be incorrect in that energy range (as discussed in Chapter 4 and Section 8.1.2). Over the rest of the energy range, the discontinuities in the ratio given by the experimental measurements and the model seem very well matched, even if their absolute magnitude is not always in agreement. The data of Rose et al. in particular agrees well with the model. Figure 8.3 confirms the superiority of CsI over KBr in terms of QE for the energy range considered.
Chapter 4 considered MCP calibration at Daresbury on beamline 1.1, which covered the 250-1400eV energy range. Two monochromator grating coatings were used in this energy range, both covering the 1800 lines mm\(^{-1}\) grating. The Ni coating was used between 250 and 850eV and the Au coating was used above 800eV. There were serious problems with removing the monochromator response (measured with the SRS in high ring current mode): so much so that some data in the higher energy range appeared to correspond to a QE of over 100%. CsI-coated MCP QE measurements from Pearson [67] were used to correct these physically impossible values, but the question of the true monochromator response remained. It seemed likely that the response of the monochromator at low ring current did not perfectly correspond to that at high ring current.

In 1996 Bootsma and van Zwet from SRON Utrecht in the Netherlands used a gas-filled propor-

Figure 8.3: The ratio of CsI QE to KBr QE over the whole energy range considered. Data taken at Daresbury is shown (dots), along with a model with coating depth 9.51D, and ratio values from Rose et al. [22].

8.1.2 Further calibration of data in the 250 - 1400eV energy range
Figure 8.4: Comparison of the beamline 1.1 Ni grating response as measured in high ring current mode (small dots) and in low ring current mode (joined dots).

...ional counter (PC) to measure the beamline 1.1 1800 mm^{-1} grating monochromator response while the beam was in low ring current mode [122]. The results of their measurements are shown in Figures 8.4 and 8.5, with the corresponding high ring current calibrations (used in Chapter 4). It can be seen that the for both grating coatings the Bootsma calibration is significantly different to that used in Chapter 4. However, many of the detailed features are the same (particularly the O-K feature at 540eV and the Ni-L feature at 850eV). Rideout [123] has used the low ring current monochromator data to re-calibrate the Daresbury MCP data obtained on beamline 1.1. A comparison of the results for CsI and KBr using the high and low ring current monochromator responses is shown in Figures 8.6 and 8.7. The Bootsma monochromator curve does not extend as low as 277eV so normalisation for absolute QE at C-K is not possible (as it was for the data which used the high ring current monochromator response - squares on the figures). Therefore data taken using the Au grating was normalised to efficiencies measured at Cu-L (shown by diamonds on the figures), and the Ni grating data was normalised to that of the Au grating at 800eV (shown by stars on the figures).

Although the Bootsma curve does alleviate the problem of efficiencies greater than 100%, it does not extend to a low enough energy to enable the origin of the severe C-K contamination...
Figure 8.5: Comparison of the beamline 1.1 Au grating response as measured in high ring current mode (small dots) and in low ring current mode (joined dots).

Figure 8.6: Absolute QE on the beamline 1.1 Ni grating, with the monochromator response removed using the Daresbury high ring current calibration and using the Dutch PC data.
on the Ni grating to be determined. There also seems to be a problem with the calculated MCP QEs at low energies. Indeed, the MCP QE is calculated as zero at 300eV: extremely unlikely when we know that at 277eV on CsI it is ~40%. In the higher energy range, the re-calculated CsI QE is greater then the maximum possible physically (63%, determined by the MCP open area). There are, therefore, obviously some major concerns with this recalibration of the data.

