A study of isotope ratio measurement by inductively coupled plasma mass spectrometry

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A STUDY OF ISOTOPE RATIO MEASUREMENT BY
INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY

by

Ian S. Begley

A Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of
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ABSTRACT

The measurement of isotopic ratios by inductively coupled plasma mass spectrometry (ICP-MS) has the benefits of ionising all metallic elements, simplifying sample preparation and reducing analysis time, when compared with thermal ionisation mass spectrometry (TIMS). However, the use of ICP-MS in isotopic ratio studies has been somewhat restricted by its failure to offer the precision and accuracy required by a variety of applications. The precision achievable by ICP-MS, typically 0.2 to 0.3 % RSD, for isotopic ratios, has generally been regarded as being primarily limited by instrumental instability.

An investigation of the sources of instrumental noise in ICP-MS has been undertaken, utilising noise spectral analysis as a diagnostic aid. Study of parametric variation upon noise production has identified the methods by which modulation of the ion signal occurs. Noise spectral analysis has allowed an understanding of the limitations imposed upon measurement precision by the various contributing noise sources to be established.

The key to improved measurement precision has been found to lie in the development of data acquisition methods which allow the predominant sources of instrumental noise to be effectively filtered from the ion signal. The methodology developed for sequential measurement of isotopes, using a quadrupole mass analyser, to reduce the deleterious influences of instrumental noise is discussed. Results are given for isotopic ratio measurement which demonstrate that a precision of approximately 0.05 % RSD can be attained.

The factors which affect the accuracy of isotopic ratio measurement are shown to be many and varied and depend to a large extent on the particular isotopes being studied. Definition of an appropriate measurement strategy for high accuracy isotope ratio measurement involves consideration of all possible causes of bias and adoption of methods for their elimination or correction. To facilitate this process a protocol has been developed and subsequently applied to various elements and instrument systems.
ACKNOWLEDGEMENTS

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PUBLICATIONS AND PRESENTATIONS

Publications

Presentations


CHAPTER ONE
INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY

1.1 INTRODUCTION

Mass spectra for ions produced in an inductively coupled plasma (ICP) were obtained for the first time in 1980 [1]. Technical difficulties in the extraction of ions from an ICP at near atmospheric pressure into a high vacuum housing had previously hindered progress. Applied Research Laboratories had filed a UK patent, which covered inductively coupled plasma mass spectrometry (ICP-MS), almost ten years earlier. Research groups at the Ames Laboratory, Iowa State University, USA and the Department of Chemistry, University of Surrey, UK were foremost in identifying the unique potential of ICP-MS. Interest stemmed from the wide elemental coverage, elemental specificity and relatively uniform sensitivity across the periodic table promised by the coupling of ICP and mass spectrometry. ICP-MS was seen as a solution to the problems being experienced in inductively coupled plasma atomic emission spectroscopy (ICP-AES) associated with spectral complexity, matrix interference effects and poor sensitivity for specific elements [2], which were seen as future limitations in areas such as geochemical and environmental analysis.

ICP-MS offers particular advantages when compared to other spectroscopic methods of analysis. In addition to its selectivity, sensitivity, wide dynamic range and speed of analysis, ICP-MS produces simple spectra and can acquire both multi-element and isotopic information. Fast sample throughput and its ability to measure all metals give ICP-MS a significant edge over other mass spectroscopic techniques.

1.2 INSTRUMENTATION

1.2.1 The inductively coupled plasma
The attraction of the ICP as an atom and ion source is a consequence of:
(i) the attainment of a sufficiently high temperature to produce the controlled and uncontaminated environment required for sample conditioning;

(ii) the rapid and complete introduction of the sample into the high temperature region of the plasma discharge;

(iii) a residence time which is sufficient for all the desired processes to occur

The first ICP specifically designed for use in spectroscopy was developed by Greenfield et al [3], based upon the earlier work of Reed [4,5]. The ICP used widely in both atomic emission and mass spectrometry is generally formed in a torch of the Fassel configuration [6], consisting of three concentric tubes through which gas, normally argon, is streamed

A two- or three-turn induction coil, fabricated from copper tube, which surrounds the torch carries a radio-frequency (r.f.) alternating current, conventionally oscillated at 27.12 MHz. A Tesla coil is used to 'seed' the plasma gas, causing the removal of electrons, which are accelerated by the electric and magnetic fields surrounding the induction coil. These accelerated electrons in turn collide with atoms giving rise to a chain reaction mechanism, whereby the ICP is sustained by collisional ionisation. The torroidial form of an ICP in which r.f. energy is coupled to the plasma gas stream provides a 'doughnut', with a gas temperature in the region of 10,000 K, from which energy is transferred mainly via thermal conduction to the nebuliser gas stream containing the sample

ICP instruments are typically operated at incident power levels of between 1 and 1.7 kW. Typical argon gas flow rates for the plasma, auxiliary and nebuliser gas are 10 to 15 l min⁻¹, 0 to 1 l min⁻¹ and 0.5 to 1.5 l min⁻¹, respectively.

1.2.2 Sample introduction
The introduction of sample into the ICP torch is critical to analysis by ICP. In principle, the sample may be in the solid, liquid or gaseous state, however, the great majority of analyses are undertaken using liquid sampling. Liquid samples are most commonly introduced by nebulisation, to generate a gas-borne aerosol. The most widely used
nebuliser is of the Meinhard design [7], which consists essentially of two concentric glass tubes. The Meinhard nebuliser has a line pressure of around 32 psi, at a nebuliser gas flow rate of 1 l min\(^{-1}\) and will uptake 2 to 3 ml min\(^{-1}\) of sample by free-aspiration. The rate of sample uptake is generally regulated by a peristaltic pump.

As droplets of diameters above 8 \(\mu \text{m}\) tend to pass through the ICP without undergoing complete desolvation and evaporation, it is necessary to employ a spray chamber to remove these from the gasborne aerosol [8]. Separation of the droplets, based upon size, is effected by forcing the nebuliser gas to change direction sharply, causing the larger droplets to impinge upon the surface of the spray chamber. Spray chambers are generally manufactured from glass and have internal volumes of 100 to 200 cm\(^3\).

**1.2.3 Ion sampling**

In order to utilise the ICP as an ion source for mass spectrometry it is necessary to use a sampling interface to bridge the pressure differential that exists between the ICP (at near atmospheric pressure) and the mass analyser (at high vacuum). The extraction of ions from the ICP occurs via an orifice, conventionally of 1 mm in diameter, which passes through the tip of a water cooled sampling cone. The extracted plasma passes into an evacuated chamber maintained at several mbar by a rotary pump, resulting in a rapid decrease in gas pressure and temperature. The kinetic energy released propels the extracted ions away from the sampling cone, giving rise to a free jet. The orifice of a conical skimmer (diameter = 0.7 mm), located at approximately 6.5 mm behind the sampling cone, allows passage of the expanding sample stream into a second vacuum chamber.

The vacuum pressure in the second chamber is sufficient, at \(10^{-4}\) mbar, for the flow of ions to become random, allowing the ion optics to collect, focus and transmit ions from the ion cloud at the rear of the skimmer to the mass analyser. The ion optics consist of a number of symmetrical electrostatic lenses positioned along the central axis of the instrument. To prevent photons and neutral species from the ICP reaching the detector and contributing to the system background, it is usual to include an on-axis photon baffle within the ion optics.
1.2.4 The mass analyser
The purpose of the mass analyser is to selectively transmit ions based upon their mass-to-charge ratio (m/z). Quadrupole mass analysers are used in most ICP-MS instruments. Typically, these have filter rods of 12 to 18 mm in diameter and are approximately 200 mm in length. Quadrupole mass analysers operate as mass filters, along which a stable ion path exists for ions of only one m/z, while ions of all other m/z are deflected away from the axis and lost. The transmitted m/z is determined by the combined amplitude of the r.f. and direct current (d.c.) potentials applied to the rod pairs and the resolution by their ratio.

To minimise loss of low-energy ions due to fringing field effects [9] at the ends of the filter rods, a r.f. only, pre-rod system is used. These consist of a set of rods of the same diameter as the filter, but of only about 25 mm in length.

Quadrupole mass analysers are utilised because of their robustness, being able to tolerate vacuum pressures up to \(10^{-5}\) mbar and ion energy spreads of about 10 eV. However, they provide only limited mass resolution, sufficient to separate elemental peaks one mass unit apart, but not enough to separate an oxide peak from an elemental peak at the same nominal mass.

1.2.5 Ion detection
It is usual to employ electron multiplier detectors in the measurement of the ions transmitted by the mass analyser in ICP-MS. For most purposes continuous dynode channel electron multipliers are utilised, which may be operated at gas pressures up to approximately \(10^{-5}\) mbar. They are capable of counting ion pulses at rates above \(10^6\) counts per second (cps) and have dark counts of below 1 cps. The detector assembly consists of a glass tube with a resistive coating of approximately \(10^8\) \(\Omega\). A voltage of around -3 kV is applied across the dynode tube to obtain a typical gain of \(10^7\). Ions entering the tube cause electron emission along its length to generate a burst of electrons with a charge of \(10^{-11}\) to \(10^{-14}\) C. This results in production of a detectable current pulse of span 3 to 10 ns.
As the arrival of transmitted ions at the electron multiplier detector occurs truly randomly, there is an uncertainty associated with counting of current pulses over a fixed time period. The magnitude of this uncertainty is governed by Poisson statistics. The standard deviation of the measurement, or counting statistic, is equivalent to the inverse of the square root of the accumulated count.

The digital technique used to count the number of current pulses produced, in a given time interval, is known as pulse counting. In pulse counting, a high-frequency amplifier and discriminator circuit convert the current pulses obtained from the dynode tube to logic pulses, which are registered by a counter. Use of a discriminator, having an appropriate threshold level, prevents multiplier noise or gain variation influencing the pulse counting measurement. Unfortunately, the digital circuitry shows counting fatigue at count rates approaching \(10^6\) cps, beyond which the system response becomes non-linear. Counting fatigue results from pulse broadening in the amplifier, the limited rise and fall times of the discriminator, and the maximum clock rate of the counter.

Electron multiplier detectors may also be used, at a lower gain, in an analogue mode to extend the linear range of the system. Use of an amplifier to measure the mean current facilitates a linear range up to approximately \(1 \mu\text{A}\), at high ion fluxes. Hutton et al. [10] have shown that detection limits in the analogue mode are typically 50 times higher than those obtained in the pulse counting mode.

1.2.6 Data collection

There are two different modes of data collection available for the acquisition of spectral information in commercial ICP-MS instruments, these are known as scanning and peak jumping. In the scanning mode, a spectral domain is swept at a uniform rate by the quadrupole mass analyser, in synchrony with the channel address of a multi-channel analyser. Each mass unit occupies the same group of channels in successive sweeps and the dwell time per channel may be as short as 10 \(\mu\text{s}\). In the peak jumping mode, the centres of the mass peaks are sequentially transmitted by jumping between selected isotopes.
Typically, several channels are allocated to each isotope and the dwell time per channel is of the order of 10 ms

1.3 ANALYTICAL CHARACTERISTICS

1.3.1 System response

The efficiency of ionisation of analyte atoms in the ICP may be estimated from the Saha equation:

\[
\frac{N_{ji}N_e}{N_{aj}} = \frac{(2\pi m_e kT)^{3/2}}{\hbar^3} \frac{2Z_{ji}e^{-E_j/kT}}{Z_{aj}}
\]

where

- \(N_{ji}\) is the ion concentration of species \(j\)
- \(N_{aj}\) is the atom concentration of species \(j\)
- \(N_e\) is the free electron concentration
- \(m_e\) is the electron mass
- \(k\) is the Boltzmann constant (1.381 x 10\(^{-23}\) J K\(^{-1}\))
- \(h\) is the Planck constant (6.626 x 10\(^{-34}\) J s)
- \(Z_{ji}\) is the partition function of ions of species \(j\)
- \(Z_{aj}\) is the partition function of atoms of species \(j\)
- \(E_j\) is the ionisation energy of species \(j\)
- \(T\) is the ionisation temperature

It is evident from the Saha equation that some 52 elements are expected to be ionised with an efficiency of 90% or more, for \(N_e = 1 \times 10^{15} \text{ cm}^{-3}\) and \(T = 7500 \text{ K}\) \([12]\). To facilitate semi-quantitative analysis, use is generally made of correction factors derived from the Saha equation. Having applied Saha derived correction factors and accounting for the isotopic abundance, the system response is, as a rule, curve-linear across the mass range. At either end of the mass range a drop in sensitivity is generally observed, while across the middle of the mass range sensitivity is fairly uniform. The drop-off in sensitivity observed at low mass is due to instrumental mass fractionation or bias.
1.3.2 Spectral interferences

The main spectral interferences which occur in ICP-MS are due to isobaric overlap, polyatomic ions (ArO⁺, ArAr⁺, etc.), refractory oxide ions (MO⁺ and MOH⁺) and doubly charged ions (M²⁺).

An isobaric overlap exists where two elements have isotopes of essentially the same mass. In reality, the masses differ by perhaps 0.005 of an atomic mass unit (u), but cannot be resolved by quadrupole-based mass analysers. It has been demonstrated that certain isobaric overlaps, such as ⁵⁰Sm on ⁵⁰Nd, may be resolved by double-focusing magnetic sector ICP-MS instruments [13]. However, all elements, except indium, have at least one isotope free from isobaric overlap.

Polyatomic ions resulting from the short lived combination of two or more atomic species can cause serious interference problems below 82 u. Argon, hydrogen, and oxygen are the dominant species in the ICP and these may combine with one another or with elements from acid matrices to form polyatomic ions. Mixed gas plasmas, whereby a second gas such as nitrogen is added to one or more of the gas streams, have been studied with a view to reducing polyatomic ions [14].

Refractory oxides occur as a result of incomplete dissociation of the sample matrix or from recombination in the plasma tail. Those elements with high oxide bond strengths usually give the greatest yield of refractory oxide ions, e.g. rare earth elements. As oxide bond strength decreases MOH⁺ is favoured, e.g. BaOH⁺

The extent of doubly charged ion formation in the ICP is dependent upon the second ionisation energy of the element. Only those elements with a second ionisation energy below that of the first ionisation energy of argon (15.76 eV) may undergo any significant degree of doubly charged ion formation. The formation of MO⁺ and M²⁺ can be minimised by reducing the amount of water reaching the ICP by cooling the spray chamber or adding a pre-desolvation system between the nebuliser and the ICP [15].
1.3.3 Non-spectral interferences

ICP-MS is more susceptible to non-spectral interferences by matrix elements than is ICP-AES [16]. The degree of suppression is dependent upon the mass and ionisation energy of the matrix element. It is generally the case that easily ionisable, light elements (e.g. Li) cause slight signal enhancements, whereas easily ionisable, heavy elements (e.g. U) cause severe suppression.

It has been suggested that several different mechanisms are responsible for the observed non-spectral interference effects and that each of these mechanisms dominates only under certain operating conditions [17]. Crain et al. [18] ascribed their observations to space charge effects resulting from changes in the flux and composition of the ion beam, originating within the interface region. Others have concluded that non-spectral interferences are caused by space charge effects brought about by ion-beam focusing in the ion optics region [19].

1.3.4 Analytical merits

The detection limits and linear range of ICP-MS are comparable with, or superior to, those of any other technique for multi-element analysis. Detection limits are generally in the range 0.1 to 10 ng l⁻¹. In the pulse counting mode, the linear range is typically 10⁵ or 10⁶, while in the analogue mode that range may be extended by at least one order of magnitude.

The measurement precision for ICP-MS is somewhat poorer than for ICP-AES at approximately 2 % RSD, however, with the use of internal standardisation or isotope dilution, a precision of the order of 0.1 to 0.5 % RSD is attainable. Accuracies of 1 % are typical when applying internal standardisation. Good accuracy can normally be achieved without matrix matching. Factors limiting the precision and accuracy of measurement will be discussed in subsequent chapters.

1.4 OBJECTIVES

ICP-MS is in principle a suitable technique for isotope ratio determination for all metallic elements. Indeed, it is unique in its ability to allow direct measurement of isotope ratios for elements with high
ionisation energies, such as B and Os. The limited precision and accuracy attainable by quadrupole based ICP-MS instruments has, however, restricted its use in isotope ratio measurement. The precision achievable by ICP-MS, typically 0.2 to 0.3 % RSD for isotope ratios, is adequate for accurate measurement of analyte concentration by isotope dilution, but is insufficient to allow study of natural variation in isotopic abundance for most elements.

The precision of isotope ratio measurements made by ICP-MS have generally been regarded as being primarily limited by instrumental instability. In Chapter 4, the sources of instrumental instability present in ICP-MS are studied by use of noise spectral analysis. It will be shown that noise spectral analysis can help in identifying the limitations imposed upon measurement precision by a variety of contributing noise sources. Subsequently, data acquisition methods can be developed which allow the predominate noise sources to be effectively filtered from the ion signal. In addition, sources of drift capable of limiting the accuracy of isotope ratio measurements will be identified and methods for their minimisation addressed. Finally, a protocol for isotope ratio measurement by ICP-MS will serve to summarise the basic steps necessary to obtain improved accuracy and precision.
References
2. M. Thompson and J.N. Walsh, "Handbook of Inductively Coupled
Plasma Spectrometry", 2nd Edition, Blackie and Son Ltd., Glasgow
7. J E. Meinhard, ICP Inf Newslett , 2, 163 (1976)
Spectrometry", Ed. K E. Jarvis, A.L Gray, I. Jarvis and J Williams,
11 L. de Galan, R. Smith and J D. Winefordner, Spectrochrm. Acta,
23B, 521 (1968).
1588 (1994)
16 G.R Gillson, D J. Douglas, J.E. Fulford, K.W Halligan and S D
17 D.C. Gregorie, Appl Spectrosc., 41, 897 (1987)
18 J.S Crain, R.S. Houk and F G. Smith, Spectrochrm. Acta, 43B,
1355 (1988).

Bibliography
"Applications of Inductively Coupled Plasma Mass Spectrometry",
Ed. A R. Date and A.L. Gray, Blackie and Son Ltd., Glasgow and London,
1989
CHAPTER TWO
ISOTOPE RATIO MEASUREMENT BY ICP-MS

2.1 INTRODUCTION

Generally, the elements have an invariant isotopic composition, however, there are a number of exceptions. Variation in the isotopic composition of certain elements has resulted from natural and anthropogenic processes. Natural variation in isotopic ratios has arisen from thermal and biological activity, which has caused the fractionation of the light elements, while, radioactive decay has given rise to a number of radiogenic elements. Anthropogenic changes in isotope ratios arise from processes undertaken in the nuclear industries and the redistribution of radiogenic elements such as lead in petrol additives. Furthermore, enriched isotope spikes are used to alter otherwise invariant isotope ratios in isotope tracer studies of metals in biological and environmental systems.

Isotope ratios are also widely used indirectly for determination of elemental concentration by isotope dilution, which involves the measurement of the change in the ratio of two selected isotopes of the element of interest upon addition of a spike which is enriched in one of these isotopes. The concentration of an element in a sample may be determined by isotope dilution for any element with at least two isotopes. Although isotope dilution is labour intensive, it yields more precise and accurate analyses than other calibration strategies and is the method of choice in certification of elemental concentrations in reference materials [1]. The methodology for isotope dilution mass spectrometry has been reviewed by Fassett and Paulsen [2].

This chapter will take the form of a review of the use of ICP-MS in isotopic analysis. Metallic elements for which isotopic analysis has been performed by mass spectrometry are presented in alphabetical order.
2.2 APPLICATIONS OF ISOTOPIC ANALYSIS

2.2.1 Boron

Boron has two naturally occurring isotopes $^{10}$B (~19\%) and $^{11}$B (~81\%). The high mobility of B in the marine environment has led to fractionation of the B isotopes. The absorption of B on marine sediments from seawater favors the $^{10}$B isotope, thus seawater has become enriched in $^{11}$B \[3\]. Variation in the $^{11}$B:$^{10}$B ratio can therefore be used as a diagnostic tool to differentiate between samples of marine and non-marine origin. In addition, there is interest in measuring the $^{11}$B:$^{10}$B ratio in biological materials, as trace levels of B are considered to play a role in bone metabolism \[4\], and in boron carbide as it is used as a neutron absorber in the nuclear industry \[5\].

High precision B isotope ratio measurements are traditionally performed by thermal ionization mass spectrometry (TIMS) based upon measurement of $^{115}$Cs$^{2+}$BO$_2$ at 308 and 309 u \[6\]. The high ionisation energy of B prevents its direct determination by TIMS. In the ICP, the degree of ionisation of B has been calculated as being 58\% \[7\], therefore, the $^{11}$B:$^{10}$B ratio may be determined directly by ICP-MS. Several studies have utilised ICP-MS for isotopic analysis of B in geological \[8,9\] and biological \[10\] samples.

The value of $^{11}$B:$^{10}$B ratios in geological materials determined by Gregoire \[8\], using ICP-MS, varied from 3.906 for tin-bearing silicate to 4.196 for conodont fossil. Relative to NASS-1 seawater these represented an isotopic shift of between -0.2 and -6.7\%. A difference of approximately 2\%, relative to NIST SRM 951, was observed by Spivack et al. \[3\] between the $^{11}$B:$^{10}$B ratios for pore fluid and foraminifera samples isolated from a deep-sea sediment core. Boron isotope ratio measurements have been made by ICP-MS with an average precision of 0.7\% RSD (relative standard deviation) \[8\], which is adequate for some geological applications. A measurement precision of 0.03\% RSD has been reported \[5\] for the determination of the $^{11}$B:$^{10}$B ratios in boron carbide samples by TIMS.

Isotope dilution ICP-MS has been utilised for the quantification of B in serum and biological reference materials using direct injection
nebulisation [10]. Smith et al. [10] used enriched boric acid (¹⁰B, 94.56 %) for isotope dilution to give a ¹¹B:¹⁰B ratio in the samples of about unity. With the aid of isotope dilution, a detection limit of approximately 1 ng g⁻¹ of B in the samples was realised.

Instrumental mass bias factors for ¹¹B:¹⁰B ratio measurements made by ICP-MS are large as a consequence of the 10 % difference in mass of the two isotopes. By mixing various quantities of NIST SRM 951 and NIST SRM 952, which have ¹¹B:¹⁰B ratios of 4.0436 and 0.0532, respectively, Gregoire [8] determined the mass bias of the Sciex Elan 250 instrument used to be +4.6 % u⁻¹. Gregoire [8] periodically ran NIST SRM 951 as a calibration standard for mass bias correction, during B isotope ratio analysis, to verify no change in mass bias had occurred.

The accuracy of ¹¹B:¹⁰B ratio determination by ICP-MS is susceptible to bias due to B contamination, primarily from glassware. In the study by Smith et al. [10], B contamination present in the blank gave a ¹¹B:¹⁰B ratio of approximately 4, while those for isotopically spiked samples were near unity. Hence, B in the blank was due to traces of B in the reagents or was leached from apparatus used during sample preparation, but did not arise from memory effects associated with direct injection nebulisation. To minimise B contamination it is necessary to utilise plasticware in preference to glassware whenever possible.

Both Gregoire [8] and Russ and Bazan [9] have investigated the dependence of measured ¹¹B:¹⁰B ratios upon non-spectroscopic matrix effects. Although Russ and Bazan [9] observed no change in the ¹¹B:¹⁰B ratio upon addition of 40 mg l⁻¹ of Pb, Gregoire [6] found addition of 96 mg l⁻¹ of Pb to cause a 12 % suppression in the B signal. Gregoire [8] concluded that use of cation exchange resins, to remove matrix elements prior to analysis, relieved B isotope ratio measurements of any bias which may arise from non-spectroscopic matrix effects.
2.2.2 Cadmium

Cadmium has eight stable isotopes, all of which are of fixed abundance in nature. The control of Cd accumulation in arable soils and produce thereof is necessary because of its toxic properties. The determination of both elemental Cd by isotope dilution [11] and Cd isotope ratios [12] can be beneficial to the understanding of Cd toxicology. The naturally occurring concentrations of elemental Cd in blood and urine are in the parts per trillion (ppt) range. These low levels have necessitated the use of hyphenated ICP-MS techniques to obtain results with sufficient accuracy. The determination of Cd isotope ratios has been undertaken by pre-concentration flow-injection ICP-MS [11] and electrothermal vaporisation ICP-MS (ETV-ICP-MS) [12].