The Dutch PC data has, however, supplied us with invaluable information concerning the actual energy of the X-rays emitted from the beamline 1.1 monochromator in low ring current mode. Figure 8.8 shows the peak position of the PC PHD for the Au-coated grating as a function of the nominal X-ray energy incident upon the PC. It can be seen that below ~900eV the peak position increases linearly with energy (as would be expected). Above 900eV, however, the curve begins to decrease, and becomes flat above 1200eV. This suggests that there is spectral contamination above 900eV. Indeed, this contamination is great enough to suggest that above 900eV the energy setting on the monochromator has no correlation with the energy of the X-rays incident on the PC. If this is the case, then the measurements we assumed had been made of the Cs and I $M_{I-III}$ edges did not cover that energy range at all (880-1220eV).
8.1.3 The 1600 to 1800eV energy range

In January 1996 data was taken on beamline 4.2 to cover the 1600 to 1800ev energy range. A preliminary analysis of this data showed no features of significance for AXAF on the CsI-coated MCP half, and so it was not considered in this thesis. The data has since been fully analysed by Rideout [123]. The azimuthal angle at Daresbury was found to be 40°, by consideration of the QE-angle curves. The beam was assumed to decay at the same rate as on beamline 1.1 (Chapter 4). Figure 8.9 shows measurements taken of the count rate at Daresbury as a function of angle. The MCP normal is at a manipulator scale reading of 214°. X-rays incident at angles below 214° are incident on the coated side of the channel.

Figure 8.10 shows measurements of the beamline 4.2 monochromator response taken on a thin Ti foil. The measurements were taken at high ring current (single bunch) after the MCP QE measurements had been taken (at low ring current). The pico-ammeter reading decreases over time as the ring current decays. The middle of the three curves was used to normalise the MCP count rate, after the Ti photo-emission efficiency was factored out (using the data of Eliseenko et al. [71]). An Al foil was inserted periodically into the beam, and the position of the Al-K
Figure 8.9: Variation of MCP QE with angle measured on beamline 4.2

Figure 8.10: Monochromator response on beamline 4.2

absorption edge measured to check that the beamline was producing the expected energy.

Relative QE from Daresbury was normalised to absolute QE using measurements taken at Leicester before the SRS experiment (Si-K energy - 1.74keV, $\text{QE}_{Csl}=44\%$, $\text{QE}_{KBr}=27\%$). The results of this analysis are shown in Figure 8.11. The major feature of these curves (the dip centered upon $\sim 1680\text{eV}$) is unlikely to be a true feature of the MCP response. Over this energy range, the MCP QE is expected to decrease monotonically as incident X-ray energy increases (apart from near absorption edges). This dip is likely to be related to the rapid drop in the peak of the measured monochromator response as ring current decreased. Eventually, the monochromator response may have settled into a shape which produced the expected monotonic
There are also significant spurious features in the response of both photocathodes above 1700eV. These are presumed to be artefacts of the monochromator. The artefacts are not seen on the measurement of the monochromator response (Figure 8.10), and are reminiscent of similar artefacts seen at higher energies the previous year on beamline 4.2 (described in Chapter 3). Rideout attributes these spurious features to the relative insensitivity of the pico-ammeter to the foil currents, but also admits the possibility that the monochromator response in low ring current mode does not correspond precisely to that in high ring current mode. Whatever the explanation, the results from this beamline reinforce the difficulty of removing the monochromator response from low ring current measurements.

Despite the calibration difficulties, features can be seen which are related to the Br L\textsubscript{II} and L\textsubscript{III} absorption edges. A high resolution scan across these edges is shown in Figure 8.12. As in Chapter 3, it is difficult to separate the spurious monochromator features from features related to the edge, but the edges themselves are clearly visible.

Figure 8.11: CsI and KBr absolute QE measured on beamline 4.2. The stars show the points at which relative QE was normalised to absolute QE.
8.2 Recent AXAF calibration efforts

Since the main body of this work was written, calibration of the AXAF HRC has taken place at the X-ray Calibration Facility (XRFC) at Marshall Space Flight Center (Huntsville, Alabama). Several papers were given at the 1997 SPIE Conference which relate to the HRC calibration. Meehan et al. mainly describes calibration of the HRC UV/ion shields (UVIS) at SAO and the Bessy 1 synchrotron in Berlin, Germany. X-ray transmission measurements and areal densities are given for witness samples from each part of the UVIS (as described in Chapter 1). Murray et al. Kraft et al. and Kenter et al. [121, 124, 125] are of more direct relevance to the MCP calibration considered here.