Since the $^{111}$Cd isotope (12.86 %) is the only Cd isotope free of isobaric interferences, Lu et al. [11] utilised enriched $^{111}$Cd as an isotopic spike in the determination of elemental Cd in biological and environmental samples by isotope dilution. The $^{111}$Cd isotope was ratioed to $^{114}$Cd (28.81 %), which suffers from an isobaric overlap with $^{114}$Sn (0.65 %). The precision of $^{114}$Cd:$^{111}$Cd ratio measurements was approximately 4 % RSD for 5 µg l$^{-1}$ of Cd at natural abundance.

Gregoire and Lee [12] have studied the Cd metabolism of sheep by use of $^{106}$Cd (80.8 %) as a stable isotope tracer in a whole-body infusion study. Enriched Cd was infused continuously at the rate of 1.5 µg h$^{-1}$ for several days. The $^{111}$Cd $^{106}$Cd ratio in blood and organ tissue samples was determined by ETV-ICP-MS. The value of the $^{111}$Cd$^{106}$Cd ratio in sheep blood samples varied from 1.53 (2 h) to 0.62 (120 h), representing a change of 60 % during Cd infusion. The precision of the Cd isotope ratio measurements were around 2 % RSD, which was adequate for monitoring change in the $^{111}$Cd$^{106}$Cd ratio with time.

Gregoire and Lee [12] found that the accuracy of the $^{111}$Cd$^{106}$Cd ratios was complicated by isobaric overlap from $^{106}$Pd (27.10 %). To correct for isobaric overlap, the $^{105}$Pd isotope was measured and the relative contribution of $^{106}$Pd at 106 m/z subtracted from the total count. The difference between measured and actual $^{111}$Cd$^{106}$Cd ratio, was found to be less than the uncertainty within measurements, hence, no
correction of mass bias was applied [12]. Lu et al. [11] observed no significant change in the $^{114}\text{Cd}:^{111}\text{Cd}$ ratio for Na or Mg matrices and acid media, suggesting the instrumental mass bias remained unaltered.

2.2.3 Calcium
Calcium has six stable isotopes ($^{40}\text{Ca}$, 96.94 %, $^{42}\text{Ca}$, 0 65 %; $^{43}\text{Ca}$, 0.14 %, $^{44}\text{Ca}$, 2 09 %, $^{46}\text{Ca}$, 0 003 %; $^{48}\text{Ca}$, 0.19 %) The role of Ca in human nutrition has been studied by use of enriched $^{46}\text{Ca}$ (34.91 %) as an in vivo tracer [13]. Turnland et al. [13] determined the $^{46}\text{Ca}:^{48}\text{Ca}$ ratio in urine and faecal samples by multiple-collector TIMS with precisions of 0.14 and 0.10 % RSD, respectively. The instrumental mass bias of the multiple-collector TIMS instrument was found to change with time, over a 75 min period a 1 4 % shift in the measured Ca ratio was observed. Use of the $^{44}\text{Ca}:^{48}\text{Ca}$ ratio for internal mass bias correction gave much improved measurement precision. The RSD of the $^{46}\text{Ca}:^{48}\text{Ca}$ ratio for 9 replicate samples was 0.76 % prior to and 0.07 % following mass bias correction.

The use of ICP-MS in Ca isotope tracer studies is unreported. The precision of isotope ratio measurements made by ICP-MS may be inadequate for this purpose. If a Ca concentration in urine of 100 mg l$^{-1}$ [14] and a sampling efficiency of 30 x 10$^{6}$ cps per mg l$^{-1}$ are assumed, the accumulated count for a 30 s integration time on $^{46}\text{Ca}$ would be of the order of 3000. Hence, the precision for $^{46}\text{Ca}:^{48}\text{Ca}$ ratio determination in natural Ca is likely to be limited, by counting statistics, to about 2 % RSD. Magnetic sector ICP-MS instruments, such as the VG Plasma 54, may prove to be suitable for determination of the $^{46}\text{Ca}:^{48}\text{Ca}$ ratio in biological materials, since they can provide sampling efficiencies several orders of magnitude above that of quadrupole ICP-MS instruments.

2.2.4 Copper
Copper has two naturally occurring isotopes $^{63}\text{Cu}$ (69.09 %) and $^{65}\text{Cu}$ (30.91 %). The $^{65}\text{Cu}:^{63}\text{Cu}$ isotope ratio is invariant in nature, however, the commercial availability of isotopically enriched Cu ($^{65}\text{Cu}$, 99.70 %) facilitates stable isotope tracer and dilution studies. There is interest in measurement of the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio in biological samples taken from patients given a spike of $^{65}\text{Cu}$ as a method of investigating the role of...
Cu in human nutrition. Ting and Janghorbani [15] employed $^{65}\text{Cu}$ as an *in vivo* tracer and $^{63}\text{Cu}$ as a reference isotope in the study of human metabolism by measurement of the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio in human faecal matter by ICP-MS.

Janghorbani and co-workers [14-18] have pioneered the use of ICP-MS for stable isotope tracer studies of metabolites in human subjects, these have included Li, Fe, Cu, Zn, Se and Br. Generally metabolic studies relying on isotopic measurements of faecal matter require a measurement precision of below 1% RSD [15]. Ting and Janghorbani [15] found ICP-MS readily and routinely gave adequate precision, < 1% RSD, for measurement of the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio. Dwell times of both 0.05 and 3 s, in the peak jumping mode of data acquisition, were found to give comparable RSDs, of between 0.1 and 0.3%, for 1 mg l$^{-1}$ of natural abundance Cu. Warren *et al.* [18] have reported a precision of 0.14% RSD for their prototype twin quadrupole ICP-MS instrument.

The influence of non-spectral interference effects upon the measurement of the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio by ICP-MS was investigated by Lu *et al* [11]. In the presence of 5000 mg l$^{-1}$ of Na, the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio decreased approximately 2 fold, indicating severe spectral interference at 63 u from $^{40}\text{Ar}^{23}\text{Na}^+$. Similarly, in the presence of 2200 mg l$^{-1}$ of Mg the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio underwent significant increase, indicating spectral interference at 65 u from $^{40}\text{Ar}^{25}\text{Mg}^+$. The Cu isotopes were presumed to be free from spectral interference following selective precipitation from faecal matter with ammonium pyrrolidinedithiocarbamate (APDC) [15]. Ting and Janghorbani [17] observed the background intensities for a deionised water blank to be 400 and 190 cps for the $^{63}\text{Cu}$ and $^{65}\text{Cu}$ isotopes, respectively. The value of the $^{65}\text{Cu}:^{63}\text{Cu}$ ratio given by these background intensities is 0.475, which would suggest the presence of Cu contamination in the blank.

To evaluate the bias in the measured $^{65}\text{Cu}:^{63}\text{Cu}$ ratio, the measured and actual Cu isotope ratios for a series of standards, prepared by mixing of enriched $^{65}\text{Cu}$ and natural Cu, have been compared [15,17,18]. The bias in the measured $^{65}\text{Cu}:^{63}\text{Cu}$ ratio was found to be linear across the
range of values of interest (0.4474 to approximately 1) [15,17,18], being about 0.5 % u\(^{-1}\) for conventional ICP-MS [17].

2.2.5 Hafnium
Hafnium has six natural isotopes (\(^{174}\)Hf, \(-0.16\) %; \(^{176}\)Hf, \(-5.2\) %; \(^{177}\)Hf, \(-18.6\) %; \(^{178}\)Hf, \(-27.1\) %; \(^{179}\)Hf, \(-13.74\) %; \(^{180}\)Hf, \(-35.2\)%). The \(^{176}\)Hf isotope is the stable \(\beta\) decay product of \(^{176}\)Lu, which has a decay constant of \(1.93 \times 10^{-11}\) a\(^{-1}\) [19]. The relative abundance of the \(^{176}\)Hf isotope provides a basis for radiometric dating. The Lu:Hf method requires measurement of the \(^{176}\)Hf:\(^{177}\)Hf ratio and the Hf and Lu concentrations in minerals to facilitate determination of their formation age [19].

The natural variation in the \(^{176}\)Hf:\(^{177}\)Hf ratio is small. The present day value is 0.28286, while, and the value at the start of Hf isotopic evolution was 0.27978 [19]. As the \(^{176}\)Hf:\(^{177}\)Hf ratio has increased by only 1 % during some 4.55 Ga, high accuracy and precision are necessary for Lu:Hf dating. The \(^{176}\)Hf:\(^{177}\)Hf ratio may be determined by TIMS with a precision of approximately 0.02 % RSD [19]. Walder et al [20,21] have attained a measurement precision of about 0.003 % RSD for \(^{176}\)Hf:\(^{177}\)Hf determination by magnetic sector ICP-MS, when normalised to \(^{179}\)Hf:\(^{177}\)Hf. The superior precision, relative to TIMS, obtained by use of the magnetic sector ICP-MS instrument was considered to be a consequence of its higher sampling efficiency [21]. The ratio of recorded ions to atoms loaded onto the filament in TIMS is about 1 to 30,000, while the ratio of recorded ions to atoms nebulised in magnetic sector ICP-MS was 1 to 5200 [21].

2.2.6 Iron
Iron has four naturally occurring isotopes (\(^{54}\)Fe, 5.82 %; \(^{56}\)Fe, 91.66 %, \(^{57}\)Fe, 2.19 %; \(^{58}\)Fe, 0.33 %). The use of enriched Fe in stable isotope tracer studies can produce large variation in the Fe isotope ratios under investigation. The investigation of key aspects of the metabolism of Fe in man requires the use of isotope tracers [14]. Initially, radio-Fe tracers were used, however, the use of radiotracers is not permitted in infants and pregnant women. Dietary Fe absorption and utilisation in these population groups must be studied by the use of stable-Fe tracers.
Several studies have used ICP-MS for determination of Fe isotope ratios in relation to Fe metabolism [14-17,22,23]. The work of Ting and Janghorbani [14-17] was based upon the use of the $^{58}$Fe isotope as an in vivo tracer, the $^{57}$Fe isotope as an in vitro tracer and the $^{54}$Fe isotope as a reference. As the least abundant of the Fe isotopes, $^{58}$Fe is the most suitable as a tracer. The $^{56}$Fe isotope was deemed unsuitable for use as a reference isotope because, at the concentrations necessary to provide sufficient ion intensities on the minor isotopes, the intensity of the $^{56}$Fe signal would cause counting fatigue and non-linear system response.

Whittaker et al [22,23] have utilised ETV-ICP-MS [22] and ICP-MS [23] in the investigation of Fe absorption in normal women. In both of these studies $^{56}$Fe was used as a reference isotope. They used the $^{54}$Fe isotope as an in vivo tracer and the $^{57}$Fe isotope as an in vitro tracer in the first study [22], however, in the second study [23] the two least abundant Fe isotopes were used as tracers, $^{57}$Fe as the in vivo tracer and $^{58}$Fe as the in vitro tracer. The $^{57}$Fe:$^{56}$Fe and $^{58}$Fe:$^{56}$Fe ratios were determined with a precision of < 0.6 % RSD by ICP-MS [23]. These values compare favourably with those of Ting and Janghorbani [14,16] for the $^{57}$Fe:$^{54}$Fe and $^{58}$Fe:$^{54}$Fe ratios in fecal matter. In the ETV-ICP-MS study [22], the measurement precisions of the $^{54}$Fe:$^{56}$Fe and $^{57}$Fe:$^{56}$Fe ratios were approximately 0.9 and 1.5 % RSD, respectively. In all cases, the measurement precision was adequate to permit monitoring of the absorption and/or excretion of the stable-Fe tracers.

The influence of spectral interference effects upon the accuracy of Fe isotope ratio measurement has been assessed by Ting and Janghorbani [16]. It is conceivable that the measurement of all four Fe isotopes may be inconvenenient by spectral overlap with an isobaric or polyatomic specie. The $^{54}$Fe, $^{56}$Fe and $^{57}$Fe isotopes suffer from spectral overlaps with $^{40}$Ar$^{14}$N$^+$, $^{40}$Ar$^{16}$O$^+$ and $^{40}$Ar$^{16}$O$^+$, respectively. However, as the elemental concentrations of Fe in fecal matter and whole-blood are of the order of 10 mg l$^{-1}$, the intensities of these polyatomic species is negligible in comparison [16,23]. In addition, isobaric overlap from $^{54}$Cr and $^{58}$Ni at 54 and 58 u, respectively, may challenge the accuracy of Fe isotope ratio measurement. With a natural abundance of 68.27 %,
the $^{58}$Ni isotope is particularly problematic, requiring chemical separation from Fe, prior to analysis [16].

Ting and Janghorbani [15] demonstrated that measurable change in the observed Fe isotope ratios can result from severe drift in individual ion intensities. The measured value of the $^{58}$Fe-$^{57}$Fe ratio in Fe of natural abundance was observed to rise gradually from 0.1414 to 0.1453 over a period of 1.5 h. This drift in the $^{58}$Fe-$^{57}$Fe ratio serves to demonstrate the need for precise correction for bias caused by detector dead time, instrumental mass bias and background interferences. Whittaker et al. [23] have shown the dependence of the measured Fe isotope ratios upon ion intensity, which exists unless the correct dead time is utilised.

To minimise inaccuracy in the measurement of unknown Fe isotope ratios, the bias factors observed in blank-corrected standards of natural abundance Fe were used for correction [23]. These correction factors averaged 3.8 and -3.1 % for the $^{57}$Fe-$^{56}$Fe and $^{58}$Fe-$^{56}$Fe ratios, respectively. Ting and Janghorbani [16] used a set of 10 standards of known $^{57}$Fe-$^{54}$Fe ratio, prepared by mixing enriched $^{57}$Fe and natural Fe, to determine the bias in the measured $^{57}$Fe-$^{54}$Fe and $^{58}$Fe-$^{54}$Fe ratios in samples.

2.2.7 Lead

Lead has four naturally occurring isotopes ($^{204}$Pb, ~1.4 %; $^{206}$Pb, ~24.1 %; $^{207}$Pb, ~22.1 %; $^{208}$Pb, ~52.4 %). Natural variation in all Pb isotope ratios has arisen from the radioactive decay of $^{238}$U to $^{206}$Pb, $^{235}$U to $^{207}$Pb and $^{232}$Th to $^{208}$Pb, as is depicted in Figure 2.1. Only $^{204}$Pb is non-radiogenic (not the stable decay product of radioactive emission) and has remained unchanged through time. The other isotopes usually consist of a radiogenic and a non-radiogenic component. When ratioed to $^{204}$Pb the Pb isotope ratios are a function of the quantities of Pb, U and Th present in the mineral at the time of formation ($t_0$) and the time (t) since formation, during which radioactive decay has occurred.
Figure 2.1. Radioactive decay series

Uranium series

$^{238}\text{U} \rightarrow ^{234}\text{Th}$
$\downarrow$
$^{234}\text{Pa}$
$\downarrow$
$^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{222}\text{Rn} \rightarrow ^{218}\text{Po} \rightarrow ^{214}\text{Pb}$
$\downarrow$
$^{218}\text{At} \rightarrow ^{214}\text{Bi} \rightarrow ^{210}\text{Tl}$
$\downarrow$
$^{214}\text{Po} \rightarrow ^{210}\text{Pb}$
$\downarrow$
$^{210}\text{Bi} \rightarrow ^{206}\text{Tl}$
$\downarrow$
$^{210}\text{Po} \rightarrow ^{206}\text{Pb}$

Actinum series

$^{235}\text{U} \rightarrow ^{231}\text{Th}$
$\downarrow$
$^{231}\text{Pa} \rightarrow ^{227}\text{Ac} \rightarrow ^{223}\text{Fr}$
$\downarrow$
$^{227}\text{Th} \rightarrow ^{223}\text{Ra} \rightarrow ^{219}\text{Rn} \rightarrow ^{215}\text{Po} \rightarrow ^{211}\text{Pb}$
$\downarrow$
$^{215}\text{At} \rightarrow ^{211}\text{Bi} \rightarrow ^{207}\text{Tl}$
$\downarrow$
$^{211}\text{Po} \rightarrow ^{207}\text{Pb}$

Thorium series

$^{232}\text{Th} \rightarrow ^{228}\text{Ra}$
$\downarrow$
$^{228}\text{Ac}$
$\downarrow$
$^{228}\text{Th} \rightarrow ^{224}\text{Ra} \rightarrow ^{220}\text{Rn} \rightarrow ^{216}\text{Po} \rightarrow ^{212}\text{Pb}$
$\downarrow$
$^{216}\text{At} \rightarrow ^{212}\text{Bi} \rightarrow ^{208}\text{Tl}$
$\downarrow$
$^{212}\text{Po} \rightarrow ^{208}\text{Pb}$

$\rightarrow$ = alpha emission $\quad \downarrow$ = beta emission

After J.G. Stark and H.G. Wallace [24].
There are several methods for determining the age and/or genesis of minerals based upon Pb geochemistry which rely upon isotopic information. These have been extensively described by Geyh and Schleicher [19]. The U-Pb and Th-Pb methods are used primarily for radiometric dating and are most commonly applied to zircons. These necessitate measurement of the concentrations of the Pb and U or Th isotopes of interest. This is generally undertaken by solid-source mass spectrometry, following isotopic spiking and separation of the elements by ion exchange. Although ICP-MS has the potential to measure the Pb, U and Th isotopes of interest simultaneously, its use in radiometric dating by the U:Pb or Th:Pb methods is as yet to be proven. However, ICP-MS has been widely used in determination of the isotopes of interest in the common lead (ratioing the Pb isotopes to $^{204}$Pb) and $^{207}$Pb $^{206}$Pb methods. These methods provide information on the genesis of minerals, but are equally important in the identification of Pb source in environmental and biological studies.

A number of studies have utilised ICP-MS in isotopic analysis of geological and environmental samples by the common lead method [25-27]. Date and Cheung [25] analysed 30 different minerals and were able to separate these into broad age groupings, each differing in $^{206}$Pb:$^{204}$Pb ratio by approximately 10%. The variation in the isotope ratios of the minerals relative to those for NIST SRM 981 were: $^{206}$Pb:$^{204}$Pb, +65 to -23%; $^{207}$Pb:$^{204}$Pb, +12 to -7%; $^{208}$Pb:$^{204}$Pb, +32 to -10%. The $^{206}$Pb:$^{204}$Pb ratio for soil samples analysed by Ketterer et al [26] varied from 18.17 to 16.60, while the accuracy relative to TIMS was around 0.5%.

The $^{207}$Pb:$^{206}$Pb method has been used by Delves and Campbell [28,29] to identify the source of Pb in tooth and blood samples of patients exposed to Pb poisoning. The values of the $^{207}$Pb:$^{206}$Pb ratios for samples from environmental sources varied from 0.890 to 0.940, equivalent to ten times the measurement accuracy. The lowest value being associated with lead piping and the highest with UK lead petrol additive. The relatively high $^{207}$Pb:$^{206}$Pb ratio of lead petrol additives during the 1980s has allowed characterisation of environmental pathways [29-31]. Krause et al. [31] found the value of the $^{207}$Pb:$^{206}$Pb...
ratio for aerosol samples to vary from 0.83, for marine regions, to 0.90, for areas of high traffic density.

Several environmental and biological studies, generally undertaken in the scanning mode of data acquisition, have taken advantage of data for all four Pb isotopes by using a number of Pb isotope ratios [33-38]. Hall et al. [36] used both the $^{208}\text{Pb}:^{206}\text{Pb}$ and $^{207}\text{Pb}:^{206}\text{Pb}$ ratios to identify the Pb source in children exposed to Pb poisoning, as regression analysis had shown these ratios to be the least correlated. Dean et al. [33] ratioed the three major Pb isotopes to obtain $^{208}\text{Pb},^{207}\text{Pb},^{208}\text{Pb},^{206}\text{Pb}$ and $^{207}\text{Pb},^{206}\text{Pb}$ ratio values for Australian and European milk powders. Only the $^{207}\text{Pb}:^{206}\text{Pb}$ ratio was found to differ significantly, being approximately 7% higher in the Australian milk powder.

The accuracy and precision of $^{207}\text{Pb}:^{206}\text{Pb}$ ratio measurements for NIST SRM 981, made by ICP-MS, from published studies are summarised in Table 2.1. The $^{207}\text{Pb}$ $^{206}\text{Pb}$ ratio is least likely of the Pb isotope ratios to be altered by dead time and mass bias, thus, accuracy and precision are liable to be equivalent to if not better than that achieved for other Pb isotope ratios. It may be seen that with the exception of the studies by Walder et al. [20,21], in which a VG Plasma 54, incorporating a double focusing magnetic sector mass analyser and seven Faraday collectors was employed, that accuracy and precision are generally about 0.5% and 0.3% RSD, respectively. Although the sampling efficiency of the VG Plasma 54 is several orders of magnitude above that for quadrupole ICP-MS, the results are encouraging in that they prove the ICP to be a suitable ion source for truly high precision analysis. Date and Cheung [25] concluded that the accuracy and precision of Pb isotope ratio measurement is controlled by a number of factors including the validity of the correction for mass bias and the counting statistic.
Table 2.1: Measurement of $^{207}\text{Pb}:{^{206}\text{Pb}}$ for NIST SRM 981

<table>
<thead>
<tr>
<th>Reference</th>
<th>Lead Conc. (ng ml$^{-1}$)</th>
<th>Acquisition Mode</th>
<th>Precision (% RSD)</th>
<th>Bias (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date [25]</td>
<td>1000</td>
<td>scanning</td>
<td>0.32</td>
<td>0.81</td>
</tr>
<tr>
<td>Hālczy [38]</td>
<td>77</td>
<td>peak jumping</td>
<td>0.33</td>
<td>-0.26</td>
</tr>
<tr>
<td>Hinners [34]</td>
<td>40</td>
<td>peak jumping</td>
<td>0.26</td>
<td>1.24</td>
</tr>
<tr>
<td>Russ [8]</td>
<td>1000</td>
<td>scanning</td>
<td>0.12</td>
<td>-0.07</td>
</tr>
<tr>
<td>Delves [26]</td>
<td>50</td>
<td>scanning</td>
<td>0.76</td>
<td>0.41</td>
</tr>
<tr>
<td>Furuta [40]</td>
<td>100</td>
<td>scanning</td>
<td>0.30</td>
<td>0.49</td>
</tr>
<tr>
<td>Miyazaki [35]</td>
<td>2000</td>
<td>peak jumping</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Walder [20]</td>
<td>1000</td>
<td>multi-collector</td>
<td>0.01</td>
<td>-0.058</td>
</tr>
<tr>
<td>Walder [21]</td>
<td>50</td>
<td>multi-collector</td>
<td>0.010</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Several of the earlier studies of the use of ICP-MS in Pb isotope ratio measurement were undertaken using instruments with limited acquisition capabilities [25,28,33,34]. In some respects these limitations restrict the relevance of the reports to isotope ratio analysis using current ICP-MS instruments. For instance, the study by Dean et al. [33] found scanning to be more favourable than peak jumping, however, acquisition in the peak jumping mode was limited to a maximum of 10 s per isotope, while scanning could be continued for an unlimited period. Correction for detector dead time was not always available [25,34], which is likely to have caused bias in the Pb isotope ratios when referenced to $^{204}\text{Pb}$. Similarly, the quadrupole rest mass was fixed in early instruments and could not be altered to suit specific applications, which reduced precision and led to the adoption of longer acquisition times [28].

To decrease the relatively high counting error associated with the $^{204}\text{Pb}$ isotope, several studies [33,34] have utilised the peak jumping mode of data acquisition to attain equivalent counts on all four Pb isotopes by use of different dwell times. Hinners et al. [34] found that by splitting the acquisition time in inverse proportion to abundance, such that 88 %
of time was spent on $^{204}\text{Pb}$, 5\% on $^{206}\text{Pb}$ and $^{207}\text{Pb}$ and just 2\% on $^{208}\text{Pb}$, almost a four fold improvement in the precision of the $^{204}\text{Pb}$/$^{206}\text{Pb}$ ratio could be gained. However, the \% RSD of the $^{207}\text{Pb}$/$^{206}\text{Pb}$ and $^{208}\text{Pb}$/$^{206}\text{Pb}$ ratios increased three fold. This technique has not found use in recent studies, perhaps because the accuracy of the isotope ratio measurement is jeopardised by the use of unequal dwell times.

The accuracy of Pb isotope ratios has formed the basis of a number of studies [26,27,39]. These have reported the development of the thallium correction method for minimising bias in Pb isotope ratios, as an alternative to the analysis of Pb calibration standards, such as NIST SRM 981, for mass bias correction. The thallium correction method involves the addition of Tl to the samples and measurement of the $^{205}\text{Tl}$/$^{207}\text{Tl}$ ratio, which is invariant in nature and has a known value of 2.3871.

Since verification of the thallium correction method [26], few studies have adopted the approach [20,21,37], while others have considered it unnecessary for their needs [31]. The weaknesses of the thallium correction method are: the acquisition time necessary to measure the Tl isotopes, which could otherwise be spent accumulating counts on the Pb isotopes; and the reduction in precision of the Pb isotope ratios which can result from correction. It is necessary to be mindful of the need to precisely correct for dead time and assure that noise is minimised in both Tl and Pb isotopes if the thallium correction method is to be used effectively. It is worthy of note that Walder et al. [20,21] have successfully used the thallium correction method for simultaneous measurement of isotopes using Faraday detectors.

With the exception of the $^{204}\text{Pb}$ isotope, which can suffer from an isobaric overlap with $^{204}\text{Hg}$ (6.85 \%), the Pb isotopes are generally free from spectral interferences. If Hg is present in the samples, even at trace level, and the $^{204}\text{Pb}$ isotope is required to be measured, it is necessary to correct for counts at 204 m/z due to $^{204}\text{Hg}$. This is most readily done by measuring another Hg isotope, generally $^{201}\text{Hg}$ (13.2 \%), from which the relative contribution of Hg at 204 m/z may be estimated [26].
2.2.8 Lithium

Lithium has two naturally occurring isotopes $^6$Li (75.2 %) and $^7$Li (92.48 %). However, commercial Li products are depleted in $^6$Li, which is used in the manufacturer of nuclear weapons. The relative abundances of the $^6$Li and $^7$Li isotopes in Li products are $\sim$6.43 and $\sim$93.57 %, respectively. The availability of isotopically enriched Li ($^6$Li, 94.88 %) facilitates stable isotope tracer and dilution studies. As Li is used as a therapeutic agent in manic-depressive illnesses and is administered at levels approaching those at which poisoning occurs, accurate determination of the exchangeable Li pool size is necessary [41]. Large variation in the $^6$Li:$^7$Li ratio during stable isotope tracer studies, in which the $^6$Li isotope has been used as an in vivo tracer, are likely. Sun et al [41] have investigated the feasibility of the use of ICP-MS in the determination of the $^6$Li:$^7$Li ratio in biological materials. The $^6$Li:$^7$Li ratio has been determined by ICP-MS with a precision of about 1 % RSD [9,41]. Ting and Janghorbani [15] have stated that a measurement precision of 1 % RSD is sufficient for stable isotope tracer studies.

The influence of matrix interference effects upon the accuracy of $^6$Li:$^7$Li ratio determination were investigated by Sun et al. [41]. They found that the addition of Na, at a concentration ratio of Na to Li of 1000:1, caused no appreciable change in the measured $^6$Li:$^7$Li ratio. Similarly, no significant difference in the measured $^6$Li:$^7$Li ratio in water, blood or urine samples was observed. Russ and Bazan [9] found the measured $^6$Li:$^7$Li to be unaltered upon addition of an equal molar concentration of Pb to Li solutions.

Lithium contamination has been highlighted as a major source of Li isotope ratio bias [9,14]. Russ and Bazan [9] found it was not feasible to assess the accuracy of the $^6$Li:$^7$Li ratio for a 1 mg l$^{-1}$ Li standard because the Li signal was dominated by contamination. Janghorbani and Ting [14] observed the $^6$Li:$^7$Li ratio to be concentration dependent at concentrations of below 0.1 mg l$^{-1}$ of Li, but concentration independent at concentrations between 0.1 and 1 mg l$^{-1}$ of Li.

The instrumental mass bias factors for measurement of the $^6$Li:$^7$Li ratio are likely to be significant since there is approximately a 15 %
difference in the mass of the two isotopes. By mixing various quantities of enriched $^6$Li and natural Li, Sun et al. [41] were able to define the relationship between the measured and actual value of the $^6$Li:$^7$Li ratios using linear regression. Correction for mass bias was applied by use of this linear function, to obtain an accuracy of about 1% for $^6$Li:$^7$Li ratio determination.

2.2.9 Mercury
Mercury has seven naturally occurring isotopes ($^{196}$Hg, 0.15%; $^{198}$Hg, 10.02%; $^{199}$Hg, 16.84%; $^{200}$Hg, 23.13%; $^{201}$Hg, 13.22%; $^{202}$Hg, 29.80%; $^{204}$Hg, 6.85%). The presence of Hg in the natural environment and the mechanisms by which it enters biological systems are of concern because of its high toxicity. To fully understand the transport, uptake and methylation of Hg in the biological system requires isotope tracer studies, in addition to concentration and speciation information [42].

Haraldsson et al. [42] have utilised ICP-MS in the determination of Hg isotope ratios. The low concentration of Hg in natural waters necessitates the use of preconcentration to permit Hg determination by isotope dilution ICP-MS [43,44]. Preconcentration of Hg on gold traps and subsequent electrothermal heating and purging of the traps with Ar has been used in several studies [42-44]. Haraldsson and co-workers [42,44] have used $^{199}$Hg (enriched to 91.95%) as a spike isotope and $^{202}$Hg as a reference isotope. Smith [43] also used $^{202}$Hg as a reference isotope, but utilised $^{201}$Hg (enriched to 91.2%) as a spike isotope.

The $^{202}$Hg:$^{199}$Hg ratio was determined with a precision of approximately 0.2 and 0.9% RSD for gold traps containing 300 and 50 pg of Hg, respectively [42]. It was found that the precision of $^{202}$Hg:$^{119}$Hg ratio determination in samples containing less than 300 pg of Hg was limited by the counting statistic. As the accumulated ion counts obtained by peak jumping were about 17 times greater than those for scanning, the peak jump mode gave higher precision for small amounts of Hg. Haraldsson et al. [42] found the measured Hg isotopes to be biased by an average of 4.1%.
Smith [43] obtained a procedural detection limit of 0.2 ng l⁻¹ for Hg in waters by isotope dilution ICP-MS. Spiking samples with enriched ²⁰¹Hg to obtain a ²⁰²Hg:²⁰¹Hg ratio of between 0.2 and 1.5 was found to yield a Hg concentration within the limits of uncertainty of the certified value of river water standard ORMS-1.

2.2.10 Neodymium

Neodymium has seven natural isotopes (¹⁴²Nd, ~27.13 %; ¹⁴³Nd, ~12.18 %; ¹⁴⁴Nd, ~23.80 %; ¹⁴⁵Nd, ~8.30 %; ¹⁴⁶Nd, ~17.19 %; ¹⁴⁸Nd, ~5.76 %; ¹⁵⁰Nd, ~5.64 %) The ¹⁴³Nd and ¹⁴⁴Nd isotopes are the stable decay products of ¹⁴⁷Sm and ¹⁴⁸Sm, respectively. Only the radioactive decay of ¹⁴⁷Sm, which has a decay constant of 6.539 x 10⁻¹² a⁻¹, provides a basis for radiometric dating [19]. The half-life of ¹⁴⁸Sm is too long to be geochronologically relevant. The Sm:Nd method requires measurement of the ¹⁴³Nd:¹⁴⁴Nd ratio and Nd and Sm concentrations in minerals to facilitate determination of their formation age [19].

High precision is required in measurement of the ¹⁴³Nd:¹⁴⁴Nd ratio because its natural variation is extremely small [19]. The ¹⁴³Nd:¹⁴⁴Nd ratio requires to be determined with an accuracy of 0.0005 % to permit radiometric dating [45]. It is clear that such high accuracy is unachievable by quadrupole ICP-MS. However, Walder et al. [20] have attained a measurement precision of about 0.004 % RSD for ¹⁴³Nd:¹⁴⁴Nd ratio determination by magnetic sector ICP-MS, when normalised to ¹⁴⁶Nd:¹⁴⁵Nd. The precision of this measurement is higher than can be obtained by TIMS for an equivalent analysis time.

Beary and Paulsen [46] have used ICP-MS in determination of ultra-trace levels of Nd in La compounds by isotope dilution. They used enriched ¹⁴⁵Nd as a spike isotope and ¹⁴⁶Nd as a reference isotope. To correct for mass bias, which was observed to drift by 1 to 2 % over an 8 h period, natural Nd was used as a control standard and was run periodically throughout analysis. The frequency of the use of mass bias correction was dictated by the rate of drift during analysis. A measurement precision of 0.2 % RSD was realised for ¹⁴⁵Nd:¹⁴⁶Nd ratio determination under optimum conditions.
2.2.11 Osmium

Osmium has seven naturally occurring isotopes ($^{184}\text{Os}$, ~0.02 %; $^{186}\text{Os}$, ~1.58 %; $^{187}\text{Os}$, ~1.6 %; $^{188}\text{Os}$, ~13.3 %; $^{189}\text{Os}$, ~16.1 %; $^{190}\text{Os}$, ~26.4 %; $^{192}\text{Os}$, ~41.0 %) The $^{187}\text{Os}$ isotope is the stable $\beta$ decay product of $^{187}\text{Re}$, which has a decay constant of $1.64 \times 10^{-11} \text{ a}^{-1}$ [19]. The relative abundance of the $^{187}\text{Os}$ isotope provides a basis for determination of the age and genesis of minerals. The Re:Os method is particularly suited for dating of sulphide ore deposits and for studying the genesis of ore deposits of platinum group elements [47]. Richardson et al. [48] have summarised geochronological applications of Os isotope ratio determination.

The development of the Re:Os method has been hampered by the high ionisation energy of Os (8.5 eV), which precludes Os isotope ratio determination by TIMS. The ICP is a suitable alternative method for excitation, as Os is ionised in the ICP with an efficiency 78 % [7]. The Re:Os method normally requires the measurement of the $^{187}\text{Os}^{188}\text{Os}$ or $^{187}\text{Os}^{188}\text{Os}$ ratio, and Os and Re concentrations in minerals to facilitate age determination. Separation of Os from Re is necessary as $^{187}\text{Re}$ (62.6 %) is potentially a very serious isobaric interference in measurement of $^{187}\text{Os}$ (1.6 %) [47]. Direct distillation of OsO$_4$ into the ICP is a convenient method for separation from Re [47-49].

The low concentration of Os in minerals, typically in the ng g$^{-1}$ range, and the minor abundance of the $^{187}\text{Os}$ isotope, cause the precision of Os isotope ratio measurements to be generally limited by the counting statistic [47]. To increase the efficiency of Os transportation to the ICP and thus the accumulated ion count, specialised sample introduction techniques have been employed [47-51]. In addition to the benefits of separation of Os from Re to be gained from distillation of OsO$_4$, Russ et al. [49] found it enhanced sensitivity by 100 times over that obtained by pneumatic nebulisation Dickin et al. [47] obtained an average precision of 15 % RSD for determination of the $^{187}\text{Os}^{188}\text{Os}$ ratio for 10 ng of Os, by distillation of OsO$_4$.

Gregoire [51] made a comparison of pneumatic nebulisation, OsO$_4$ distillation and electrothermal vaporisation (ETV) for the determination of Os isotope ratios The ETV method was found to give greatest
sensitivity, however, the transient nature of the signal resulted in a measurement precision for the $^{187}\text{Os}:^{188}\text{Os}$ ratio equivalent to that obtained by distillation of $\text{Os}_4$. An average precision of 0.34 % RSD for determination of the $^{187}\text{Os}:^{188}\text{Os}$ ratio in geological materials obtained by ICP-MS is comparable to that attainable by any other mass spectroscopic technique [48].

The $^{187}\text{Os}:^{188}\text{Os}$ ratio requires to be determined with an accuracy of 0.5 % to permit radiometric dating [45]. Russ et al. [49] observed Os isotope ratios to deviate from their actual values by an average of 1.5 % u$^{-1}$. Mass bias correction of the $^{187}\text{Os}:^{188}\text{Os}$ ratio has been applied by normalisation to $^{192}\text{Os}:^{188}\text{Os}$, which has a known value of 3.0827 [49,50].

As stated above, $^{187}\text{Os}$ suffers from an isobaric overlap with $^{187}\text{Re}$, although distillation provides separation of these two elements, Russ et al. [49] used the $^{185}\text{Re}$ isotope as a monitor for Re contamination. They observed no ion peak at 185 m/z, however correction may have been applied for $^{187}\text{Re}$ at 187 m/z if Re contamination had been present. Similarly, $^{192}\text{Os}$ suffers from an isobaric overlap with $^{192}\text{Pt}$, which if present as a contaminant may have had influence upon the measured $^{192}\text{Os}:^{188}\text{Os}$ ratio, however, an insignificant quantity of Pt contamination was observed.

2.2.12 Potassium

Potassium has three stable isotopes ($^{39}\text{K}$, 93.10 %; $^{40}\text{K}$, 0.012 %; $^{41}\text{K}$, 6.88 %). There is interest in determination of K isotope ratios in biological samples because K is of importance in various metabolic and physiological processes. It has been suggested that enriched $^{41}\text{K}$ may be used for measurement of lean body mass [52]. In addition, K isotope tracers provide a method for the study of chemical interaction between groundwater and rock enclosures in aquifers [52].

Jiang et al. [52] have examined the feasibility of the use of ICP-MS for K isotope ratio determination. Generally determination of the $^{39}\text{K}:^{41}\text{K}$ ratio is hindered by spectral interferences from $^{38}\text{Ar}^+\text{H}^+$ and $^{40}\text{Ar}^+\text{H}^+$. Use of a low incident power, high nebuliser gas flow rate and sampling depth of 35 mm above the load coil (a l c.) were found to reduce the
background at 39 and 41 m/z to only 50 cps, for the ICP-MS instrument used in one study [52]. These optimised operating parameters provided a precision of 0.3 to 0.9 % RSD for measurement of the $^{39}$K-$^{41}$K ratio in KCl solutions in the concentration range 1 to 50 mg l$^{-1}$. Potassium is present in biological materials at concentrations in the range 200 to 2000 mg l$^{-1}$ [14].

Jiang et al. [52] observed the difference between measured and actual K isotope ratios to be dependent upon the voltage applied to the photon baffle within the ion optics. The accuracy of $^{39}$K-$^{41}$K ratio determination was found to be biased by approximately -9 %, representing an instrumental mass bias of about 4.5 % u$^{-1}$. Hence, it was considered necessary to undertake external mass bias correction using NIST SRM 985.

As Na and K are present in biological materials at similar concentrations, Jiang et al. [52] assessed the influence of Na induced interference effects upon K isotope ratio determination. The $^{39}$K-$^{41}$K ratio was observed to decrease gradually with increase in Na concentration. Jiang et al. [52] concluded that it was necessary to chemically separate K from biological matrices prior to K isotope ratio determination, to overcome inaccuracies associated non-spectral interference effects.

2.2.13 Selenium

Selenium has six stable isotopes ($^{74}$Se, 0.87 %; $^{76}$Se, 9.02 %; $^{77}$Se, 7.58 %, $^{78}$Se, 23.52 %; $^{80}$Se, 49.82 %; $^{82}$Se, 9.19 %). All six Se isotopes are of fixed nature abundance, however, enriched $^{82}$Se is available for use as a spike in stable isotope tracer studies. The role of Se in health is of importance as Se deficiency has been linked with a variety of disorders [53]. Stable isotope ratio study of Se metabolism requires to be conducted for a period of up to a month because regulation of Se in the body is via the kidneys [14].

Ting, Janghorbani and co-workers have developed methods for determination of Se isotope ratios by ICP-MS, for sample introduction by pneumatic nebulisation [54] and hydride generation [55]. Both sample introduction techniques were suitable for determination of Se
isotope ratios in urine, however, only hydride generation gave sufficient sensitivity to allow Se isotope ratio measurement in blood, or in cases of Se deficiency. The $^{82}\text{Se}$ isotope was used as an *in vitro* tracer and the $^{77}\text{Se}$ isotope as a reference because it is the only Se isotope free from isobaric overlap.

To facilitate isotope dilution analysis, Ting *et al.* [55] measured three Se isotopes ($^{74}\text{Se}$, $^{77}\text{Se}$ and $^{82}\text{Se}$), to allow determination of two isotope ratios ($^{82}\text{Se},^{77}\text{Se}$ and $^{74}\text{Se},^{77}\text{Se}$). A measurement precision of approximately 1 % RSD was routinely obtained for both Se isotope ratios, which was adequate for study of Se metabolism. The measured $^{74}\text{Se}$ $^{77}\text{Se}$ ratios in a variety of biological matrices were within 1 SD of the actual ratio. However, the measured $^{82}\text{Se},^{77}\text{Se}$ ratio for bovine liver and red blood cells deviated from the actual ratio by 2.7 and 2.2 %, respectively. Ting *et al.* [55] suggested these bias factors were the result of an unidentified spectral interference at $82\text{ m/z}$. Background intensities on $^{74}, 77$ and $^{82} \text{m/z}$ were approximately 10, 4 and 5 %, respectively, of the signal intensity for a 2 ng ml$^{-1}$ solution of Se.

2.2.14 Strontium

Strontium has four naturally occurring isotopes ($^{84}\text{Sr}$, ~0 56 %; $^{86}\text{Sr}$, ~9 86 %; $^{87}\text{Sr}$, ~7.00 %; $^{88}\text{Sr}$, ~82.58 %). The $^{87}\text{Sr}$ isotope is the stable $\beta$ decay product of $^{87}\text{Rb}$, which has a decay constant of $1.42 \times 10^{-11} \text{ a}^{-1}$ [19,56]. The decay of $^{87}\text{Rb}$ to radiogenic $^{87}\text{Sr}$ changes the Sr isotopic composition of minerals, thus, the relative abundance of $^{87}\text{Sr}$ in minerals containing Rb provides a basis for radiometric dating. The Rb:Sr method is one of the most important standard methods in geochronology [19]. Normally measurement of the $^{87}\text{Sr}:^{86}\text{Sr}$ ratio and Sr and Rb concentrations in minerals is necessary to facilitate age determination.

As Rb and Sr are generally present at similar concentrations in minerals, natural variation in the $^{87}\text{Sr}^{86}\text{Sr}$ ratio is small [56]. It is necessary to determine the $^{87}\text{Sr}^{86}\text{Sr}$ ratio with an accuracy of 0 005 % to permit radiometric dating [45]. The $^{87}\text{Sr}^{86}\text{Sr}$ ratio may be determined by TIMS with a precision of less than 0 001 % RSD [56]. Walder *et al.* [57] have attained a measurement precision of about 0.01 % RSD for $^{87}\text{Sr}^{86}\text{Sr}$ ratio determination by magnetic sector ICP-MS.
The $^{86}\text{Sr}:/^{88}\text{Sr}$ ratio, which has a known value of 0.1194 [19], is conventionally used for correction of instrumental mass bias. Walder et al. [57] observed use of this method for internal mass bias correction to produce superior levels of internal and external precision than had been obtainable for U or Pb isotope ratio determination with external mass bias correction. However, the mean value for the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, on three consecutive days was consistently high by approximately 0.01 %

Separation of Sr from Rb is necessary prior to the determination of the $^{87}\text{Sr}^{86}\text{Sr}$ ratio to prevent serious isobaric overlap from $^{87}\text{Rb}$ (27.83 %) at 87 m/z. Chromatographic separation of these two elements on ion exchange resins is an effective method for quantitative separation [19]. The $^{85}\text{Rb}$ isotope may be used to monitor Rb contamination and thus, to estimate the contribution of Rb to the accumulated ion count at 87 m/z.

The accuracy with which the age of minerals may be determined by the Rb Sr method depends primarily upon the measurement of the Rb and Sr concentrations [19,58] Conventionally, isotope dilution TIMS is used for routine determination of Rb and Sr concentrations, a measurement precision of about 0.6 % RSD is typical [58]. Rb is di-isotopic, hence, there is no means of measuring mass bias during analysis by TIMS. Ward and Bell [58] periodically monitored mass bias during isotope dilution ICP-MS using a natural Rb standard, to realise a precision of 0.17 % RSD for determination of Rb concentration.

2.2.15 Tin

Tin has ten stable isotopes, all of which are of fixed natural abundance. The presence of organotins in the marine environment, tributyltin and triphenyltin compounds are used as anti-fouling agents, and their transport and uptake in the biological system are of concern because of their toxicity [59]. The commercial availability of isotopically enriched Sn ($^{118}\text{Sn}$, 97.79 %) facilitates stable isotope tracer and dilution studies. Okamoto [60] has utilised isotope dilution ICP-MS in development of biological reference materials for total Sn determination.
The natural concentration of Sn in biological materials is in the μg g⁻¹ range, which has made the certification of Sn in these materials problematic [60]. Okamoto [60] used the ¹¹⁸Sn:¹²⁰Sn ratio, which has a natural value of 0.743, for determination of Sn by isotope dilution. Spectral overlap was not observed on either of these Sn isotopes. Fish tissue samples were spiked with 0.05, 0.10 and 0.15 g of enriched ¹¹⁸Sn to obtain ¹¹⁸Sn:¹²⁰Sn ratios of approximately 1.00, 1.25 and 1.50, respectively. All three spikes gave comparable Sn concentrations, with an overall mean of 2.37 ± 0.04 μg g⁻¹.

2.2.16 Uranium

Uranium has three long lived isotopes (²³⁴U, ~0.0055 %; ²³⁵U, ~0.72 %; ²³⁸U, ~99.2745 %). However, commercial U products are depleted in ²³⁵U, which is used in the manufacturer of nuclear weapons. The measurement of U isotope ratios is vital in determination of the composition of nuclear fuel materials and to monitor its effect upon the environment [21]. High precision isotopic analysis of U materials has conventionally been undertaken by TIMS. As reduction in sample size and sample preparation lessens radiation exposure, alternative methods, including ICP-MS, have been evaluated [9,21,61-63].

Conventional ICP-MS, with pneumatic nebulisation, has been used for U isotope ratio analysis [9,61]. Pin et al. [61] realised an average measurement precision of 0.29 % RSD for determination of the ²³⁸U:²³⁵U ratio in NIST SRM U500, which has a certified value of 1.0003. Although the measurement precision for U isotope ratio determination by TIMS is typically below 0.1 % RSD, the rapid sample throughput of ICP-MS made it a viable alternative to TIMS [61]. Walder et al. [21] utilised magnetic sector ICP-MS to attain a measurement precision of 0.13 and 0.01 % RSD for the ²³⁴U:²³⁸U and ²³⁵U:²³⁸U ratios, respectively, for a 50 ng ml⁻¹ solution of NIST SRM U500.

Uranium isotope ratio determination by ICP-MS is free from spectral interference, however, Russ and Bazan [9] found background correction essential for accurate measurement because of the low abundance of the ²³⁴U and ²³⁵U isotopes. They used the average count on 233, 240 and 241 m/z for subtraction of the background from each
of the U isotopes. Russ and Bazan [9] also found the large difference in the abundance of the U isotopes to cause the U isotope ratios to vary as detector dead time. Hence, precise evaluation of the dead time was necessary to facilitate accurate measurement. Russ and Bazan [9] and Pin et al. [61] observed instrumental mass bias factors of around 2% u⁻¹, which were corrected for by use of NIST SRM U005 as a calibration standard.

2.2.17 Zinc
Zinc has five stable isotopes (⁶⁴Zn, 48.89%; ⁶⁶Zn, 27.81%; ⁶⁷Zn, 4.11%; ⁶⁸Zn, 18.56%; ⁷⁰Zn, 0.62%) All five Zn isotopes are invariant in nature, however, isotopically enriched Zn is available for use in stable isotope tracer and dilution studies. Zn bioavailability may be studied by the use of stable-Zn tracers. Interest in the bioavailability of Zn is a result of the dependence of Zn absorption upon physiological state and the presence of potentiating or inhibiting foods in the intestine [64].