Murray et al. describe measurements taken at SAO and the XRFC to calibrate the HRC-I and HRC-S. Initial calibration at SAO (before the XRFC experiments) included measurements of the detector components at subsystem level. After the flight plates were selected and CsI-coated, their absolute QE was measured at 8 energies. These QE values for the HRC-I have been shown previously in Figure 8.1.

The detector housing was then fully assembled, and the overall HRC QE was measured at SAO, again at 8 energies. At this point, the flight UVIS were damaged, but the replacement filters seem to have the same characteristics as the originals. A number of further measurements were planned at SAO (including calibrating the QE at 22 energies). These further measurements had to be abandoned due to time constraints.

The detector was then shipped to the XRFC for testing with the AXAF High Resolution Mir-
ror Assembly (HRMA), the Low Energy Transmission Grating (LETG) and the High Energy Transmission Grating (HETG). Unfortunately, upon operation of the fully assembled HRC, some anomalous features were noticed. A 91kHz noise signal was present when the high voltage was turned on, resulting in spurious event signals. This problem was fixed by increasing the event trigger threshold, for the HRC-I from 10 to 32 Data Units (DU) and for the HRC-S from 10 to 40DU (out of a 255DU maximum). The second problem resulted from saturation of the HRC electronics. Up to 20-30% of HRC-I events were being wrongly positioned. This was fixed by lowering the MCP voltages by 40 volts/plate. Finally, it had been decided during assembly of the HRC that the UVIS should be run at ground potential, rather than the original +100V with respect to the top of the MCP.

These ‘quick fixes’ caused a variety of difficulties. Running the UVIS at ground potential led to ‘ghosting’ in the PSF, especially on the HRC-I. Lowering the MCP high voltage led to large non-uniformities in QE and gain. Raising the trigger threshold led to the elimination of many ‘real’ events, and so the detector QE was considerably lower than would be expected.

Despite these problems, a wide range of measurements were made at the XRCF. These included the effective area (both on and off axis), count rate linearity and point spread function (PSF) for the HRMA/HRC-I and HRMA/HRC-S. Some of the preliminary results are described in Kenter [125] and Kraft [124]. No evidence of count rate non-linearity was found for the HRMA/HRC-I, although some was present for the HRMA/HRC-S above 30 counts s$^{-1}$. Most of the measurements were taken with the image slightly out of focus, so that fewer counts were abstracted from a small area. In order to measure the PSF, the HRC was moved in a serpentine pattern, and this pattern later removed from the images. The PSF was found to be $\sim 45\mu$m FWHM, with a half power radius of $25\mu$m. (Note the HRC plate scale is $49\mu$m arcsec$^{-1}$). Additional measurements were taken of the HRC-S with the LETG. These included effective area and energy resolution, and are discussed in Kraft [124].

After testing at the XRCF, the HRC assembly was returned to SAO for further flat field measurements. The problems with high gain and the 91kHz noise ripple were solved. The high gain problem derived from the initial design requirement, which had assumed a lower gain than that produced by low noise CsI-coated MCPs. A resistive divider was added to the electronics to reduce the gain by 50%. The 91kHz noise ripple was traced to a faulty filter network and this
was replaced. The high voltage and trigger thresholds could then be returned to their original values. Further measurements of QE and uniformity were made, showing a marked improvement in the uniformity of the HRC-I and HRC-S detector efficiency, although the gain still showed considerable variation. The relative HRC-I QE increased by 15-25% under the new experimental configuration compared to measurements taken at the XRCF. Overall, the HRC tests at the XRCF seem to have been reasonably successful, although there were major problems with some of the electronics. These highlight the need to fully assemble and calibrate all flight instruments at the subcomponent level well in advance of any higher-level testing. The data from the XRCF calibration and subsequent measurements have not yet been published in full.