Radio-Zn tracers have been widely used, however, the direct comparison of Zn absorption from different dietary sources is prevented by the existence of only one Zn radioisotope with a convenient radioactive half-life [64]. It is possible to spike two or more foodstuffs, each with a different stable-Zn tracer, for direct comparison of their influence upon Zn absorption. Serfass et al. [64] determined the ⁶⁷Zn:⁶⁸Zn and ⁷⁰Zn:⁶⁸Zn ratios in faecal matter. Similarly, Ting and Janghorbani [15] used the ⁷⁰Zn isotope as an in vivo tracer, the ⁶⁷Zn isotope as an in vitro tracer and the ⁶⁸Zn isotope as a reference. The ⁶⁷Zn and ⁷⁰Zn isotopes are most appropriate for use as tracers because of their low natural abundances.

The measurement precision for Zn isotope ratio determination by ICP-MS has typically been in the range 0.3 to 1.0% RSD [15,64-67]. For example, Patterson et al. [67] realised a measurement precision of between 0.3 and 0.8% RSD for determination of the ⁶⁶Zn:⁶⁷Zn, ⁶⁸Zn:⁶⁷Zn and ⁷⁰Zn:⁶⁷Zn ratios for natural abundance Zn in the concentration range 200 to 600 ng ml⁻¹. The precision resulting from counting statistics accounted for 0.1 to 0.5% RSD. Serfass et al. [64] found increase of the integration time and decrease of the dwell time to
improve precision, a 2 s integration time and 50 ms dwell time being optimal.

The influence of spectral interference effects upon the measurement of Zn isotope ratios by ICP-MS has been examined by several workers [15,64-67]. The $^{67}$Zn, $^{68}$Zn and $^{70}$Zn isotopes have generally been observed to be free from spectral interferences. Although the $^{70}$Zn isotope suffers from an isobaric overlap with $^{70}$Ge, this is not generally problematic as Ge is not found at significant concentrations in biological materials. The isobaric overlap of $^{64}$Ni with $^{64}$Zn is more problematic and may necessitate chemical separation of Zn from Ni, if the $^{64}$Zn isotope is to be utilised. As the $^{64}$Zn isotope is the most abundant of the Zn isotopes it is not generally used in isotope tracer studies. Polyatomic interference from $^{35}$Cl$^{35}$Cl$^+$ on $^{70}$Zn may severely hinder accurate Zn isotope ratio determination in matrices such as urine and blood, which contain high concentrations of Cl [64]. Matrix separation of Zn from Cl containing matrices has been performed by solvent extraction with dithiocarbamates [15,64-67].

Long term instrumental drift in Zn isotope ratio measurements made by ICP-MS have been observed by several workers [64,65]. To retain accuracy it is necessary to monitor the instrumental mass bias throughout analysis, normally a natural Zn standard has been used for mass bias correction. A more direct approach to mass bias correction was proposed by Roehl et al. [68], based upon the use of Ga as a monitor of change in mass bias factors for Zn isotope ratios, as reported by Amarasingwardena et al. [65]. Roehl et al. [68] used linear regression to evaluate the relationship between changes in the $^{71}$Ga $^{69}$Ga ratio and the Zn isotope ratios. The coefficients of regression were then used to customise the mass bias correction equations for each batch of analyses.
References


CHAPTER THREE
INSTRUMENTATION AND CALIBRATION PROCEDURE

3.1 INTRODUCTION

The instrumentation used in Chapters 4 through 7 is described in this chapter. Experimentation has been undertaken at four sites using four somewhat different ICP-MS instruments. However, the majority of research has been undertaken using the instrument described in Section 3.2.1. The use of any of the other ICP-MS instruments is noted in the procedure for the relevant experiment. In addition, the methods used for tuning and calibration are described.

3.2 ICP-MS INSTRUMENTATION

3.2.1 Second UK ICP-MS instrument
The ICP used employed a 27 MHz crystal-controlled supply (Plasma-Therm, Kresson, NJ, USA, Model 2500F) with an automatic impedance-matching network. A glass concentric nebuliser (J.E Meinhard, Santa Cruz, CA, USA, Model TR-30-CZ), peristaltic pump (Gilson, Villiers Le Bel, France, Model Minipuls 2) and water-cooled single pass spray chamber, of the Surrey design [1], were used for sample introduction. The plasma source was centred about the sampling orifice, which was located approximately 12 mm a.l c.

The quadrupole mass analyser was a VG Micromass (Altrincham, Cheshire, UK) Model 12-12S, fitted within the vacuum system of the second UK ICP-MS instrument, as has been described by Date and Hutchinson [2]. A modified lens stack (FI Elemental, Winsford, Cheshire, UK) was used for ion focusing. Reduction of the overall length of the lens stack was necessary to accommodate it in the vacuum housing (Figure 3.1). Lenses L3 and L4, which are at the rear of the lens stack, were reduced in length by 5 and 3 mm, respectively. The primary function of lenses L3 and L4 is to prevent over focusing of the ion beam following its passage through the differential amplifier. The detector was a continuous dynode channel electron multiplier (Galileo, Sturbridge, MA, USA, Model 4870 V), positioned at right angles to the instrument axis.
Generally the same operating conditions were used throughout experimentation, these are summarised in Table 3.1.

Figure 3.1. Cross-section of vacuum housing and modified lens stack

A = quadrupole mass analyser housing, B = rear of lens stack (L3 and L4), C = front of lens stack (collector, L1 and L2), D = second vacuum stage chamber, E = first vacuum stage chamber

The length of the lens stack behind the differential aperture is normally 48 mm, 10 mm longer than the distance available in the mass spectrometer housing. To make the lens stack fit into the space available, L3 was reduced by 5 mm and L4 by 3 mm.
Table 3.1 · Operating conditions of the 2nd UK ICP-MS instrument

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Incident power</td>
<td>1300 W</td>
</tr>
<tr>
<td>Reflected power</td>
<td>&lt; 5 W</td>
</tr>
<tr>
<td>Plasma gas flow rate</td>
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</tr>
<tr>
<td>Auxiliary gas flow rate</td>
<td>0.01 l min⁻¹</td>
</tr>
<tr>
<td>Nebuliser gas flow rate</td>
<td>0.75 l min⁻¹</td>
</tr>
<tr>
<td>Solution uptake rate</td>
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</tr>
<tr>
<td>Sampling distance</td>
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</tr>
<tr>
<td>1st vacuum stage pressure</td>
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</tr>
<tr>
<td>2nd vacuum stage pressure</td>
<td>1 x 10⁻⁴ mbar</td>
</tr>
<tr>
<td>3rd vacuum stage pressure</td>
<td>5 x 10⁻⁶ mbar</td>
</tr>
<tr>
<td>Extraction potential</td>
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</tr>
<tr>
<td>Collector potential</td>
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</tr>
<tr>
<td>L1 potential</td>
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</tr>
<tr>
<td>L2 potential</td>
<td>-51 V</td>
</tr>
<tr>
<td>L3 potential</td>
<td>-56 V</td>
</tr>
<tr>
<td>L4 potential</td>
<td>-57 V</td>
</tr>
<tr>
<td>Quadrupole mass analyser resolution*</td>
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<tr>
<td>Detector supply voltage</td>
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</tr>
<tr>
<td>Discriminator level</td>
<td>64 mV</td>
</tr>
</tbody>
</table>

* at 10 % of the peak height

3.2.2 PlasmaQuad ICP-MS instruments
Three generations of VG PlasmaQuad instruments (FI Elemental, Winsford, Cheshire, UK) have been used for short periods of experimentation. A VG PlasmaQuad I was used for Zn isotope ratio determination, a VG PlasmaQuad II for some of the work on Ag isotope ratios and a VG PlasmaQuad II+ for B isotope ratio determination. These instruments are loosely based upon the ICP-MS instrument described in Section 3.2.1, however, the construction and parts have undergone periodic upgrading. These upgrades have enhanced the efficiency of ion transmission, the VG PlasmaQuad II and
II⁺ instruments routinely have a sensitivity of 30 x 10^6 cps per mg l⁻¹, compared to 2 x 10^6 cps per mg l⁻¹ for the second UK ICP-MS instrument.

3.3 MEASUREMENT ELECTRONICS

A schematic diagram of the instrumentation utilised in the collection of ion current signals for calculation of noise power spectra is shown in Figure 3.2. The ion current from the electron multiplier (Galileo 4780V) was amplified using an operational amplifier current follower, with variable gain, which was built in-house, by the electronics workshop. Amplified signals were low pass filtered using in-house constructed Butterworth filters. These were constructed to comply with the Nyquist sampling theorem, which states that the signal being collected should be band-limited to frequencies below half the sampling rate to prevent aliasing. A 5th order Butterworth filter with a -3 dB point at 400 Hz was used for a sampling rate of 1 KHz. Similarly, a 2nd order Butterworth filter with a -3 dB point at 10 Hz was used for a sampling rate of 20 Hz. A sample and hold amplifier (Metrabyte, Taunton, MA, USA, SSH-4) and 12-bit analogue to digital (A/D) converter (Metrabyte DAS20) were used to digitise the analogue signal for processing by an IBM compatible computer, using ASYST 3.1 software (Keithley, Rochester, NY, USA).

3.4 CHEMICALS

The high purity water used throughout was produced by passing demineralised water through a laboratory-reagent grade water system (Liquipure, Bicester, Oxfordshire, UK), operated at 18 MΩ. The purified water is referred to as 18 MΩ water in this work.

All standard solutions used in this work, with the exception of Ag, were 10 000 µg ml⁻¹ Specpure ICP solutions (Johnson Matthey, Royston, Herts, UK). The Ag standard solution was 1000 µg ml⁻¹ Spectrosol solution (BDH Ltd., Poole, Dorset, UK). The acids used were: nitric and hydrofluoric acids, Aristar (BDH Ltd.) and nitric acid, low in Pb for foodstuffs analysis (BDH Ltd.).
The reference materials used were: NIST SRM 981, natural lead; NIST SRM 987, strontium carbonate and NIST SRM 951, boric acid (Promochem Ltd, Welwyn Garden City, Herts, UK).

Working solutions of reference materials were prepared with the aid of polypropylene beakers and volumetric flasks (Analytical Supplies Ltd., Little Easton, Derbyshire, UK). All solutions were stored in polypropylene bottles (Analytical Supplies Ltd.).

3.5 CALIBRATION PROCEDURE

3.5.1 Optimisation
Optimisation was performed following a warm-up period of approximately 30 min, with the aid of a tune solution, consisting of 50 ng ml⁻¹ of In, Ce and U in 1 % HNO₃. The sampling distance (distance
above load coil), the nebuliser gas flow rate and then lens stack potentials were tuned, to provide maximum signal response at 115 m/z for $^{115}$In. Generally, a signal response of 50,000 to 100,000 cps was obtained for 50 ng ml$^{-1}$ of In. If the maximum attainable signal response was below 50,000 cps, then the peristaltic pump tubing, nebuliser, spray chamber, ICP torch or cones normally required maintenance.

To complete optimisation, the background signal at 225 m/z and the degree of formation of oxide and doubly charged species were inspected. These were deemed to be acceptable if:

(i) the background count at 225 m/z was below 50 cps,
(ii) the signal response from $^{140}$Ce$^{16}$O$^{+}$ at 156 m/z, was less than 3 % of the signal response at 140 m/z for $^{140}$Ce$^{+}$;
(iii) the signal response from $^{238}$U$^{++}$ at 119 m/z, was less than 2 % of the signal response at 238 m/z for $^{238}$U$^{+}$.

If re-tuning was necessary to meet these criteria, it normally involved adjustment of the nebuliser gas flow rate or the potentials applied to the extraction and collector lenses.

3.5.2 Quadrupole mass analyser resolution
The resolution of the quadrupole mass analyser was inspected on a weekly basis. Resolution was measured for a prominent isotope of the element being studied at the time. A 60 s scan, across 512 channels was performed, with approximately 100 channels being assigned to each u. The resolution was calculated as the peak width at 10 % of the peak height.

3.5.3 Mass scale and mass response calibration
Ross and Heifte [3] proposed the elements used for study of mass-dependent matrix-interference effects should be selected such that:

(i) there is an equal mass difference between each adjacent analyte pair;
(ii) each element has a major isotope with a natural abundance of above 50 %;
(iii) no major isotope suffers from spectral overlap from background ions;
(iv) each element has an ionisation efficiency of 90 % or more.

These criteria are equally relevant to the set of elements used for mass scale and mass response calibration. The multi-element calibration standard used in this work consisted of 50 ng ml$^{-1}$ of Be, Mg, Co, In, Ce, Pb and U in 1 % HNO$_3$. Beryllium and Co are mono-isotopic, while, Mg, In, Ce, Pb and U all have isotopes with a relative abundance above 50 %. Only Be, which has been calculated to have an ionisation efficiency of 75 % [4], does not satisfy (iv), above. Finally, there are no background ions, for a HNO$_3$ matrix, which overlap with the major isotopes of these elements.

Mass scale calibration is necessary to define the relationship between the digital to analogue (D/A) channel address and mass. Calibration of the mass scale over the entire mass range was performed using the multi-element calibration standard, following an interval of at least 1 h after light-up to allow the ICP-MS instrument to equilibrate.

Mass response calibration is necessary to facilitate semi-quantitative analysis, as it provides a method for prediction of mass response factors. In this work, mass response calibration was performed using the multi-element calibration standard to determine the curvature of the mass response curve and hence identify the extent of instrumental mass bias. If excessive mass bias or non-standard mass response curves were observed, the lens stack was re-tuned to rectify these effects, prior to analysis.
References
CHAPTER FOUR
NOISE SPECTRAL ANALYSIS

4.1 INTRODUCTION

4.1.1 Noise spectra
To gain a fundamental understanding of the noise characteristics of an instrument system requires knowledge of its noise spectrum. The noise spectrum may identify or help in identifying the types, origins and contributions of the noise components. In the frequency domain, noise may be one of three distinct types:

(i) white noise, which is distributed evenly across all frequencies;
(ii) 1/f noise, also referred to as flicker noise, which occurs at low frequencies at an intensity inversely proportional to the frequency raised to the power $n$, where $0 < n < 1$;
(iii) interference noise occurring at discrete frequencies characteristic of system components.

4.1.2 A review of noise spectral analysis in ICP
A large number of studies have utilised noise spectra for signals from ICP-AES and ICP-MS instruments to gain an understanding of the frequency characteristics and origin of instrumental noise [1-19]. Fundamental investigations of noise spectra in ICP-AES [1-4] have identified three types of excess noise:

(i) low frequency and 1/f noise, attributed to sample introduction processes;
(ii) discrete noise at frequencies associated with the a.c. line frequency and its harmonics;
(iii) discrete frequency noise in the audible region associated with the ICP.

Measurement of noise spectra in ICP-MS [5-10] has shown excess noise types to be essentially similar to those observed for ICP-AES. However, the influence of operational parameters upon the frequency and magnitude of excess noise components in ICP-MS has been found to differ somewhat from those characteristic of ICP-AES [5,6]. Crain et
al [6] have suggested that these differences are due to changes in plasma gas dynamics caused by interaction between the plasma and the sampling interface.

The influence of incident power, plasma gas flow rate and observation height upon the position and intensity of noise components in noise spectra have been investigated for ICP-AES and ICP-MS instruments [1,2,4-6,8,9,11-16]. In both instrumental systems, the frequency of the audible noise peak increases with increasing incident power, and is accompanied by variation in magnitude and bandwidth [2,4-6,8,9,15]. Goudzwaard and de Loos-Vollebregt [4] have also shown 1/f noise in ICP-AES to increase in magnitude and bandwidth with increasing incident power. Raising the plasma gas flow rate has a similar influence to that of incident power on the audible noise peak, however, above a critical flow its frequency decreases as the flow rate continues to increase, while variations in magnitude and bandwidth are less profound [2,4-6,8,9,15]. The effect of observation height upon the position and intensity of noise components has been found to be dependent upon the instrument system [5,6]. In ICP-AES, the magnitude of excess noise components is dependent upon observation height, with maximum excess noise occurring at the optimum observation height [4]. A similar effect is observed in ICP-MS, however, in addition, the audible noise peak shifts to lower frequencies as the sampling depth is decreased [5,6].

Several studies have been undertaken with a view to determining the origin of the phenomena causing audible noise, and its frequency shift with variation in ICP operating conditions [2,5,9,11-14,16]. Belchamber and Horlick [2], having obtained simultaneous emission signals from monochromators positioned at right angles, concluded that the audible noise was the result of rotation of the plasma discharge. Davies and co-workers [11,12,20,21] extensively studied noise reduction resulting from the use of extended laminar flow torches, which were found to eliminate the audible noise attributed to plasma rotation. However, Winge et al. [13] have shown audible noise in their plasma to be due to radial rather than rotational fluctuation. Use of high-speed motion picture photography, when combined with noise spectral analysis, prove that audible noise was due to a fluid mechanic
phenomenon involving axisymmetric oscillation of the plasma as the plasma gas flowed from the torch into the surrounding static air. The axisymmetric oscillations developed into vortex rings with increasing height above the load coil.

Use of extended torches, chimneys and linear flow torches have been investigated as methods for reduction of audible noise associated with vortex ring formation in ICP-AES [14,16,17]. Montaser et al. [17] concluded that extended torches of laminar and tangential flow designs removed audible noise from ICP-AES, and gave comparable white noise levels and detection limits. Easley et al. [14] reported that the use of a chimney, positioned over the ICP discharge, also reduced noise associated with vortex ring formation. However, the notch in the chimney, which provided a clear optical path to the monochromator, was found to generate a noise peak of lower frequency and magnitude than that of the previously observed audible noise peak.

Extended torches and chimneys are unsuitable for the reduction of audible noise in ICP-MS, as a consequence of the deeper sampling position, however, Ince et al. [9] found the use of a bonnet to be an effective alternative. The bonnet device was fitted to the end of the ICP torch to sheath the discharge from the surrounding atmosphere, and hence, reduce audible noise. With the bonnet device in place, the magnitude of the audible noise peak was reduced to below the white noise level of approximately -50 dB [24].

In both ICP-AES and ICP-MS systems, the major source of signal instability has been illustrated as often being the result of sample introduction processes [2,6]. Belchamber and Horlick [2] utilised spectral analysis to assess the noise characteristics of cross-flow, ultrasonic and Meinhard concentric nebulisers, concluding that the latter gave the weakest 1/f noise component. More recent studies have compared the noise spectra for GMK Babington-type [10], Jarrell-Ash high-solids [22], and direct injection nebulisers [23] with that of the Meinhard concentric nebuliser. These were found to produce equivalent, if not less 1/f noise than the Meinhard concentric nebuliser. The main source of low frequency, discrete frequency noise, due to sample introduction, using concentric and cross-flow nebulisers has
been linked with pulsations induced by individual rollers, or revolution of the roller wheel of the peristaltic pump [4,5,23]. Luan et al. [23] have studied the noise characteristics of aerosols produced by nebulisation with the aid of a variety of pumps and spray chambers. They found low frequency, interference noise could be eliminated by replacement of the peristaltic pump with a dual piston pump, designed for use in liquid chromatography. In addition, the use of a double-pass spray chamber was found to be preferential to a single-pass spray chamber, as it was observed to help reduce the white noise level. In a recent study, Pollmann et al. [10] found cooling of the spray chamber from 25 to 5 °C also reduced the white noise level.

4.2 LOW FREQUENCY RANGE NOISE SPECTRA

4.2.1 Introduction
Hobbs et al. [25] have conclusively demonstrated that the majority of excess noise occurring at low frequencies in ICP-AES is associated with nebulisation and vaporisation processes. The origin of drift, or very low frequency noise, in ICP has been classified by Carre et al [26] as arising from:

(i) change in the transfer of energy from the plasma to the sample,
(ii) variation in the efficiency of the sample production and transportation

Change in the transfer of energy may occur as a consequence of variation in the incident power or gas flow rates. Change in the efficiency of sample introduction may be induced by irregularity in the nebuliser gas flow rate or solution uptake rate, partial nebuliser blockage, or fluctuation in the spray chamber or solution temperature.

Furuta et al. [5] have suggested it is reasonable to assume that noise in the low frequency spectral region is alike in ICP-AES and ICP-MS. Although a direct comparison has not been made, the low frequency noise spectra obtained by Furuta et al. [5], among others, have indeed been characteristic of those observed in ICP-AES.
4.2.2 Collection and calculation of low frequency range noise spectra
The collection of data was undertaken following an interval of at least 1 h after light-up of the plasma to allow the ICP-MS instrument to equilibrate. Noise spectra were collected in the range 0 to 5 Hz, using the instrumentation described in Section 3.3. The gain of the operational amplifier current follower was set at 320,000 and the sample and hold amplifier was configured to accept signals in the range ±5 V. The ASYST 3.1 programs generated for the collection of ion current information and the calculation of noise spectra in the range 0 to 5 Hz are given in the Appendix. Each data set consisted of 1024 data points, acquired at a sampling rate of 20 Hz, providing noise spectra with a frequency resolution of 0.02 Hz. Noise spectra were calculated by Fourier transformation, taking the sum of the square of the real and imaginary components of the transformed data, and signal averaging eight data sets in the frequency domain. The resulting noise spectra were translated to a spreadsheet software package for presentation.

4.2.3 Low frequency range noise spectra for analyte ions
Noise spectra obtained for ion current monitoring of the $^{208}$Pb$^+$ signal for nebulisation of a solution containing 100 ng ml$^{-1}$ of Pb, at various solution uptake rates are shown in Figure 4.1. A 1/f noise component extending to approximately 1 Hz was observed, similar to that found in ICP-AES for use of a glass concentric nebuliser [2]. Variation of the solution uptake rate was found to cause a shift in the frequency at which discrete noise peaks occurred, as had been observed previously by Goudzwaard and de Loos-Vollebregt [4]. The frequencies of the discrete noise peaks were found to closely match the rate at which the individual rollers on the pump head of the peristaltic pump squeezed the pump tubing, as shown in Table 4.1.

<table>
<thead>
<tr>
<th>Frequency of pump rotation (Hz)</th>
<th>Noise frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>1.35</td>
<td>1.62</td>
</tr>
<tr>
<td>2.62</td>
<td>2.46</td>
</tr>
<tr>
<td>3.27</td>
<td>3.30</td>
</tr>
</tbody>
</table>

Table 4.1: Variation in low frequency noise with change in peristaltic pump rate
Figure 4.1: Noise spectra obtained for ion current monitoring of $^{208}$Pb$^+$ at various solution uptake rates.
It has been widely reported that the magnitude of pump related interference peaks are dependent upon the diameter of the pump tubing and the rate of rotation of the pump head. Use of small bore tubing and a pump speed of above 2 Hz are known to minimise pump related noise. Fluctuation in the $^{208}\text{Pb}^+$ signal intensity obtained from nebulisation of 100 ng ml$^{-1}$ of Pb observed over a 4 s period, at a solution uptake rate of 0.24 ml min$^{-1}$, is shown in Figure 4.2 to demonstrate the amplitude of pump noise under non-ideal conditions.

4.2.4 Low frequency range noise spectra for polyatomic ions

Figure 4.3 shows noise spectra obtained over the frequency range 0 to 5 Hz for ion current monitoring of the $^{40}\text{Ar}^{40}\text{Ar}^+$ signal for free-aspiration and pumped delivery of 18 MΩ water to the nebuliser. These noise spectra show a white noise level of circa -65 dB, approximately 10 dB above that observed for monitoring of the $^{208}\text{Pb}^+$ ion current obtained from a solution containing 100 ng ml$^{-1}$ of Pb (Figure 4.1). As the intensity of the $^{40}\text{Ar}^{40}\text{Ar}^+$ ion current was around 20 times larger than that of the $^{208}\text{Pb}^+$ ion current, the change observed in noise amplitude may be indicative of the white noise being shot noise limited. Shot noise is proportional to the square root of the signal strength.

Discrete noise peaks were observed at 2.46 and 4.92 Hz, the latter being a harmonic of the former, in the noise spectrum of the $^{40}\text{Ar}^{40}\text{Ar}^+$ ion current, for pumped delivery of 18 MΩ water (Figure 4.3). Although the $^{40}\text{Ar}^{40}\text{Ar}^+$ species could not have been modulated directly by rotation of rollers on the pump head of the peristaltic pump, these noise peaks are clearly present. Furuta et al. [5] considered similar observations to be the result of pulsation in the plasma solvent loading. It is also conceivable that pulsation in the solution uptake rate, instilled by the peristaltic pump, causes modulation of species being sampled to occur by variation in the pressure differential, between the sampled region of the plasma and the first vacuum stage, brought about by changing plasma conditions.

Discrete noise peaks were absent from the noise spectrum for free-aspirated solution uptake, however, the $1/f$ noise component was observed to have increased in magnitude (Figure 4.3). This may be
Figure 4.2: Modulation of the $^{208}$Pb signal by pump related noise for a solution uptake rate of 0.24 ml min$^{-1}$. 
Figure 4.3: Noise spectra obtained for ion current monitoring of $^{40}\text{Ar}^{40}\text{Ar}^+$ for free-aspiration and pumped delivery of deionised water.
explained by fluctuation in solution uptake rate during free-aspiration which is eliminated by the use of a peristaltic pump.

4.3 AUDIBLE FREQUENCY RANGE NOISE SPECTRA

4.3.1 Collection and calculation of audible frequency range noise spectra
Audible noise spectra were calculated for both ion current and pulse counting data. The collection of data was undertaken for ion current monitoring using the instrumentation described in Section 3.3 and for pulse counting by single ion monitoring. In both instances, data collection was undertaken following an interval of at least 1 h after light-up to allow the instrument to equilibrate.

The ion current information was gathered using the ASYST 3.1 program given in the Appendix. The gain of the operational amplifier current follower was set at 117,000 and the sample and hold amplifier was configured to accept signals in the range ± 0.5 V. Each data set consisted of 1024 data points, acquired at a sampling rate of 1 kHz to provide noise spectra with a frequency resolution of 1.0 Hz. Twenty-four data sets were averaged in the frequency domain to give noise spectra in the range 0 to 400 Hz.

The pulse counting data was acquired in the multi-channel analyser using single ion monitoring, with a dwell time per channel of 640 μs. The dwell time acted as a low pass and anti-aliasing filter having a high frequency cut-off at the frequency given by twice the inverse of the dwell time. A dwell time of 640 μs provided a sampling rate of 1562 Hz and a cut-off frequency of 781 Hz. Each data set consisted of 4096 data points to provide spectra with a frequency resolution of 0.4 Hz. Signal averaging of twenty data sets was undertaken in the frequency domain.

4.3.2 Audible frequency range noise spectra for ion current monitoring
A typical noise spectrum in the range 0 to 400 Hz obtained for ion current monitoring of the $^{40}\text{Ar}^{40}\text{Ar}^+$ signal, for nebulisation of 18 MΩ water, is given in Figure 4.4. Similar noise spectra were obtained for
Figure 4.4: Noise power spectrum in the frequency range 0-400 Hz obtained for ion current monitoring of $^{40}$Ar$^{40}$Ar$^+$. 
ion current monitoring of the $^{208}$Pb$^+$ signal for a solution containing 1000 ng ml$^{-1}$ of Pb. The interference noise components occurring at 100, 150, 200 and 250 Hz are all considered to be related to the interference noise at 50 Hz. If these noise components were simply harmonics of the 50 Hz a.c. line noise then their intensities would fall-off rapidly with increasing harmonic number. However, the 100 Hz noise component is clearly the dominant of the noise components related to the 50 Hz a.c. line noise.

The prominence of the 100 Hz noise component may be explained by the use of a 3 phase power supply to the r.f. generator, which provides the ICP with energy. In principle, a 3 phase power supply and balanced full wave bridge rectifier should only give rise to interference noise at twice (100 Hz) and higher harmonics of the a.c. line frequency [9]. If it is presumed that interference noise peaks occurring at the a.c. line frequency and its harmonics are predominantly the result of signal modulation in the plasma, the principle interference noise peak would occur at 100 Hz.

Goudzwaard and de Loos-Vollebregt [4] found that, in ICP-AES, the noise intensity of components occurring at 100 and 200 Hz were proportional to the square of the analyte concentration, while the noise intensity of those occurring at 50, 150 and 250 Hz were independent of analyte concentration. Their observation may suggest that the 100 and 200 Hz noise components principally arise from signal modulation in the plasma, while the 50, 150 and 250 Hz noise components are largely due to pick-up of 50 Hz a.c. line noise in wiring and circuitry.

The $1/f$ noise component shown in Figure 4.4, extends to a higher frequency than those found in Figures 4.1. and 4.3. The difference in the rate at which the $1/f$ noise components decay is likely to be a consequence of the period of time associated with collection of the data sets. The collection of each data set required approximately 51 s for the low frequency noise spectra and 1 s for the audible frequency noise spectra. As $1/f$ noise, or flicker noise, is caused by instrumental drift, and as it is likely that the drift observed over 1 s and 51 s will differ, then the rate of decay of the $1/f$ noise component will also change.
The discrete noise component occurring at 324 Hz in Figure 4.4 is due to audible noise arising from the ICP discharge. The origin of audible noise has been proposed as being derived from the rotation of the discharge as a consequence of non-linear flow of plasma gas [2], and also, the passage of vortex rings down the central axis of the ICP discharge due to the flow of plasma gas into the surrounding static air [13]. The dependence of the frequency of audible noise upon plasma operating conditions is described in Section 4.4.1.

4.3.3 Audible frequency range noise spectra for pulse counting
Generally, noise spectra for ICP-MS instruments have been calculated from ion current signals obtained at the electron multiplier, however, Koperdraad [8] obtained noise spectra from pulse counting data, collected in the multi-channel analyser using single ion monitoring. Noise spectra derived from the collection of data in the multi-channel analyser have the benefit of including instrumental noise arising within the data acquisition hardware (see Section 4.5). In addition, the frequency range investigated could be extended beyond 400 Hz.

A noise spectrum in the frequency range 0 to 780 Hz obtained for nebulisation of 1000 ng ml\(^{-1}\) of Pb by single ion monitoring at 208 m/z in the pulse counting mode, is given in Figure 4.5. The collection of repetitive scans requires the transferral of individual scans to disk, causing a delay of several seconds between scans and therefore preventing continuous collection. These delays may have an adverse effect upon the accuracy of noise spectra if the noise characteristics of the instrument were to change between scans.

The excess noise components occurring at 475, 525 and 575 Hz in Figure 4.5 are unique to this study. It is likely that the noise components at 475 and 575 are the lower and upper sidebands of the 525 Hz noise component. That is, the a.c. line frequency (50 Hz) has been amplitude modulated on a carrier with a frequency of 525 Hz. The most probable source of this modulated frequency spectrum is the rotary pump in the 1st vacuum stage [8].

The presence of the audible noise component arising from the ICP discharge is notably absent from Figure 4.5. Although the intensity of
Figure 4.5:

Noise spectrum obtained from pulse counting data for 239Pu.

- Noise Amplitude / dB
- Frequency / Hz

-70 -60 -50 -40 -30

0 100 200 300 400 500 600 700 800
the audio-frequency noise was highly variable, it was generally observed to be less intense in analyte ion signals than for Ar species.

4.4 AUDIO-FREQUENCY NOISE

4.4.1 Variation in the frequency of audible noise

Figure 4.6 shows the influence of incident power upon the audible noise frequency, observed from noise spectra for ion current monitoring of the $^{208}\text{Pb}^+$ signal, for a solution containing 1000 ng ml$^{-1}$ of Pb. Increasing the incident power, within the range 800 to 1300 W, was found to result in displacement of the audible noise to higher frequency. Rise in the frequency of the audible noise with increase in incident power has previously been observed in ICP-AES and ICP-MS instruments [1,2,4-6,11-14].

The dependence of the frequency of audible noise upon the plasma gas flow rate was found, from ion current monitoring of the $^{208}\text{Pb}^+$ signal to be similar to that for the incident power, whereby, increasing the plasma gas flow rate resulted in movement of the audible noise to higher frequency (Figure 4.7). Once again, this trend is common in both ICP-AES and ICP-MS instruments, although Belchamber and Horlick [2] found that for their ICP-AES instrument, the frequency of audible noise decreased with increase in the plasma gas flow rate, for flow rates of above 19 l min$^{-1}$.

As shown in Figure 4.8, variation in the nebuliser gas flow rate, between 0.63 and 0.94 l min$^{-1}$, resulted in no appreciable change in the frequency of audible noise. Similarly, no significant shift in the frequency of audible noise was observed for lateral movement of the ICP discharge about the sampling orifice (see Figure 4.9).

Figure 4.10 shows the influence of the distance separating the load coil and the sampling orifice upon the frequency of audible noise. As has been observed for other ICP-MS instruments [5,6,9], the frequency of audible noise was found to decrease upon increasing the distance between the load coil and the sampling orifice. In ICP-AES, the frequency of the audible noise is reported as being independent of observation height [2,4]. Hence, although the method of development
Figure 4.6: Dependence of the frequency of audible noise upon incident power observed for ion current monitoring of $^{208}\text{Pb}^+$, for a solution containing 1000 ng ml$^{-1}$ of Pb.
Figure 4.7: Dependence of the frequency of audible noise upon plasma gas flow rate observed for ion current monitoring of $^{208}\text{Pb}^+$, for a solution containing 1000 ng ml$^{-1}$ of Pb.
Figure 4.8: Dependence of the frequency of audible noise upon nebuliser gas flow rate observed for ion current monitoring of $^{208}\text{Pb}^+$, for a solution containing 1000 ng ml$^{-1}$ of Pb.
Figure 4.9: Dependence of the frequency of audible noise upon displacement of the plasma from the central axis of the mass spectrometer observed for ion current monitoring of $^{208}\text{Pb}^+$, for a solution containing 1000 ng ml$^{-1}$ of Pb.
Figure 4.10: Dependence of the frequency of audible noise upon observation height observed for ion current monitoring of $^{208}\text{Pb}^+$, for a solution containing 1000 ng ml$^{-1}$ of Pb
of oscillations within the ICP discharge would appear to be the same for both instrument systems, the routes by which signal modulation occurs must differ.

4.4.2 Hypothesis for shift in the frequency of audible noise
If the axisymmetric oscillation of the ICP discharge is assumed to be due to vortex ring formation in the plasma gas flow, as photographed by Winge et al. [10], then it is the rapid changes in the radial dimension of the ICP discharge which act as the carrier waveform in signal modulation. At the sampling orifice, rapid change in the radial dimension of the ICP discharge would be observed as a dilation and contraction, producing a time-dependent oscillation in the density of analyte ions in the sampling region.

It is probable that a relationship exists between the gas flow velocities in the ICP discharge and the rate of vortex ring formation. The rise in the frequency of audible noise with incident power (Figure 4.6) and plasma gas flow rate (Figure 4.7) are considered to be the result of increase in the rate of vortex ring formation. This may be due to increase in the gas velocity in the region of the plasma flame into which static air is being entrained. Indeed, Cicerone and Farnsworth [27] have observed increase in gas velocity to result from rise in incident power and plasma gas flow rate. They postulated that increase in gas velocity was a consequence of the heating and expansion of argon in the central channel of the ICP discharge.

No appreciable change in the frequency of audible noise was observed upon varying the nebuliser gas flow rate (Figure 4.8), suggesting the rate of vortex ring formation remained constant. Somewhat surprisingly, Cicerone and Farnsworth [27] found the gas velocity in the central channel of the ICP discharge to be independent of nebuliser gas flow rate, this they concluded was due to the increased mass flow balancing the reduced gas temperature. Their analysis may imply that the rate of vortex ring formation and thus, the frequency of the audible noise is unchanged by the nebuliser gas flow rate, as has been observed herein.
The similarity of trends in the frequency of audible noise and gas velocity upon parametric variation may imply that the gas velocities in the central channel and in the region in which air entrainment occurs are alike.

Cicerone and Farnsworth [27] observed a rise in gas velocity in the central channel of the ICP discharge upon increasing the observation height from 6 to 15 mm, however, a decrease in the frequency of audible noise was found upon increase of the distance between the load coil and the sampling orifice (Figure 4.10). As is known from noise studies in ICP-AES [2,4], the rate of formation of vortex rings does not alter, probably as no change in gas velocity in the region of the ICP discharge in which they are formed has occurred. Why opposing effects are observed in the frequency of audible noise in ICP-MS and the gas velocity in the central channel in ICP-AES is unknown. However, the presence of the sampling cone and perhaps more importantly the vacuum behind the sampling orifice may cause the velocity profiles for the two instrument systems to differ.

4.5 WHITE NOISE

The RSD of a measured signal can be approximated from the mean noise level in dB (N) by use of Equation 4.1:

\[
\text{RSD} = 10^{N/20} \tag{4.1} [6]
\]

A white noise level of between -60 and -65 dB was observed in audible frequency range noise spectra (Figures 4.4 and 4.5), representing a RSD of 0.06 to 0.1 %.

As mentioned in Section 1.2.5, the random arrival of ions at the electron multiplier causes there to be an uncertainty associated with ion detection, known as the counting statistic, which is equal to the square root of the accumulated count. Hence an accumulated count of 10 000 has an associated counting statistic of 100, representing a RSD of 1 %. The magnitude of the ion signal during collection of audible frequency range noise spectral data was approximately \(2 \times 10^6\) counts s\(^{-1}\) for \(^{40}\text{Ar}^{40}\text{Ar}^+\) and \(1 \times 10^6\) counts s\(^{-1}\) for \(^{208}\text{Pb}^+\) (1000 ng ml\(^{-1}\) of Pb). Each
scan of the $^{40}\text{Ar}^{40}\text{Ar}^+$ ion current signal took 1,048 s, giving an accumulated count of approximately $2 \times 10^6$, while each scan of the $^{208}\text{Pb}^+$ signal intensity in single ion monitoring required 2.621 s, giving an accumulated count of circa $2.6 \times 10^6$. Hence, the counting statistic for the noise spectra shown in Figures 4.4 and 4.5 represents a RSD of between 0.06% and 0.07%. The counting statistic can therefore be considered the major source of white noise under these conditions.

As the white noise levels observed in noise spectra for single ion monitoring (Figure 4.5) and ion current monitoring (Figure 4.4) are equivalent, it may be assumed that the contribution made by the data acquisition hardware to the overall white noise level is small, since no significant change is evident upon its inclusion.

4.6 RELATIVE CONTRIBUTIONS OF VARIOUS NOISE SOURCES

Digital signal processing was utilised to determine the improvement in precision which could be attained by removing the influence of specific frequencies from ion current signals. This was accomplished by computing the Fourier transform, as for generation of noise spectra, and multiplying this by the required digital filter. The inverse Fourier transform was then computed to give the filtered signal. By comparison of the instability in the filtered ion current signal with that in the original ion current signal, the contribution of excess noise, in the frequencies removed by the digital filter, to the overall instability could be assessed.

Calculations were carried out for a number of data sets acquired by ion current monitoring as described in Section 4.3.1. The improvement in precision of the ion current signal, upon filtering all frequencies between 0 and 400 Hz in increments of 2 Hz, have been used to generate a breakdown of the overall instability, by noise type, given in Table 4.2. It should be noted that the contribution of random noise to the overall instability is dependent upon the data collection period, as the major source of random noise, the counting statistic, varies as the inverse of the square root of the period of data collection. The information presented in Table 4.2 is based upon data collected over a
period of 24 s, at a count rate of approximately $2 \times 10^6$ counts s$^{-1}$, for ion current monitoring $^{40}$Ar$^{40}$Ar$^+$. 

Table 4.2: Breakdown of overall instability by noise type

<table>
<thead>
<tr>
<th>Noise Type</th>
<th>Percentage of total instability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random</td>
<td>40</td>
</tr>
<tr>
<td>$1/f$</td>
<td>40</td>
</tr>
<tr>
<td>Frequency dependent</td>
<td>20</td>
</tr>
</tbody>
</table>

4.7 SUMMARY

The noise spectra obtained for ion current monitoring of $^{208}$Pb$^+$ and $^{40}$Ar$^{40}$Ar$^+$ signals were very much characteristic of those found in ICP-AES. However, the excess noise component detected at 525 Hz has not previously been observed in noise spectra for ICP-MS. The influence of plasma operating conditions upon the frequency of the audio-frequency noise peak was found to follow the trends previously reported [5,6]. These trends are considered to result from change in plasma gas velocity within the region of the ICP discharge into which air entrainment occurs.

The overall instability of ion current signals was found to be composed of approximately 40% random noise, 40% $1/f$ noise and 20% frequency dependent noise. In addition, upwards of 60% of the white noise observed in noise spectra was calculated as being due to the counting statistic.
References

CHAPTER FIVE
REDUCTION OF PRECISION LIMITING NOISE

5.1 INTRODUCTION

5.1.1 Comparison of mass spectroscopic techniques
There are a number of mass spectroscopic techniques available for the inorganic analysis of liquid and solid samples, these include thermal ionisation mass spectrometry (TIMS), secondary ion mass spectrometry (SIMS), glow discharge mass spectrometry (GD-MS) and ICP-MS. TIMS is one of the oldest of these techniques, having been developed in the 1920s, yet remains the most precise for isotopic ratio analysis of most elements in the periodic table [1]. A typical TIMS instrument can provide a measurement precision for isotopic ratio analysis of < 0.005 % RSD, being limited only by the counting statistic and detector noise. TIMS is, however, restricted to the analysis of elements with a low ionisation energy. Additionally, the necessity to load the evaporation-ionisation filament with a purified form of the analyte requires extensive sample preparation, causing analysis to be relatively time consuming.

The use of ICP-MS for isotopic ratio analysis has become accepted in applications for which a measurement precision of approximately 0.2 % RSD is adequate, see Chapter 2. However, TIMS remains the technique of choice for measurement of natural variation in isotopic ratios. Improvement in the precision attainable by ICP-MS would provide a time and cost efficient method of isotopic ratio analysis to rival other mass spectroscopic techniques. In this chapter, the acquisition parameters are optimised to maximise measurement precision, based upon the noise spectral information given in Chapter 4.

5.1.2 A review of noise reduction techniques utilised in ICP
A number of relatively simple noise reduction techniques have been applied to elemental analysis by ICP, these include signal averaging, signal integration and correlation or internal standardisation techniques. The signal averaging and signal integration techniques allow the noise frequency bandwidth to be limited. Internal standardisation is performed by division of the analyte signal for samples and standards.
by the corresponding reference signal. The Myers-Tracey correction method [2] is one commonly applied form of internal standardisation.

The influence of the signal integration period upon measurement precision in ICP-AES has been studied by Belchamber and Horlick [3]. They illustrated that increasing the signal integration time from 10 ms to 30 s gave no significant improvement in precision, indeed, signal integration times of below 1 s were found to be desirable. Only if the signal-to-noise ratio of the instrument system is limited by white noise will the measurement precision improve, in proportion to the square root of the signal integration time. Belchamber and Horlick [3] concluded that relatively short signal integration times were advantageous because 1/f noise was limiting the measurement precision. In an earlier publication, Boumans [4] established that flicker noise, which has a 1/f noise profile, was the dominant noise type in ICP-AES, for circumstances where the signal strength was well above the detection limit.

Belchamber and Horlick also assessed the benefits of internal standardisation by study of cross correlation functions [5]. It has long been known that internal standardisation may be effective in compensating for drift in ICP-AES, given that the internal standard closely matches the excitation energy, ionisation energy, atomic weight and volatility of the analyte [6]. Correlation coefficients of > 0.9 were observed by Belchamber and Horlick [5] for correlation of CaII emission with SrII and ScII emissions, giving a 2 fold improvement in the measurement precision for Ca. Use of ArI emission as an internal standard gave a negative correlation, causing Belchamber and Horlick [5] to speculate that flicker noise arose from variation in the flow rate of the nebuliser gas.

Several studies have addressed optimisation of instrumental parameters for precise measurement of isotopic ratios by ICP-MS [7-12]. These studies were discussed within Chapter 2. The study by Ting and Janghorbani [7] is perhaps the most complete. They found many, but not all of the trends observed were the result of reducing the counting statistic, through increasing the analyte sensitivity of the ICP-MS instrument. However, under optimised conditions, the precision of
measured isotopic ratios has at best been 2 to 3 times that imposed by the counting statistic.

Furuta [12] studied the influence of dwell time per channel upon the precision of Pb isotope ratio measurement, in the scanning mode. Reduction of the dwell time, from 0.64 to 0.08 ms, was found to improve the measurement precision via elimination of low frequency noise. It had been hoped that audio-frequency noise could also be smoothed by use of high scan rates. However, it was observed that dwell times of < 0.02 ms caused mass spectra to become distorted. In such instances, it was assumed that the scan rate was beyond the capabilities of the quadrupole mass analyser.

5.2 SELECTION OF ACQUISITION MODE FOR DATA COLLECTION

The first step in reduction of precision limiting noise was to determine which of the acquisition modes was the more efficient for the accumulation of ion counts. The importance of the accumulated count upon the white noise level, and hence, the measurement precision, was discussed in Section 4.5. The percentage of acquisition time spent accumulating counts for one of a pair of isotopes in the scanning and peak jumping modes are compared in Table 5.1. A number of assumptions have had to be made to permit this comparison. In the scanning mode, it has been assumed that the minimum number of acquisition channels (512) and mass range (4.67 u) were selected, and the peak width was 0.8 u. For peak jumping, it has been assumed that 3 acquisition points per peak were utilised. In both acquisition modes a settle time of 10 ms was assumed. The settle time is the interval allowed for mass relocation and stabilisation of the quadrupole mass analyser. A settle time of 10 ms is conventional for VG PlasmaQuad instruments. Typically, the peak jumping mode provides approximately triple the integration time per isotope than the scanning mode, as shown in Table 5.1. Hence peak jumping is the more efficient of the modes for data collection and has been utilised herein, except where stated otherwise.
Table 5.1: Integration time as a percentage of the acquisition time

<table>
<thead>
<tr>
<th>Dwell Time (ms)</th>
<th>Integration Time (%)</th>
<th>Dwell Time (ms)</th>
<th>Integration Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.92</td>
<td>48</td>
<td>0.64</td>
<td>17</td>
</tr>
<tr>
<td>40.96</td>
<td>46</td>
<td>0.32</td>
<td>16</td>
</tr>
<tr>
<td>20.48</td>
<td>43</td>
<td>0.16</td>
<td>15</td>
</tr>
<tr>
<td>10.24</td>
<td>38</td>
<td>0.04</td>
<td>14</td>
</tr>
<tr>
<td>5.12</td>
<td>30</td>
<td>0.02</td>
<td>12</td>
</tr>
</tbody>
</table>

* for 3 acquisition points per isotope and a settle time of 10 ms
** for 512 acquisition channels and a mass range of 4.67 u

5.3 ISOTOPE RATIOING

5.3.1 Method of data collection
The acquisition method used in the peak-jumping mode is determined by a number of software definable parameters. The parameter set utilised was as follows: acquisition points per peak (3), mass step between points (0.05 u); dwell time per point (varied); settle time between peaks (varied); number of sweeps (varied); and number of replicates (10). The use of 3 acquisition points per peak was adopted as this allowed monitoring of the peak profile for the measured isotopes. If the mass calibration was accurate, the second point would have a higher signal intensity than the first and third points, for which the signal intensities would be equivalent. A working solution containing 500 ng ml⁻¹ of Ag in 1 % HNO₃ was used for isotope ratio measurement by the second UK ICP-MS instrument, unless stated otherwise.

5.3.2 The high-pass filtering effect of isotope ratioing
Low frequency noise has been shown to make a significant contribution to the overall instability of the ion current signal (Table 4.1). If the mass peaks of interest are swept rapidly, such that the time separating the measurement of isotopes is much smaller than the period of the low frequency noise, then the signal intensity can be considered unchanged.
and the isotopic ratio unaffected by the low frequency noise. It is the period of time which elapses between the start of measurement of the first isotope and the end of measurement of the second isotope, referred to hereafter as the elapse time, which determines the range of noise frequencies suppressed upon ratioing. The elapse time for an acquisition procedure involving measurement of a single isotopic ratio is given by:

\[
\text{Elapse time} = 2 \times t_d \times n_p + t_s \quad (5.1)
\]

where \( t_d \) is the dwell time per point (s), \( n_p \) is the number of points per peak, and \( t_s \) is the settle time (s).

If noise components with periods longer than twice the elapse time contribute to the overall instability, the measurement precision will benefit from isotope ratioing. That is, the ratioing of isotopes acts as a high-pass filter with a cut-off frequency equivalent to twice the elapse time (Equation 5.2). The cut-off frequencies associated with isotope ratioing, for feasible dwell times of less than 100 ms, are tabulated in Table 5.2

\[
f_{\text{lower cut-off}} = \frac{1}{2((n_t \times t_d \times n_p) + ((n_t - 1)t_s))} \quad (5.2)
\]

where \( n_t \) is the number of isotopes measured.