8.3 Further work

A further calibration period is planned at the Daresbury SRS for October 1997. This period will draw on the experiences described in this thesis, and try to resolve some of the issues highlighted here. The main problem to have arisen from previous SRS measurements has been the difficulty in removing the beamline monochromator response from the MCP response. When the beam is being run in high ring current, the monochromator response is relatively easy to measure. However, in low ring current no beam monitor is available at Daresbury. We had assumed that the monochromator responses would map linearly from high ring current to low ring current, but this does not appear to be the case. Specific problems have been seen with spurious features on beamline 4.2 (described Chapter 3 and above in Section 8.1.3) and with spectral contamination on beamline 1.1 (described in Chapter 4 and above in Section 8.1.2). An accurate measurement of the low ring current monochromator response is the highest priority in the October 1997 experiments. To this end, the beam flux will be measured during low ring current mode using a thin windowed single wire argon-methane proportional counter and a sealed, beryllium windowed Xe/CO₂ proportional counter. This should allow absolute QE calibration at the SRS, without recourse to QE measurements made at Leicester, and will also enable confirmation of the monochromator response.

The 1997 experiments will use two AXAF-like MCPs, each half-coated with CsI and half bare.
The QE of KBr-coated MCPs is less important to the AXAF project, now that CsI is the photocathode for both HRC-I and HRC-S. The bare area on the plate will allow direct measurement of the QE improvement gained by using a CsI photocathode. The two detectors will be used on three beamlines. Beamline 1.1 will again be used to measure QE in the 300-1000eV range, reconfirming our measurements of the slow onset and edge shifts in the Cs and I MIV and MV edges. However, the high energy spectral contamination see by the Dutch team (see Section 8.1.2) rules out beamline 1.1 for measurements above 1000eV. Therefore beamline 3.4 will be used to measure the response of the Cs and I MIV to MIII edges over the energy range 800 to 1560eV. Finally, the highest energy end of the AXAF response, 4-10keV, will be looked at using beamline 4.2. The energy range above 6keV has not been previously calibrated at the SRS. The 4-6keV measurements will also enable us to confirm the QE variation seen about the Cs and I L edges.

8.4 Final conclusions

The use of the Daresbury Synchrotron Radiation Source to calibrate MCPs has been very successful. Measurements have been taken of the QE variation about atomic edges between 50 and 6000eV for MCPs coated with CsI and KBr. Of particular note are large features related to the MIV, V and L edges of Cs and I. Large energy shifts (~13eV) have been seen on the Cs MIV and MIV edges, and the slow onset of the features related to the I MIV and MIV edges has been noted. Energy shifts have also been seen on the Cs LI, II and I LI edges, and a large white line is visible on the Cs LIII edge. These features are of particular importance for the HRC-S, where features related to the QE of the MCP must be removed before the presence of astrophysical emission and absorption lines can be determined.

Several problems hindered the calibration of the monochromator responses from Daresbury. The SRS was necessarily operating in low ring current mode and the monochromator responses were measured at high ring current. It appears that the assumption of linearity between the two current modes may not be entirely justified. This implies that the general shape of the QE-energy curves produced may be in error. However, this problem does not significantly effect the validity of the measurements made on edge-related QE features.
An attempt has been made to model the QE results from Daresbury. A model which assumed zero bias angle for the MCPs was found to produce inaccurate results, so the coating depth down the channel was remodelled to reflect more closely the actual coating depth for a channel with bias angle of $6^\circ$. This resulted in significant improvement in the accuracy of the model. The linear absorption coefficient was then modelled in order to reproduce the white lines seen in experimental measurements. Although not entirely successful, this approach could be extremely useful if extended slightly.

In addition to the synchrotron QE measurements which make up the bulk of the thesis, measurements were taken of the gain decay of low noise AXAF-like MCPs, which showed that the low noise glass was comparable to conventional glass in its gain characteristics. The effect of thermally annealing CsI-coated MCPs was also considered and successfully modelled.

The work described in this thesis has been part of a steep learning curve in the measurement of MCP QE using synchrotron radiation. These are the first measurements of their type which have been attempted, and as such some problems were to be anticipated. Nevertheless, the results obtained are extremely important, particularly in relation to the calibration of the AXAF HRC. Measurements to be taken at the SRS in October 1997 will draw on the experiences of previous experiments. Many of the issues raised here should be resolved and a more accurate analysis of the data already collected will be possible.
Bibliography


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