The improvement in measurement precision for the \(^{107}\text{Ag}:^{109}\text{Ag}\) isotope ratio observed upon decreasing the elapse time, for use of a Meinhard TR-30-CZ glass concentric nebuliser, is shown in Figure 5.1. The elapse time was reduced by decreasing the dwell time per point, of which there were 3 per isotope, from 81.92 to 5.12 ms. The integration time per isotope was held constant at 49.152 s, by increasing the number of sweeps. By retaining a fixed integration time the accumulated count, and thus the counting statistic remained fairly constant.
Figure 5.1. Effect of dwell time on the relative standard deviation (RSD) for measurement of the $^{107}$Ag:$^{109}$Ag isotope ratio. The settle time between peaks was 10 ms.
Table 5.2: Lower cut-off frequency given by isotope ratioing *

<table>
<thead>
<tr>
<th>Dwell time (ms)</th>
<th>Elapse time (s)</th>
<th>Cut-off frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.92</td>
<td>0.502</td>
<td>1</td>
</tr>
<tr>
<td>40.96</td>
<td>0.256</td>
<td>2</td>
</tr>
<tr>
<td>20.48</td>
<td>0.133</td>
<td>4</td>
</tr>
<tr>
<td>10.24</td>
<td>0.071</td>
<td>7</td>
</tr>
<tr>
<td>5.12</td>
<td>0.041</td>
<td>12</td>
</tr>
<tr>
<td>2.56</td>
<td>0.025</td>
<td>20</td>
</tr>
<tr>
<td>1.28</td>
<td>0.018</td>
<td>28</td>
</tr>
</tbody>
</table>

* for 3 points per peak and a settle time of 10 ms

Reducing the elapse time from approximately 500 to 41 ms was beneficial to measurement precision (Figure 5.1), presumably, as the detrimental influences of 1/f and peristaltic pump induced noise were eliminated. Use of dwell times of < 5 ms did not result in any appreciable change in the measurement precision, possibly because the decrease in elapse time obtained was marginal, as a consequence of employing a settle time of 10 ms. It was therefore considered necessary to determine whether reduction of the elapse time, via the settle time, would benefit the measurement precision.

The influence of reducing the settle time upon measurement precision of the 107Ag:109Ag isotope ratio, is shown in Figure 5.2. For a dwell time of 2.56 ms, reducing the settle time, from 10 to 2 ms, gave a marginal improvement in measurement precision. Variation of the settle time in this range was observed to have no significant bearing upon the accuracy of the 107Ag:109Ag isotope ratio. However, reducing the settle time to < 0.5 ms was found to cause a measurable change in the 107Ag:109Ag isotope ratio, suggesting the quadrupole mass analyser had insufficient time to stabilise following mass relocation.

The influence of elapse time upon precision for Ag isotope ratio determination was investigated using a VG PlasmaQuad II instrument, fitted with a cross-flow nebuliser, to ensure the trends shown in Figures 5.1 and 5.2 were not specific to the second UK ICP-MS instrument. As
Figure 5.2: Effect of settle time on the relative standard deviation (RSD) for measurement of the $^{107}$Ag:$^{109}$Ag isotope ratio. The dwell time per channel was 2.56 ms.
the VG PlasmaQuad II instrument had a higher ion efficiency, it was necessary to reduce the concentration of Ag in solution from 500 to 100 ng ml\(^{-1}\). The elapse time was decreased by reducing the dwell time from 81.92 to 1.28 ms. Other acquisition parameters utilised were: acquisition points per peak (3); mass step between points (0.05 u); settle time between peaks (2 ms); and number of replicates (10). The integration time per isotope was held constant at 49.152 s, by increasing the number of sweeps. Reduction of the dwell time, from 81.92 to 5.12 ms, gave improved measurement precision, however, below 5.12 ms no further improvement was observed for use of the cross-flow nebuliser (Figure 5.3). A measurement precision of approximately 0.05 % RSD was obtained for dwell times of 5.12 ms and below, of which 0.035 % RSD could be associated with the counting statistic. Hence, no further improvement in measurement precision was obtained for dwell times of < 5.12 ms, as white noise had become the limiting noise source.

5.4 SIGNAL AVERAGING

5.4.1 Introduction
Signal averaging may be beneficial to enhancement of the measurement precision by reduction of any of the noise types discussed to in Chapter 4. However, to clarify the strategy adopted herein, signal averaging will be considered solely in terms of its effect upon the reduction of non-random noise, while the reduction of random noise will be considered to be governed by the signal integration period (Section 5.5).

Signal averaging of non-random noise is operational at two separate levels during data collection, these are:

(i) the low-pass and anti-aliasing (preventing under-sampled high frequency noise appearing at spurious low frequencies) influence of the dwell time,
(ii) the summation of sweeps in the multi-channel analyser

5.4.2 The low-pass filtering effect of signal averaging
Dwell time acts as a low pass and anti-aliasing filter having a high frequency cut-off at the frequency given by the twice the inverse of the
Figure 5.3: Effect of dwell time on the relative standard deviation (RSD) for measurement of the $^{107}\text{Ag}^{109}\text{Ag}$ isotope ratio using a VG PlasmaQuad II instrument.
dwell time (Equation 5.3). Attainable cut-off frequencies given by Equation 5.3 are tabulated in Table 5.3.

\[ f_{\text{upper cut-off}} = 2 \left( \frac{1}{t_d} \right) \]  

(5.3)

Table 5.3: Upper cut-off frequency given by signal averaging

<table>
<thead>
<tr>
<th>Dwell time (ms)</th>
<th>Cut-off frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.92</td>
<td>24</td>
</tr>
<tr>
<td>40.96</td>
<td>49</td>
</tr>
<tr>
<td>20.48</td>
<td>98</td>
</tr>
<tr>
<td>10.24</td>
<td>195</td>
</tr>
<tr>
<td>5.12</td>
<td>391</td>
</tr>
<tr>
<td>2.56</td>
<td>781</td>
</tr>
<tr>
<td>1.28</td>
<td>1563</td>
</tr>
</tbody>
</table>

It is apparent from Equations 5.2 and 5.3 that the dwell time is crucial in reduction of non-random noise by both isotope ratioming and signal averaging. Decreasing the dwell time is beneficial in reduction of low frequency noise by isotope ratioming, while increasing the dwell time is beneficial in reduction of high frequency noise by signal averaging. Thus, it is necessary to tailor the dwell time to account for the opposing effects it has upon measurement precision. As signal instability due to 1/f noise is generally more detrimental to measurement precision than high frequency noise components (Table 4.2), it was considered best to optimise dwell time for maximum effectiveness in isotope ratioming.

5.4.3 The comb filtering effect of signal averaging

The summation of sweeps is an effective means of noise reduction as isotope peak profiles are added coherently in the multi-channel analyser, while noise components are reduced by smoothing. The frequency of interest in the summation of sweeps is that derived from the time taken between replicate measurements of the same isotope, referred to hereafter as the cycle time. For an acquisition procedure in which two isotopes are monitored, to provide a single isotope ratio, the cycle time is given by.
Cycle time $= 2(t_d \times n_p + t_s)$  \hspace{1cm} (5.4)

The frequency domain representation of the accumulation of sweeps is similar to that given by a comb filter, whose teeth are centred at the averaging frequency and its harmonics [13] The width of the band-pass at these frequencies is given by:

$$f_{\text{bandwidth}} = \frac{0.866}{(n_s \times t_c)} \hspace{1cm} (5.5) [13]$$

where $n_s$ is the number of sweeps and $t_c$ is the cycle time (s)

Noise frequencies outside these band-pass regions are reduced by the accumulation of sweeps. While the cycle time is somewhat fixed by the dwell time required for isotope ratioing, the number of sweeps can be increased to gain a decrease in the bandwidth of the teeth. For example, with a typical cycle time of 81 ms, and 25 sweeps, a tooth bandwidth of 0.44 Hz is obtained, however, for 500 sweeps the tooth bandwidth is reduced to 0.02 Hz. Increasing the number of sweeps accumulated, therefore, improves noise reduction at frequencies in close proximity to the averaging frequency or its harmonics. It is of course necessary to select a cycle time that does not correspond with a prominent noise component, such as that at 50 Hz owing to pick-up from a.c. power lines.

5.5 SIGNAL INTEGRATION PERIOD

If the majority of non-random noise were removed by the combined efforts of isotope ratioing and signal averaging, the counting statistic would most probably be precision limiting. Assuming the counting statistic to be limiting, the signal-to-noise ratio should improve in proportion to the square root of the signal strength [14]. The improvement in precision of the $^{107}\text{Ag}:^{109}\text{Ag}$ isotope ratio observed upon increasing the signal integration period, for an elapse time of 71 ms (dwell time = 10.24 ms), is shown as a log-log plot in Figure 54.
Figure 5.4. Influence of isotope integration time upon signal-to-noise ratio (SNR) for measurement of the $^{107}\text{Ag}:^{109}\text{Ag}$ isotope ratio.
The line representing the counting statistic has a gradient of 0.5, as is characteristic of random noise. The signal-to-noise ratio of the isotope ratio is shown to benefit from improvement in the signal-to-noise ratio of the counting statistic, suggesting the counting statistic is the limiting noise type.

The influence of the signal integration period upon the measurement precision of the $^{107}$Ag signal intensity is shown as a log-log plot in Figure 5.5. The operating parameters were identical to those used for measurement of the Ag isotope ratio. Increasing the signal integration period beyond several seconds is shown to have no appreciable influence upon measurement precision. The RSD of the $^{107}$Ag signal intensity was found to be approximately 0.4% for signal integration periods of 6.14 s and above. The difference in rates of improvement in measurement precision shown in Figures 5.4 and 5.5 clarifies the importance of isotope ratioing in elimination of $1/f$ noise.

The improvement in precision of the $^{107}$Ag:$^{109}$Ag isotope ratio observed upon increasing the analyte concentration, for an elapsed time of approximately 133 ms (dwell time = 20.48 ms), is shown in Figure 5.6. Comparison of the rise in signal-to-noise ratio of the $^{107}$Ag:$^{109}$Ag isotope ratio observed upon increasing the analyte concentration and the integration period (Figure 5.4) shows there to be some divergence from the counting statistic for increase of the integration period. This would suggest that although the counting statistic continues to be the limiting noise source, the magnitude of an additional noise type is increasing as the integration period. It is suggested that the most probable explanation is that an increase in the signal integration period causes the significance of instrumental drift to rise, due to the prolonging of the time taken in acquisition of the 10 replicate integrations, which constitute a determination. That is to say, the RSD for 10 integrations is influenced by change in the observed isotope ratio between integrations, arising from drift occurring incoherently in both isotopes. Hence, while $1/f$ noise at frequencies above that associated with the time taken in acquisition of a single integration (2 min) is minimised, drift occurring within the 20 min period required to undertake 10 replicate integrations is to the detriment of measurement precision.
Figure 5.5: Influence of isotope integration time upon signal-to-noise ratio (SNR) for measurement of $^{107}$Ag.
Figure 5.6: Influence of Ag concentration upon signal-to-noise ratio (SNR) for measurement of the $^{107}$Ag:$^{109}$Ag isotope ratio.
5.6 MEASUREMENT PRECISION FOR OPTIMISED ACQUISITION PARAMETERS

The measurement precision of the $^{107}\text{Ag}^{109}\text{Ag}$ isotope ratio, for 5 consecutive determinations, extending over a 1 h 40 min period, is shown in Figure 5.7. The operating parameters utilised were: dwell time per point (10.24 ms); settle time between peaks (10 ms); and number of sweeps (1600). It was observed that although the error due to the counting statistic remained unchanged, the measured precision oscillated about a mean of approximately 0.05 % RSD. Fluctuation in measurement precision with time was also found using a VG PlasmaQuad II instrument, for a solution of 50 ng ml$^{-1}$ of Ag in 1 % HNO$_3$. In this instance the operating parameters were: dwell time per point (2.56 ms); settle time between peaks (2 ms); and number of sweeps (2582). Five consecutive determinations provided a measurement precision of between 0.059 and 0.077 % RSD (mean = 0.068 % RSD), while the contribution made by the counting statistic was constant at 0.042 % RSD.

Using either ICP-MS instrument a measurement precision approaching 0.05 % RSD was achieved. However, in both instances the measured precision was approximately twice that due to the counting statistic.

5.7 ASSESSMENT OF THE SCANNING MODE

5.7.1 Introduction
The peak jumping mode has been used throughout this chapter as it provides a more efficient method for collection of ion counts than does the scanning mode. However, as use of the scanning mode is commonplace, the noise reduction techniques discussed above are applied to data acquired in the scanning mode in this section.

The parameter set utilised for data collection in the scanning mode was as follows: number of acquisition channels (512); mass range (4.67 u); dwell time per channel (varied); settle time between scans (10 ms); number of scans (varied); width of integration window (0.8 u); number of replicates (10).
Figure 5.7: Variation in the relative standard deviation (RSD) for 5 consecutive determinations of the $^{107}$Ag:$^{109}$Ag isotope ratio.
5.7.2 Isotope ratioing

In the scanning mode, the elapse time between beginning acquisition of the lighter isotope and completing acquisition of the heavier isotope (1) will differ from the elapse time between beginning acquisition of the heavier isotope and completing acquisition of the lighter isotope (2). Assuming that the isotopes of interested are located centrally within the mass range to be scanned, the elapse time in (1) will be shorter than that in (2), because the settle time occurs but once per scan, upon relocation of the quadrupole mass analyser to the initial mass position. As a consequence, the roll-off from the cut-off frequency will be lower and reduction of low frequency noise will be less effective than for an equivalent filter in the peak jumping mode. The reduction of noise will none the less occur from the frequency given by the inverse of twice the elapse time associated with (1):

\[ f_{\text{lower cut-off}} = \frac{1}{2 \left( \frac{m_h - m_l}{m_r} \right) n_c \times t_d} \]  

(5.6)

where 
- \( m_h \) is the highest integrated mass on the heavier isotope (u)
- \( m_l \) is the lowest integrated mass on the lighter isotope (u)
- \( m_r \) is the mass range (u)
- \( n_c \) is the number of acquisition channels

5.7.3 Signal averaging

As was discussed in Section 5.4, signal averaging may result from the low-pass filtering and anti-aliasing influence of the dwell time per channel and the summation of scans in the multi-channel analyser. While dwell times in the peak jumping mode are of the order of 10 ms, for the scanning mode, dwell times are typically < 500 \( \mu \)s. Hence, the upper cut-off frequency in the scanning mode is much higher, e.g. for a dwell time of 80 \( \mu \)s, frequencies up to 25 kHz are unattenuated by signal averaging within each channel.

Reduction of the dwell time, from 640 to 20 \( \mu \)s, was found to be detrimental to the measurement precision of the \(^{107}\text{Ag}^{109}\text{Ag}\) isotope ratio (Figure 5.8). A relatively constant integration time was retained throughout to prevent loss of precision from a reduced accumulated
Figure 5.8: Effect of dwell time on the relative standard deviation (RSD) for measurement of the $^{107}\text{Ag}:{^{109}\text{Ag}}$ isotope ratio in the scanning mode.
count. The rise in the RSD of the $^{107}$Ag:$^{109}$Ag isotope ratio may infer that increase in the band-pass of the filter associated with the dwell time is more influential than is the decrease in the band-pass of the filter associated with isotope ratioing. That is, a greater quantity of instrumental noise was introduced at high frequencies than was removed at low frequencies upon decreasing the dwell time.

The improvement in precision of the $^{107}$Ag:$^{109}$Ag isotope ratio observed upon increasing the analyte concentration, for a dwell time of 80 µs, is shown in Figure 5.9. As before, the line representing the counting statistic has a gradient of 0.5, however, the signal-to-noise ratio of the $^{107}$Ag:$^{109}$Ag isotope ratio increases at a lower rate. Since the line representing the $^{107}$Ag:$^{109}$Ag isotope ratio has a gradient of $< 0.5$, it can be assumed that the counting statistic is not the limiting noise source. Non-random noise is likely to remain unattenuated as a consequence of the width of band-pass of the filter associated with the dwell time.

5.8 SUMMARY

Optimisation of peak jumping acquisition parameters gave improved measurement precision for isotopic analysis. Under optimised conditions, instrumental noise was reduced in a number of ways. Noise at frequencies below 7 Hz was attenuated by isotope ratioing, while noise above 195 Hz was attenuated by signal averaging within each channel. Between these frequencies only discrete frequency noise within a band-pass of 0.01 Hz about the averaging frequency (12.28 Hz) and its harmonics remain unattenuated. Thus, the influence of non-random noise upon the precision of the isotopic ratio was minimal. By contrast, the scanning mode was not found to be as effective in reduction of non-random noise.
Figure 5.9: Influence of Ag concentration upon signal-to-noise ratio (SNR) for measurement of the $^{107}\text{Ag}:^{109}\text{Ag}$ isotope ratio in the scanning mode.
References
CHAPTER SIX
INSTRUMENTAL INSTABILITY AND INACCURACY IN ISOTOPE RATIO MEASUREMENT

6.1 INTRODUCTION

Accurate isotope ratio measurement requires careful consideration and/or correction for the possible influences of analyte concentration, mass calibration, dead time, mass bias and interferences, as will be discussed within this chapter.

The general use of quadrupole mass analysers in ICP-MS fundamentally limits the accuracy and precision to which isotope ratio measurements may be made. Quadrupole mass analysers are specifically designed, and hence perform optimally, in scanning of relatively large mass ranges. As such, they are inherently less stable than magnetic sector mass analysers and less well suited to highly precise and accurate isotopic ratio measurement. However, quadrupole mass analysers are capable of providing sufficient accuracy to be useful in isotopic ratio studies involving most of the metallic elements which show natural variation in isotopic abundance.

Those forms of instrumental instability which show a mass dependence are particularly detrimental to the accuracy and precision of isotopic ratio measurement. Mass dependent instabilities are well known in quadrupole based mass analysers, the most common of these being mass bias. Although mass bias effects have been proposed as arising by a number of mechanisms [1-3], all cause the ion transmission to vary with mass, causing measured isotope ratios to deviate from their nominal value.

6.2 TIME DEPENDENT VARIATION IN SIGNAL INTENSITY

6.2.1 Illustration of signal instability

Data for 50 consecutive integrations, undertaken at 2 mm intervals, in the peak jumping mode for nebulisation of 500 ng ml\(^{-1}\) Ag are shown in Figure 6.1. The operating parameters utilised were: dwell time per point (10.24 ms); settle time between peaks (10 ms); and number of sweeps...
Figure 6.1: Variation in the Ag isotope intensities and the $^{107}$Ag:$^{109}$Ag isotope ratio over 50 consecutive, 2 minute integrations.
For both the $^{107}\text{Ag}$ and $^{109}\text{Ag}$ isotopes, a slow decrease in signal intensity was observed during the first 30 integrations. This variation is reflected, in reverse, in the $^{107}\text{Ag}:^{109}\text{Ag}$ isotope ratio. Although the rate of change in the signal intensities of both Ag isotopes is generally equivalent, there are a few notable exceptions. For example, integrations 23 and 39, for which the value of the isotope ratio is remote from the mean value.

The result of a study of fluctuations in the $^{206}\text{Pb}$ and $^{207}\text{Pb}$ isotope intensities, and their ratio over a 4 h period (2 min per integration) for nebulisation of 1000 ng ml$^{-1}$ of Pb is summarised in Figure 6.2. The operating parameters utilised were as for collection of the data presented in Figure 6.1, with the exception of the settle time, which was reduced to 2 ms. The isotope intensities appear to have undergone a sinusoidal change, during the 4 h period. The influence of this sinusoidal change is reflected in the isotope ratio, causing the precision of the $^{206}\text{Pb}:^{207}\text{Pb}$ isotope ratio, averaged for 12 determinations (1 determination being the average of 10 consecutive integrations) to rise to about 0.12 % RSD. Approximately twice the mean of the measurement precision for individual determinations.

6.2.2 Influence of ICP related instability
Instabilities associated with the ICP ion source may arise from either a change in energy transfer from the plasma to the sample, or variation in the efficiency of the nebulisation and transportation of sample [4]. As these should influence both isotopes coherently, the direct influence of instability arising from the ICP ion source upon the isotope ratio should be rendered insignificant. However, Figures 6.1 and 6.2 imply that drift over a time scale of tens of minutes, and/or intermittent noise have an unequal influence upon the isotopes of interest.

Mennet and Ivaldi [5] have shown that ratioing of measured emission line intensities, obtained by ICP-AES, is effective in cancellation of flicker noise in cases for which a correlation coefficient of $> 0.95$ exists between line intensities. By re-plotting the signal intensity data given in Figure 6.2 as a correlation plot of $^{207}\text{Pb}$ vs. $^{206}\text{Pb}$ (Figure 6.3), a correlation coefficient of 0.9995 was obtained. This high degree of correlation indicates that flicker noise, arising primarily from instability
Figure 6.2: Variation in the $^{206}\text{Pb}$ and $^{207}\text{Pb}$ isotope intensities and the $^{206}\text{Pb} : ^{207}\text{Pb}$ isotope ratio over 120 consecutive, 2 minute integrations.
Figure 6.3: Relationship between the $^{207}$Pb and $^{206}$Pb isotope intensities measured over 120 consecutive, 2 minute integrations.
of the nebuliser and/or the ICP, cancel when measuring the $^{206}$Pb:$^{207}$Pb isotope ratio.

In an attempt to directly differentiate between instabilities arising from the ICP and those associated with the quadrupole mass analyser, a number of consecutive determinations were undertaken, for a fixed mass-to-charge ratio (m/z) at the centre of the $^{206}$Pb isotopic peak, using an identical data acquisition procedure as utilised in measurement of the $^{206}$Pb:$^{207}$Pb isotope ratio. By monitoring the $^{206}$Pb isotope, for nebulisation of 1000 ng ml$^{-1}$ of Pb, in both sets of channel addresses by locking the quadrupole mass analyser in a fixed mass position, noise coherent to both isotopes was passed into the isotope intensities and their ratio as before. However, incoherent noise arising from the mass analyser would have been removed. For a fixed m/z, the RSD of the $^{206}$Pb:$^{207}$Pb isotope ratio was found to be equivalent to the counting statistic, as shown in Table 6.1. Hence, the non-random noise observed in Figures 6.1 and 6.2 appears to have arisen from within the quadrupole mass analyser or its associated ion optics.

Table 6.1. Measurement precision for fixed mass position

<table>
<thead>
<tr>
<th></th>
<th>206Pb:207Pb*</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSD** (%)</td>
<td>0.037</td>
</tr>
<tr>
<td>Counting Statistic (%)</td>
<td>0.035</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>0.003</td>
</tr>
</tbody>
</table>

* for fixed mass of ~206.0 u
** calculated for 1 standard deviation (n = 6)

6.3 MASS SCALE SHIFT

6.3.1 Introduction
The stability of the mass scale calibration (the relationship between measured mass, represented by a 32 bit channel address, and actual mass) is generally limited by the constancy of the d.c. and r.f. potentials applied to the quadrupole rod pairs [6]. The combined influence of the
applied d.c. and r.f. potentials causes the quadrupole to act as a band pass filter. The pass-band (m/z) is determined by the combined amplitude of the r.f. and d.c. potentials and the roll-off (resolution) by their ratio. Scanning of masses is performed by sweeping the r.f. and d.c. potentials, while retaining a constant d.c. to r.f. ratio.

If the combined amplitude of the r.f. and d.c. potentials alters as a result of drift, an unwanted shift in the transmitted mass will result. A change of the order of 0.05% in the amplitude of the r.f. potential, for a m/z of 100, would cause a mass shift of approximately 0.05 u. Daily shift in mass scale calibration for quadrupole mass analysers used in gas analysis is typically ±0.02 u [6], however, ambient temperature change could easily cause additional shift. For the larger quadrupole mass analysers employed in ICP-MS daily shift is less than ±0.10 u, in the absence of temperature effects [7]. As the resolution of the quadrupole mass analyser is inversely proportional to the ratio of the d.c. to r.f. potential, any shift in mass scale calibration caused by change in one, but not both, of the applied potentials would also cause the resolution to change.

The VG 12-12S quadrupole mass analyser, fitted in the second UK ICP-MS instrument, has a valve based supply, which derives the d.c. and r.f. potentials from the same power source, thus, helping to constrain mass shift. However, valve based supplies are more sensitive to temperature change than solid-state supplies. It has previously been found that mass shift can be minimised if room temperature is thermostatically controlled to within ±0.2 °C [8] and the quadrupole rest mass is set slightly below the mass of the lightest isotope in the measurement sequence [9]. If the rest mass were distant from the masses of interest, it is feasible that the measured isotope ratio(s) for the initial integration may be biased, as incorrect mass location can result from ‘jumping’ of large mass distances.

6.3.2 Mass dependence of mass scale shift
A multi-element solution, comprising Be, Mg, Co, In, Ce, Pb and U, each at a concentration of 50 ng ml⁻¹, was used to examine the mass scale calibration, at regular intervals over a period of 5.5 h. Mass scans were undertaken across the mass range 4.7 to 240.3 u, utilising
4096 data acquisition channels, to give a step size of approximately 0.058 u. Clearly, such a low mass resolution is insufficient to allow direct monitoring of mass scale shift. Regression analysis was performed upon each mass scan to obtain a linear relationship between channel number and actual mass. The linear regression equations for each mass scan allowed calculation of the observed mass for each isotope and, hence, the mass shift relative to the initial mass scan.

Figure 6.4 shows the mass shift observed for the $^{59}$Co, $^{115}$In, $^{140}$Ce, $^{208}$Pb and $^{238}$U isotopes over the period of the experiment. It may be seen that the magnitude of the mass shift increased with isotopic mass. To a first approximation, doubling of the isotopic mass doubled the severity of the mass shift, as may be observed by comparison of the $^{59}$Co and $^{140}$Ce or the $^{115}$In and $^{238}$U isotopes. As mass is proportional to the sum of the d.c. and r.f. potentials, the highest applied potential is required for measurement of the $^{238}$U isotope. The electrical components of the power supply will dissipate more heat and be less stable, yet more sensitive to ambient temperature change while generating high potentials. As a consequence, the mass stability at low mass is superior to that at high mass, as shown in Figure 6.4.

### 6.3.3 Influence of mass scale shift on real data

A mass spectrum for lead obtained in the scanning mode across 512 data acquisition channels, for the nebulisation of 100 ng ml$^{-1}$ Pb, is shown in Figure 6.5. The mass range 202.97 to 209.94 u was divided across the 512 channels to provide a step size of approximately 0.013 u. The mass spectrum shown in Figure 6.5 has undergone smoothing using Fourier spectral analysis with Blackman windowing to remove random noise. Prior to Fourier smoothing, the mass peaks were distorted by random noise which prevented accurate location of mass peak centres.

A total of thirty mass scans were acquired at 2 min intervals, the first of these being that shown in Figure 6.5. During the collection of these mass scans, the room temperature rose by several °C. Change in the temperature of air used for cooling of the power supply to the quadrupole mass filter was known to cause mass shift. Increase in air
Figure 6.4 : Influence of isotopic mass upon observed mass shift.
Figure 6.5: Mass spectrum for Pb obtained in the scanning mode across 512 data channels.
Figure 6.6: Auto-correlation function for Fourier smoothed Pb mass spectrum.
temperature resulted in movement of peak centres to higher channel addresses, causing measured masses to lie to the left of peak centres.

The auto-correlation plot of the mass spectrum, given in Figure 6.5, is shown in Figure 6.6. By correlating time delayed mass spectra with the initial mass spectrum (Figure 6.5), cross-correlation functions were calculated. The central region of the auto-correlation plot for \( t = 0 \) and cross-correlation plots for \( t = 20, 40 \) and 60 mins are shown in Figure 6.7. By using a software algorithm to search for the point of maximum amplitude in the correlation plots, the mass displacement could be determined. From Figure 6.8, it may be seen that over a 1 h period, the rate of mass shift was relatively constant, on average being approximately 0.02 u per 10 min.

The mass displacement measured from cross-correlation functions was used to re-adjust the integration windows, such that they cupped the centre of the isotopic peaks. Correcting for mass shift in this manner significantly reduced drift in the value of the \(^{208}\text{Pb}:^{206}\text{Pb} \) isotope ratio, as is shown in Figure 6.9. Prior to correction of mass shift, the observed value of the \(^{208}\text{Pb}:^{206}\text{Pb} \) isotope ratio decreased by almost 10 % over a 1 h period (Figure 6.9). Upon relocation of the integrated regions of the isotopic peaks, to combat mass shift, variation in the observed isotope ratio was controlled to within 1 % of the mean value.

6.3.4 Influence of mass scale shift on mock data
To assess the influence of mass scale shift upon isotope ratio measurement, while retaining a constant mass resolution, the mass spectrum shown in Figure 6.5, was utilised to simulate mass shift. Integration windows of 0.4 u width were positioned about the centres of the \(^{206}\text{Pb} \) and \(^{208}\text{Pb} \) isotopic peaks. The initial location of the integration windows were those found to give the highest degree of correlation between isotopic peaks. By moving the integration window across the isotopic peaks, in increments of 0.013 u (1 DAC step), drift in mass location was simulated. From the data presented in Figure 6.10, it may be seen that a mass shift of 0.1 u, caused the observed isotope ratio to change by approximately 0.5 %.
Figure 6.7: Central section of cross-correlation functions for Pb mass spectra obtained 0, 20, 40 and 60 minutes after that given in Figure 6.5.
Figure 6.8: Mass shift for the Pb isotopes observed in cross-correlation functions.
Figure 6.9: Reduction of drift in the $^{208}\text{Pb} : ^{206}\text{Pb}$ isotope ratio obtained by relocation of the integration windows to account for mass shift observed in cross-correlation functions.
Figure 6.10: Influence of mass shift upon the $^{206}$Pb and $^{208}$Pb isotope intensities and the $^{208}$Pb:$^{206}$Pb isotope ratio obtained by simulation of mass shift based upon movement of the integration windows across the isotopic peaks.
As movement of the integration window, to higher masses caused a rise in the observed isotope ratio, while the reverse was true for movement to lower masses (Figure 6.10), it may be concluded that the observed change in the value of the $^{206}$Pb/$^{208}$Pb isotope ratio is a consequence of a quantisation error in selection of mass by the multi-channel analyser. In this instance, the quantisation error is such that the nominal centre of the $^{206}$Pb isotope peak lies slightly to the left (lower mass) of the centre of the initial integration window, relative to that of the $^{208}$Pb isotope peak.

6.3.5 Mass shift in the peak jumping mode

Typically, 3 points per isotope, located at masses $m$, $m - 0.05$, and $m + 0.05$, where $m$ is the mass of the isotope of interest, are measured in the peak jumping mode of data acquisition. Assuming the mass scale calibration to be accurate, the central data acquisition channel should have a higher ion count than that of either the first or third data acquisition channels, which ought to have equivalent ion counts. By monitoring the relative signal intensities of the channels across the mass peak, mass shifts of the order of $\pm 0.02$ u could be observed. Movement from the mass scale calibration was regularly observed by this means for Pb isotope ratio measurement.

Correction for mass scale shift was attempted in the peak jumping mode, by use of 3 and 5 acquisition points per isotope, to which Gaussian curves were fitted. It was hoped that curve fitting would permit the location of the peak centres and their displacement with time. However, this proved to be ineffective, as location of the peak centres was imprecise. The S/N ratio for individual acquisition points was too low to permit exact curve fitting.

In the peak jumping mode, the entire mass range (300 u) is covered by 65,536 channels, providing a step size of 0.005 u. This mass resolution is approximately 4 times greater than that used in the mass scans discussed above, however, it is feasible that the quantisation error observed in the scanning mode (Figure 6.10), will also have a finite influence upon isotope ratio measurements made in the peak jumping mode.
6.3.6 Summary of the effects of mass scale shift
It has been shown that mass shift is a mass dependent instability, and as such can bias isotope ratios if not controlled. The severity of mass shift increases with mass, hence, the detrimental influence upon U isotope ratio measurement is likely to be severe compared to that upon B isotope ratio measurement. In the scanning mode, correction for mass shift is feasible by the re-alignment of integration windows following data collection, however, this technique is not applicable to data collected in the peak jumping mode. Finally, the integral nature of the mass scale causes there to be a quantisation error associated with mass location, which may contribute to the inaccuracy of measured isotope ratios (Figure 6.10).

6.4 DEAD TIME

6.4.1 Introduction
At count rates of above approximately 0.4 MHz, continuous dynode electron multipliers, such as the Galileo 4870V used in the ICP-MS instruments in this study, begin to count fewer events than actually occur. The interval during which the electron multiplier is 'hung-up' is termed the dead time. In addition, the counting logic circuitry also exhibits a finite response time, sometimes referred to as sag [10], which may result from pulse broadening in the amplifier, the limited rise and fall times of the discriminator, or the maximum clock rate of the counter. Most pulse counting systems show dead times of 10 to 30 ns.

As ions arrive randomly at the electron multiplier, the mean rate of ion arrival may be estimated by measuring the number of ion pulses generated by the electron multiplier during a dwell time. If the ion count measured during the dwell time is known, the sensitive time, during which the pulse counting system is available for use, may be calculated thus:

\[ T_s = T_d - ND \]  \hspace{1cm} (6.1)[11]
where 

\begin{align*} 
T_s &= \text{the sensitive time (s)} \\
T_d &= \text{the dwell time (s)} \\
N &= \text{the measured ion count} \\
D &= \text{the dead time (s)} 
\end{align*}

Reduction of the sensitive time $T_s$ by the dead time $D$ produces a proportional reduction in the count $N$ and a corresponding increase in the counting statistic $N^{1/2}$. However, the effect of dead time on a count is to modify the nature of the distribution as well as the mean rate of the ion pulses actually counted, causing it to be no longer strictly Poisson [11]. For count rates of above 0.5 MHz, the distribution, to a close approximation, is Gaussian [11].

Bayne and Smith [12] have demonstrated that the probability distribution obtained upon ratioing two Poisson distributed variables may not necessarily be accurately approximated by a normal or any other well known probability distribution. If the accumulated count for at least one of the isotopes to be ratioed is relatively small ($< 1000$), the range of values that the ratio may have is given by a set of rational numbers. In such instances, Bayne and Smith [12] found the probability distribution to be non-symmetric, skewed to the right, and to have more than one mode.

If the count rate is $< 0.5$ MHz and the accumulated count $> 1000$ then the probability $P_n$ of $n$ ion current pulses occurring during the dead time $D$ is governed by the Poisson formula:

\begin{equation} 
P_n = \frac{(\rho D)^n}{n!} \exp(-\rho D) 
\end{equation} 

where $\rho$ is the mean rate of arrival of ions at the detector (Hz)
If the count has a Poisson distribution, the measured count rate $N$ may be corrected for dead time $D$ utilising the equation:

$$N' = \frac{N}{1 - ND} \quad (6.3)$$

where $N'$ is the estimated count rate (Hz)

It is necessary to precisely determine the dead time to minimise the dependence of isotope ratios upon analyte concentration and isotopic abundance. There are two commonly employed methods for the measurement of dead time, however, neither are universally applicable. The first involves measuring one or more ratios at a number of analyte concentrations, if the dead time is correctly chosen the isotope ratio(s) should be independent of analyte concentration [13] The second involves calculation of the observed mass bias for two or more ratios, if all isotope ratios have equivalent mass bias factors then the dead time is correct. The first of these methods is susceptible to background interferences, while the second may only be applicable over a very limited mass range (see Section 6.5).

6.4.2 Influence of dead time upon estimated counts and their ratios

Figure 6.11 shows the magnitude of the variation in the estimated count, which is obtained by applying dead time correction, using Equation 6.3, to measured count rates of up to 0.5 MHz. Shifts of as much as 2 % of the measured count rate result from correction for a dead time of 50 ns. Concentration dependent error in the estimated count, arising from incorrect selection of the dead time, is demonstrated in Figure 6.12. The measured count rates have been selected as to require correction for a dead time of 25 ns, to provide a constant estimated count. Under-estimation or over-estimation of the instrumental dead time by just 5 ns is shown to cause the estimated count to alter by as much as 0.2 %, for a measured count rate of 0.5 MHz. However, it is the variation in the magnitude of the error, relative to the true count, from a measured count rate of 0.01 MHz to 0.5 MHz, which is detrimental to the accuracy of isotope ratio measurement.
Figure 6.11: Influence of the dead time used in dead time correction upon the measured count.
Figure 6.12: Concentration dependent error in the measured count arising from incorrect selection of the dead time used in dead time correction.
In Figure 6.13, the dead time has been under-estimated by 5 ns, a dead time correction of 20 ns has been applied, where as a 25 ns dead time provides accurate correction. It may be seen that isotope ratios can become biased by several parts per thousand as a consequence of inaccurate selection of the dead time utilised in dead time correction. As the gradient of the lines shown in Figure 6.13 increase as the ratio of A:B, it may be assumed that the further the measured isotope ratio lies from unity the more susceptible that ratio is to error arising from inaccurate correction for dead time. Hence, accurate measurement of the 204Pb:206Pb isotope ratio in natural abundance materials is more difficult to achieve than is accurate 207Pb:206Pb isotope ratio measurement, for measurement systems utilising pulse counting techniques.

6.5 MASS BIAS

6.5.1 Introduction
Mass bias is a general term given to the discrimination and fractionation of isotopes based upon their mass, which occurs within an instrument system. Mass bias may be measured and therefore corrected for by use of an external standard of known isotopic composition or a fixed, constant ratio within the sample. External mass bias correction has been widely used in ICP-MS, but may be of limited value if the instrumental mass bias is unstable, i.e. varies on a short to medium time scale. Internal mass bias correction is superior in that it allows near continual monitoring of change in mass bias and will successfully correct for non-spectral interferences due to high concentrations of matrix elements [14].

There are three algorithms which may be applied to the correction of mass bias in ICP-MS, these are based upon linear, power law and exponential relationships between mass bias and mass difference [15].
Figure 6.13: Relative error in isotopic ratio A:B arising from incorrect selection of the dead time used in dead time correction. A dead time of 20 ns has been applied where a 25 ns dead time provides accurate correction.
If mass bias is assumed to be a linear function of mass, to the precision of the data, mass bias correction may be performed using Equation 6.4.

\[(A/B)_{\text{corr}} = (A/B)_{\text{obs}} (1 + an)\]  \hspace{1cm} (6.4)

where

- \((A/B)_{\text{corr}}\) is the mass bias corrected ratio of isotopes A and B.
- \((A/B)_{\text{obs}}\) is the observed ratio of isotopes A and B.
- \(a\) is the bias per unit mass.
- \(n\) is the mass difference between isotopes A and B (u).

If mass bias is, however, a power law function of mass, Equation 6.5 may be utilised to correct for mass bias. Both the linear and power law algorithms have been shown to give equivalent results as the mass bias approaches zero [16].

\[(A/B)_{\text{corr}} = (A/B)_{\text{obs}}(1 + a^n)\]  \hspace{1cm} (6.5)

Finally, should an exponential relationship exist between mass bias and mass difference, mass bias correction may be performed using Equation 6.6.

\[(A/B)_{\text{corr}} = (A/B)_{\text{obs}} \exp^{an}\]  \hspace{1cm} (6.6)

Taylor et al. [15] found the power law and exponential functions to be more successful in correction of mass bias than the linear function for U isotope ratio measurement, by multiple collector ICP-MS. Both Ketterer et al. [14] and Longerich et al. [16] found empirically that the power law correction works well for Pb isotope ratio measurements, utilising Tl as an internal standard. However, Roehl et al. [17] have stated 'there is at present no theoretical basis for the assumption that the power law accurately describes mass bias observed in quadrupole ICP-MS instruments'.

6.5.2 External mass bias correction

Use of an external isotopic reference is the only feasible method of mass bias correction for elements, such as boron and uranium, for
which all isotopic ratios are variable in nature. Use of NBS U500 isotopic reference material is preferred for external mass bias correction of the \(^{238}\text{U}^{235}\text{U}\) isotope ratio, as it has a value close to unity, and is thus unaffected by errors which may result from non-linearity of the detector system. It is, however, necessary to assume that the magnitude of the mass bias does not vary between analyses when utilising an external isotopic reference.

**6.5.3 Internal mass bias correction**

Internal mass bias correction requires the element of interest to have three or more isotopes and for at least two of these isotopes to have a known and geologically constant isotope ratio. Osmium, neodymium and strontium, are among the elements which permit use of isotopes of fixed natural abundance in the normalisation of the data to an accepted ratio. Russ et al. [18] made use of the linear function, given in Equation 6.4, for internal mass bias correction in Os isotope ratio measurement.

The thallium correction method for minimisation of mass bias in Pb isotope ratio measurement is the only widely reported method involving addition of an internal isotopic reference, to be used in ICP-MS [14,16,19-22]. Thallium is a suitable internal isotopic reference as it is of convenient mass and its isotopes are of a fixed natural abundance. Mass bias correction using the thallium correction method involves use of the power law function given in Equation 6.5. The addition of gallium as an internal isotopic reference in Zn isotope ratio analysis has been once reported [17], in this instance, the algorithm used for mass bias correction involved non-linear curve fitting based upon regression analysis.

**6.5.4 Relationships between observed isotope ratios**

By plotting two different isotope ratios measured over a period of at least 1 hr, one against the other, the relationship that exists between the isotopic ratios should be indicative of the nature of the mass bias. Platinum was used for the purpose, as it provides two isotope ratios which are fixed and constant in nature and are close to unity. Platinum is only 10 u removed from Pb, and as such, is likely to show similar mass bias effects to Pb and Th. As the mass response curve is typically steepest at either end of the mass range, the magnitude of the mass bias...
around 195 u would generally be significant, above the precision of the
data, while this may not always be so in the central mass region (80 to
160 u).

Variation in the values of the $^{194}\text{Pt}:{^{196}\text{Pt}}$ and $^{194}\text{Pt}:{^{195}\text{Pt}}$ isotopic ratios
observed during 80 acquisitions, each of a duration of 2 minutes, is
shown in Figure 6.14  The change in the value of the $^{194}\text{Pt}:{^{196}\text{Pt}}$ isotope
ratio is approximately double that observed in the value of the
$^{194}\text{Pt}:{^{195}\text{Pt}}$ isotope ratio, over the same period. If the mass bias is
assumed to be a linear function of mass, the relationship that exists
between isotopic ratios $^{194}\text{Pt}:{^{196}\text{Pt}}$ and $^{194}\text{Pt}:{^{195}\text{Pt}}$ will be of the form $y = mx + c$
The gradient of the slope $m$ is given by:

$$m = \frac{a_{ab}}{a_{cd}}$$  (6.7)

where $a_{ab}$ is the mass difference between isotopes a and b, the
ratio of a to b having been plotted on the y-axis (u)

$a_{cd}$ is the mass difference between isotopes c and d, the
ratio of c to d having been plotted on the x-axis (u)

If mass bias and mass difference were related by either a power law or
exponential function, the relationship observed between two measured
isotopic ratios during mass bias shift would be of a non-linear form

If a linear relationship were to exist between mass bias and mass shift a
plot of $^{194}\text{Pt}:{^{196}\text{Pt}}$ versus $^{194}\text{Pt}:{^{195}\text{Pt}}$ would give $m = 2$. The best fitting
linear relationship for the data given in Figure 6.14 has a gradient of
1.82 and a correlation coefficient of 0.67  The similarity between the
predicted and observed gradients suggests that a detectable shift in
mass bias has occurred during the period of the experiment (around 3
h) and that, in this instance at least, mass bias is to a first
approximation linearly related to mass difference. The correlation
coefficient is sufficient to suggest that fluctuation in the magnitude of
the mass bias is the major form of drift being experienced. Mass bias
correction resulted in improvement in accuracy, but reduction in the
precision of the Pt isotope ratios as a consequence of shifts arising from
sources other than mass bias.
Figure 6.14: Relationship between the $^{194}\text{Pt} : ^{196}\text{Pt}$ and $^{195}\text{Pt} : ^{196}\text{Pt}$ isotope ratios measured over 80 consecutive, 2 minute integrations.
Variation in the measured value of the $^{207}\text{Pb}::^{206}\text{Pb}$ and $^{205}\text{Tl}::^{203}\text{Tl}$ isotopic ratios with time is shown in Figures 6.15 and 6.16. In both figures, the data were collected over a period of approximately 3 h. The $^{207}\text{Pb}::^{206}\text{Pb}$ isotope ratio was studied as it has the closest value to unity of any of the Pb isotope ratios. The Pb used was NIST SRM 981, which has a certified value for the $^{207}\text{Pb}::^{206}\text{Pb}$ isotope ratio of 0.91476. The best fitting linear relationship for the data given in Figure 6.15 has a gradient of 0.32 and a correlation coefficient of 0.87. While the best fit linear equation through the data shown in Figure 6.16 has a gradient of 0.27 and a correlation coefficient of 0.59. Assuming a linear relationship exists between mass bias and mass shift, the gradient of the both slopes ought to be 0.5.

While the isotopes of Pt studied spanned 3 u, the Tl and Pb isotopes span a total of 5 u. It may be that this increase in mass range causes the assumed linear relationship between mass bias and mass difference to be no longer valid.

6.6 SUMMARY

Instabilities which limit the accuracy and precision of isotope ratio measurements made by ICP-MS may conceivably originate within either the ICP or the quadrupole mass analyser. The external precision for isotope ratio measurement was found to be limited by non-random noise arising within the quadrupole mass analyser or its associated ion optics. Mass bias, mass scale shift and detector dead time were shown to influence the extent to which external precision and accuracy were limited.

Mass scale shift was found to cause mass dependent instability, the severity of which was observed to increase with isotopic mass. The imprecision, resulting from mass scale shift, for measured isotope ratios, therefore, increased as the isotopic mass of the analyte. In addition, the integral nature of the mass scale was shown to cause there to be a quantisation error associated with mass location. Inaccurate correction of detector dead time was observed to cause significant bias in measured isotope ratios. The magnitude of this bias was found to increase as the value of the isotope ratio extended from unity.
Instrumental mass bias is well known in ICP-MS [1-3], however, the relationship which exists between mass bias and mass is not. Internal mass bias correction may be applied based upon a linear, power law or exponential relationship between mass bias and mass [15]. A linear relationship between mass bias and mass was observed to be appropriate in instances in which the isotopes studied spanned no more than 3 u.
Figure 6.15: Relationship between the $^{207}$Pb,$^{206}$Pb and $^{205}$TI,$^{203}$TI isotope ratios observed on 26th August, 1993.
Figure 6.16: Relationship between the $^{207}\text{Pb}:^{206}\text{Pb}$ and $^{205}\text{Tl}:^{203}\text{Tl}$ isotope ratios observed on 23rd August, 1993.
References
7. J. Batey, FI Elemental, Winsford, Cheshire, UK, personal communication
12 C K. Bayne and D.H. Smith, Oak Ridge National Laboratory, TN, USA.
CHAPTER SEVEN
ACCURATE AND PRECISE ISOTOPE RATIO MEASUREMENT

7.1 INTRODUCTION

The detrimental influence that instrumental sources of noise and drift may have upon isotopic ratio measurement has been highlighted in previous chapters. The precision of isotopic ratio measurements made by quadrupole ICP-MS has at best approached 0.1 % RSD [1], and then, only for isotopes of similar abundance (e.g. $^{107}$Ag/$^{109}$Ag). For isotopic ratios involving an isotope of low abundance, such as $^{204}$Pb, a precision of 0.2 - 1.0 % RSD is typical [2]. Accuracies for isotopic ratio measurement of 0.25 % are attainable [3], although 0.5 % is more typical. In this chapter the methodology used in attaining highly accurate and precise isotopic ratio measurement by ICP-MS will be discussed for three elements (B, Zn and Pb), which differ widely in mass, number of isotopes, natural abundance and variation in the value of isotope ratios.

Figure 7.1 depicts the measurement of an isotope ratio as a hypothetical transfer function that results in the addition of noise and offset to give the measured isotope ratio. Beginning at the top of Figure 7.1, the true ratio is envisaged as being altered by noise and offset, each the overall sum of a number of contributing factors, to produce the measured ratio. Techniques for limiting the magnitude of the unwanted components contributing to noise, based on knowledge of noise power spectra, were discussed in Chapter 5. To bring the measured isotope ratio in line with the true ratio there are a number of correction procedures, outlined in Chapter 6, which can be used to compensate for the various unwanted components, which contribute to the offset. With Figure 7.1 as a basis, rationalisation of the interacting factors will be shown to lead to establishment of a protocol for operation which gives optimum precision and accuracy for isotopic ratio measurement.
Figure 7.1: Hypothetical transfer function for isotopic ratio measurement.
7.2 PROTOCOL FOR ISOTOPIC RATIO MEASUREMENT

7.2.1 Introduction
The four noise types, given in Figure 7.1, are all likely to contribute to the precision of isotopic ratio measurement. 'Poisson' refers to the theoretical counting statistic, resultant on the uncertainty associated with the rate of arrival of ions at the detector. 'Ion Source' relates to all internal noise arising during sample introduction and plasma processes, these include audible-frequency noise associated with gas dynamic phenomena occurring in the plasma discharge and peristaltic pump noise. 'Detection' refers to internal noise (Johnson and shot) arising within measurement circuits used in detection and counting of ions. Designated as 'Pick-Up' are external and interference noise components, such as those associated with the a c. line frequency and its harmonics. Methods for reduction of these noise types, all of which are a consequence of non-ideal instrumentation, were detailed in Chapter 5. The implications of the limited choice of data acquisition parameters; the measurement of more than two isotopes; and isotopes of low natural abundance upon noise reduction are examined for B, Zn and Pb isotopic ratio measurement later in the chapter.

The impacts of 'Background', 'Mass Bias', 'Mass Scale Shift' and 'Pulse Pile-Up' combine to give an offset, which is equivalent to the bias observed in the 'raw' measured ratio. While, the same techniques are apply for noise reduction, independent of the isotopes studied, the techniques used for minimisation of the influences of background, mass bias, mass scale shift and pulse pile-up are to some degree determined by the element under investigation.

7.2.2 Background
In Figure 7.1, the effects of spectral interference and analyte contamination are given as inputs to the background, which in turn contributes to the offset. That is to say, the background may be determined from the sum of analyte contamination and spectral interference from molecular species and ions other than those of the analyte element. In this context, analyte contamination relates to sample-to-sample memory effects or contamination occurring during
sample preparation, which may cause the measured isotopic signature to differ from that of the sample material.

The relative contribution made by the background upon bias, observed in the measured ratio, is to a large extent determined by the analyte under investigation. Background is likely to be of little importance, given the other forms of offset present, in U isotopic ratio measurement, but may be of some significance in B or Pb isotopic ratio measurement, as will be discussed below. While the background for B may be almost exclusively due to analyte contamination, for Pb it will probably be the result of both isobaric interference and analyte contamination.

Initially, it is necessary to establish whether background is problematic. This can be done by measuring the isotopic ratios of the procedural blank. In the absence of background, be it from spectral interference, analyte contamination or a combination of both, the ratio(s) should be normally distributed about unity. If the isotopic ratios for the procedural blank deviate significantly from unity, then background can be assumed to have a measurable impact upon the offset. From the values of the isotopic ratios obtained, it should be possible to identify whether the background arises from analyte contamination, or is due to spectral interference(s) on specific isotopes. Should analyte contamination be the cause of the background, then it may be possible to take action to identify and reduce contamination arising during sample preparation. Otherwise, blank subtraction of all subsequent data will require to be undertaken, however, this may result in deterioration of the precision of isotopic ratios, if the correction applied represents a significant fraction of the count rate for the sample.

7.2.3 Mass bias
Mass bias, as a source of offset, was covered in the Section 6.5. As discussed previously, there are a number of established methods available for mass bias correction (external mass bias correction or internal mass bias correction using linear, power law or exponential correction algorithms). Under ideal circumstances, both external and internal mass bias correction will consistently produce equivalent mass bias factors, as drift in mass bias with time is low or negligible to
within the precision of the data. If a suitable isotopic reference is available and mass bias factors have been observed to remain constant for periods of 1 h or more, then external mass bias correction is probably the best option, as it reduces the number of isotopes to be measured and in doing so ultimately enhances measurement precision. External mass bias correction can also ensure that the abundance of isotopes of interest in the standard are similar to those of the sample, where this may not be practical for an internal standard. However, matrix effects may not necessarily be compensated for by use of an external standard.

If internal mass bias correction is to be utilised, the most appropriate algorithm may be chosen by examining the curvature of the mass response curve in the mass region associated with the isotopes of interest. Typically, the mass response curve will be relatively flat in the centre, but will decay exponentially at either end of the mass range, normally 5 to 250 u. Mass response calibration was undertaken on a daily basis, at least 1 h after light-up, to determine the nature of the curvature.

Assuming the shape of the mass response curve is typical, the linear algorithm may be valid for isotopes within the range 60 to 160 u and beyond if the isotopes to be ratioed are only separated by one mass unit. Power law or exponential algorithms would be anticipated as being more appropriate at the extremes of the mass range and where the isotopes of interest span a region of five or more mass units.

7.2.4 Mass scale shift
Mass scale shift has seldom been identified as a source of offset in previous studies involving isotopic ratio measurement by ICP-MS, although the mass transmission given by quadrupole mass analysers is inherently unstable and susceptible to fluctuations in ambient temperature, as was shown in Section 6.3. Preventative action can be taken to minimise mass scale shift by stringently controlling the temperature within the vicinity of the ICP-MS instrument and in particular that surrounding the r.f. generator associated with the quadrupole mass analyser. Realignment of data to compensate for mass scale shift was found to be an effective means for reduction of bias in
isotopic ratios. A high density of measurement positions across the isotopic peaks is, however, necessary for realignment to be successful. Hence, data acquisition requires to be undertaken in the scanning mode, which does not allow reduction of noise to counting statistic levels.

For data collected in the peak jumping mode, no effective method for direct correction of mass scale shift was found. However, a mass scan undertaken after every third sample or on an hourly basis, requires only 30 seconds of analysis time and allows recalibration of the mass scale, if necessary. Since the severity of the mass scale shift increases as the distance between isotopes being ratioed, in instances where the isotopes being measured extend over several mass units, ratioing of the lightest and heaviest isotopes provides a means of indirectly monitoring mass shift. Assuming this monitor ratio is normally distributed about its mean value, integrations having values which lie out with ±2 standard deviations of the mean, may be taken to be statistical outliers. The iterative use of this method for removal of statistical outliers has been found to be effective, where no indication of mass shift was observed in the isotopic ratios of interest.

7.2.5 Pulse pile-up

Pulse pile-up results from the inability of the detector and counting system to reliably log the arrival of ions at the detector for high count rates. Offset arising from pulse pile-up can be limited by ensuring the most abundant of the isotopes being measured does not exceed a count rate of 0.5 MHz. By limiting analyte concentration to levels below that which give a count rate of 0.5 MHz for the major isotope, the dead time of the measurement system will be consistent for all measured isotopes. Higher count rates may result in additional pulse broadening in the amplifier, causing the dead time to rise during measurement of the major isotope.

It is necessary to ensure the voltage applied across the dynode tube of the electron multiplier is sufficient for all ions to be recorded, that is to say, the applied voltage ought to lie centrally within the plateau region. It has been suggested that to prevent signal loss, the applied voltage should be regularly set to a value 500 V above that which gives an electron production efficiency of 50% [4]. The discriminator level
should also be set to ensure the threshold level is high enough to prevent noise spikes or gain variation from being mistakenly measured as ions, yet low enough to ensure ion pulses of low intensity do not go unmeasured. It is necessary to ensure the applied voltage and discriminator level are regularly checked to prevent poor long term reproducibility, since the magnitude of current pulses decreases as the electron multiplier ages.

Dead time correction is generally automatically applied to the ion count accumulated in individual channel addresses. As was shown in Section 6.4.2, isotopic ratios, especially those with values far removed from unity, become biased if the dead time utilised in correction is inaccurate. There are well established methods for determination of instrumental dead time, which require to be utilised prior to undertaking any series of isotopic ratio measurements. Determination of the instrumental dead time for Zn, B and Pb isotopic ratio measurement, each undertaken using a different ICP-MS instrument, will be discussed below.

7.3 ZINC ISOTOPE RATIO MEASUREMENT

7.3.1 Introduction
As discussed in Chapter 2, there is interest in utilising isotopically enriched Zn in stable isotope tracer and dilution studies to monitor elemental uptake and bioavailability of dietary zinc. Zinc has five isotopes, all of which are invariant in nature, with relative abundance ranging from 0.62% (\textsuperscript{70}Zn) to 48.89% (\textsuperscript{64}Zn). The breadth of values of the Zn isotopic ratios, ranging from 1.498 for \textsuperscript{66}Zn:68Zn to 78.855 for \textsuperscript{64}Zn:70Zn, necessitates careful compensation for instrumental bias to permit accurate measurement of all isotope ratios. Generally, the further an isotopic ratio extends from unity the more difficult it becomes to measure accurately, because errors occurring in ion counting are most likely to bias ratios in which the magnitude of the two signals differ by a large amount. Hence, one would anticipate the \textsuperscript{64}Zn:70Zn isotope ratio to be the most difficult to measure accurately as its value lies furthest from unity and the isotopes to be ratioed are separated by the largest mass difference.
7.3.2 Data acquisition parameters and noise reduction

Zinc isotope ratio measurement was made using a VG PlasmaQuad I instrument (FI Elemental, Winsford, Cheshire, UK). The data acquisition parameters selected for use are summarised in Table 7.1. Using these acquisition parameters, the quadrupole mass analyser will transmit each of the Zn isotopes in ascending mass, for the duration of the dwell time (10.24 ms). On completing the dwell upon the $^{70}$Zn isotopic peak, the quadrupole mass analyser rapidly returns to transmission of 64 m/z, where it remains for the period of the settle time (2 ms). The measurement sequence is re-started by dwelling for 10.24 ms upon the centre of the $^{64}$Zn isotopic peak. This sequence is replicated 1960 times during the acquisition time of 120 s. Within the period of the acquisition time each of the Zn isotopes is measured for a total time of 19.6 s.

Table 7.1: Data acquisition parameters for Zn isotope ratio measurement

<table>
<thead>
<tr>
<th>Acquisition Mode</th>
<th>Peak Jumping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole Rest Mass</td>
<td>67 u</td>
</tr>
<tr>
<td>Quadrupole Settle Time</td>
<td>2 ms</td>
</tr>
<tr>
<td>Detector Dead Time</td>
<td>15 ns</td>
</tr>
<tr>
<td>Discriminator Level</td>
<td>20</td>
</tr>
<tr>
<td>Number of Isotopes</td>
<td>5</td>
</tr>
<tr>
<td>Dwell Time per Channel</td>
<td>10.24 ms</td>
</tr>
<tr>
<td>Points per Peak</td>
<td>1</td>
</tr>
<tr>
<td>Acquisition Time</td>
<td>120 s</td>
</tr>
<tr>
<td>Replicate Measurements</td>
<td>5</td>
</tr>
</tbody>
</table>

Peak jumping was selected in preference to scanning, primarily because a greater proportion of the available acquisition time could be spent in accumulation of counts on the isotopes of interest (see Table 5.1), keeping the theoretical counting statistic to a minimum.

As all five Zn isotopes were measured for a dwell time of 10.24 ms, the low-pass and anti-aliasing filtering effect of the dwell time is experienced equally by all isotopes. A dwell time of 10.24 ms yields a
high frequency cut-off of 49 Hz (Equation 5.3). Use of a single measurement position, on the apex of the isotopic peaks, provides an elapse time, the time between start of measurement on the first isotope and end of measurement on the second isotope, of no more than 59.2 ms (see Equation 5.1). Ratioing of Zn isotopes is occurring at a rate of between 16.8 and 44.5 Hz for the $^{64}\text{Zn}^{70}\text{Zn}$ and $^{66}\text{Zn}^{67}\text{Zn}$ isotopic ratios, respectively. From Equation 5.2, it can be determined that in the case of the $^{66}\text{Zn}^{67}\text{Zn}$ isotope ratio noise at frequencies below 22.3 Hz is reduced by ratioing, while for the $^{64}\text{Zn}^{70}\text{Zn}$ isotope ratio it is frequencies below 8.4 Hz which are attenuated. These ratioing frequencies are sufficient to minimise the detrimental influence of $1/f$ and peristaltic pump induced noise (see Section 4.3).

The summation of 1960 sweeps is effective in reducing noise with frequencies between the ratioing frequency (e.g. 8.4 Hz for the $^{64}\text{Zn}^{70}\text{Zn}$ isotope ratio) and the high cut-off frequency associated with the dwell time (e.g. 49 Hz) The frequency of interest in summation of sweeps is that derived from the time taken between replicate measurements of an isotope, referred to as the cycle time (61.2 ms). Only noise frequencies in close proximity to 16.3 Hz, the reciprocal of 61.2 ms, and its harmonics are not attenuated by the summation of sweeps. The bandpass at these frequencies is given by Equation 5.5, for 1960 sweeps the bandpass has a width of just 0.007 Hz.

Selected data acquisition parameters were assessed for use in minimising sample introduction and plasma noise by holding the quadrupole mass analyser at a fixed position (67 m/z), while, the multi-channel analyser collected data in the five channels associated with the Zn isotopes, in the normal manner. Given suitable acquisition parameters, the measured precision ought to approximate the theoretical counting statistic. From Table 7.2, it may be seen that all isotopic ratios, with the exception of the $^{66}\text{Zn}^{70}\text{Zn}$ isotope ratio, have average RSDs of within 125 % of the counting statistic. Although it is possible to attain a measured precision equivalent to the counting statistic for a single isotope ratio, it becomes increasingly difficult to do so as the number of isotopes to be measured rise and the range of cut-off and band-pass frequencies increase.
The short term precision for the Zn isotopic ratios of interest, for analyte concentrations of 100 and 500 ng ml$^{-1}$, are summarised in Table 7.3. It can be seen that the data acquisition parameters are adequate for reduction of instrumental noise sources. The majority of uncertainty in all measured Zn isotopic ratios is due to counting statistics. The measurement precision for most Zn isotopic ratios involving $^{70}$Zn may be seen to be lower than the counting statistic, however, this is unlikely to be accurate. It is suggested that the theoretical counting statistic for the $^{64}$Zn $^{70}$Zn and $^{66}$Zn$^{70}$Zn isotopic ratios is in error as a consequence of the low count rate on $^{70}$Zn, which was of the order of 800 Hz for a Zn concentration of 100 ng ml$^{-1}$.

Table 7.2: Precision of Zn isotope ratios for fixed mass position

<table>
<thead>
<tr>
<th>Determination</th>
<th>RSD* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$^{64}$Zn $^{68}$Zn</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{66}$Zn $^{68}$Zn</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{64}$Zn $^{70}$Zn</td>
<td>0.14</td>
</tr>
<tr>
<td>$^{64}$Zn $^{67}$Zn</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{66}$Zn $^{70}$Zn</td>
<td>0.18</td>
</tr>
<tr>
<td>$^{66}$Zn $^{67}$Zn</td>
<td>0.15</td>
</tr>
<tr>
<td>Counting Stat. **</td>
<td>0.08</td>
</tr>
</tbody>
</table>

* for 5 replicate measurements
** based upon mean count for $^{66}$Zn
Table 7.3. Short term precision for Zn isotope ratio measurement

Analyte Concentration (ng ml-1)

<table>
<thead>
<tr>
<th></th>
<th>100</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSD* (%)</td>
<td>Counting Stat.</td>
<td>RSD* (%)</td>
</tr>
<tr>
<td>64Zn:68Zn</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>66Zn:68Zn</td>
<td>0.26</td>
<td>0.19</td>
</tr>
<tr>
<td>64Zn:70Zn</td>
<td>0.30</td>
<td>0.80</td>
</tr>
<tr>
<td>64Zn:67Zn</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>66Zn:70Zn</td>
<td>0.42</td>
<td>0.81</td>
</tr>
<tr>
<td>66Zn:67Zn</td>
<td>0.25</td>
<td>0.34</td>
</tr>
</tbody>
</table>

* for 5 replicate measurements

7.3.3 Mass calibration

Where possible mass calibration for isotopic ratio measurement should be undertaken using elements within a mass window of 10 to 20 u, centred about the isotopes of interest. For Zn isotope ratio measurement, a mass calibration solution containing Co, Ni, Cu and Ga, in addition to Zn, was utilised. The isotopes used in mass calibration were $^{59}$Co, $^{62}$Ni, $^{65}$Cu, $^{66}$Zn, $^{68}$Zn, $^{69}$Ga and $^{71}$Ga. To ensure the peak identification algorithm, within the body of the software, reliably located the centres of the isotopic peaks, it was found necessary to reduce the number of data channels per mass unit to below twenty. To do so, the width of the scan region required to be extended to run from 41.5 to 79.5 u, to give approximately 13 data channels per mass unit.

7.3.4 Dead time correction

As outlined in Section 6.4.1, there are two commonly employed methods for measurement of the dead time. Both of these methods were investigated for use in measurement of Zn isotopic ratios. The method for determination of the dead time involving calculation of the observed mass bias for two or more ratios, for a variety of dead times, was found to be the more effective. The correct dead time being that which gave equivalent mass bias factors for all measured Zn isotopic ratios.
Zinc isotopic ratios involving the $^{68}$Zn isotope were found to show mass bias factors distinct from those that did not, perhaps as a consequence of spectral interference and were, therefore, omitted from determination of the dead time. The $^{64}$Zn:$^{70}$Zn isotope ratio gave a consistently higher mass bias factor than any of the other remaining isotopic ratios, possibly as a result of its high value (78.855) and was also rejected for use in determination of the dead time. The mass bias factors for the 3 remaining Zn isotopic ratios, which vary in value from 6.766 ($^{66}$Zn:$^{67}$Zn) to 44.855 ($^{68}$Zn:$^{70}$Zn), are shown to converge at a dead time of approximately 15 ns in Figure 7.2.

7.3.5 Mass bias correction
There are a number of reasons why external mass bias correction may be the most applicable for use in Zn isotopic ratio measurement. Firstly, as the Zn isotopes to be measured span 6 mass units, from $^{64}$Zn to $^{70}$Zn, the observed mass bias is likely to vary between isotopes, as a result of the curvature of the mass response curve. Secondly, it may be far from ideal to use a single isotope ratio, such as $^{64}$Zn:$^{66}$Zn, with a value of 1.758, for internal mass bias correction, given the wide range of values of the Zn isotopic ratios. Thirdly, external mass bias correction is likely to be less susceptible to spectral interference, due to polyatomic species, if their constituent elements are present at an equivalent level in both the standards and samples, i.e. matrix matched. Finally, the stability of the VG PlasmaQuad I instrument utilised was observed to be good, therefore, short-term variation in mass bias was assumed to be low.

The measured mass bias factors for the 6 Zn isotopic ratios of interest, obtained for a solution containing 500 ng ml$^{-1}$ of Zn, are given in Table 7.4. The mass bias factors range in magnitude from 1.62 % u$^{-1}$ for the $^{66}$Zn:$^{67}$Zn isotope ratio to 3.56 % u$^{-1}$ for the $^{64}$Zn:$^{68}$Zn isotope ratio. In many ways, the mass bias factors given in Table 7.4 are suggestive of a typical mass response curve, for which response decreases as the square of mass at the lower end of the mass range.
Figure 7.2: Dependence of observed mass bias for measured Zn isotopic ratios upon the dead time used in dead time correction.
Table 7.4: Mass bias factors for Zn isotope ratios

<table>
<thead>
<tr>
<th></th>
<th>Bias Factor (% u-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64Zn:68Zn</td>
<td>3.56</td>
</tr>
<tr>
<td>66Zn:68Zn</td>
<td>2.71</td>
</tr>
<tr>
<td>64Zn:70Zn</td>
<td>3.02</td>
</tr>
<tr>
<td>64Zn:67Zn</td>
<td>3.38</td>
</tr>
<tr>
<td>66Zn:70Zn</td>
<td>2.25</td>
</tr>
<tr>
<td>66Zn:67Zn</td>
<td>1.62</td>
</tr>
</tbody>
</table>

7.3.6 Interference effects

The $^{67}\text{Zn}$, $^{68}\text{Zn}$ and $^{70}\text{Zn}$ isotopes have generally been found to be free from interference effects [5-9]. The $^{70}\text{Zn}$ isotope suffers from an isobaric overlap with $^{70}\text{Ge}^+$ (20.52 %), and the $^{64}\text{Zn}$ isotope from an isobaric overlap with $^{64}\text{Ni}^+$ (1.16 %). Potential interference from polyatomic species occurs on the $^{68}\text{Zn}$ ($^{40}\text{Ar}^{14}\text{N}^{14}\text{N}^+$) and $^{70}\text{Zn}$ ($^{40}\text{Ar}^{14}\text{N}^{16}\text{O}^+$) isotopes.

Nitric acid blanks were generally found to give count rates of < 30 Hz for the $^{67}\text{Zn}$ and $^{70}\text{Zn}$ isotopes, approximately 70 Hz for the $^{66}\text{Zn}$ and $^{68}\text{Zn}$ isotopes and > 100 Hz for the $^{64}\text{Zn}$ isotope. These background intensities are suggestive of a little interference on the $^{64}\text{Zn}$ isotope, from Ni present in the acid matrix, and on the $^{68}\text{Zn}$ isotope from $^{40}\text{Ar}^{14}\text{N}^{14}\text{N}^+$. It was assumed that a large proportion of N species found in the sampling region of the plasma were due to the nitric acid contents of solutions. To investigate whether the percentage of nitric acid in solution had any influence upon the measured Zn isotopic ratios, isotopic ratio measurements were made for 100 ng ml$^{-1}$ Zn solutions containing 1, 3 and 5 % HNO$_3$. Table 7.5 shows there to be no significant variation in any of the Zn isotopic ratios upon increasing the HNO$_3$ concentration from 1 to 5 %. It is quite probable, however, that the range of nitric acid concentrations investigated is insufficient to effectively show the true nature of the interference. The largest observed changes occurred in the $^{64}\text{Zn}$-$^{70}\text{Zn}$ and $^{66}\text{Zn}$-$^{70}\text{Zn}$ isotopic ratios, which are furthest from unity and therefore most susceptible to bias.
Table 7.5: Influence of nitric acid concentration upon Zn isotope ratios

<table>
<thead>
<tr>
<th>HNO₃ Conc (%)</th>
<th>Measured Ratio*</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2.259</td>
<td>2.255</td>
</tr>
<tr>
<td>64Zn 68Zn</td>
<td>1.405</td>
<td>1.405</td>
<td>1.404</td>
</tr>
<tr>
<td>66Zn 68Zn</td>
<td>63 398</td>
<td>62 712</td>
<td>62.687</td>
</tr>
<tr>
<td>64Zn 70Zn</td>
<td>10 674</td>
<td>10.639</td>
<td>10.640</td>
</tr>
<tr>
<td>66Zn:70Zn</td>
<td>39.434</td>
<td>39.075</td>
<td>38.941</td>
</tr>
<tr>
<td>66Zn 67Zn</td>
<td>6.639</td>
<td>6.629</td>
<td>6.609</td>
</tr>
</tbody>
</table>

* mean of 5 blank subtracted measurements

7.3.7 Accuracy
The accuracy of the measured Zn isotopic ratios for 6 meat digests, expressed as a percentage bias from the natural abundance ratios, are given in Table 7.6. Typically, the measured value deviates from the natural abundance value by 0.2 to 1.0%. It is worth noting that all ratios in which the 64Zn isotope forms the numerator show a positive bias, which is as would be anticipated if Ni were present as a contaminant. This bears some relation with the high mass bias factors observed for ratios involving the 64Zn isotope. External mass bias correction was undertaken only once, prior to measurement of the samples for which data is given in Table 7.6. This is by no means ideal, as change in the instrumental mass bias may have occurred over the 1.5 h period of analysis. The validity of the mass bias correction is best checked on at least an hourly basis by re-running the isotopic working standard.
Table 7.6. Accuracy for Zn isotope ratio measurement

<table>
<thead>
<tr>
<th></th>
<th>Digest 1</th>
<th>Digest 2</th>
<th>Digest 3</th>
<th>Digest 4</th>
<th>Digest 5</th>
<th>Digest 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>64Zn:68Zn</td>
<td>0.64</td>
<td>0.78</td>
<td>0.84</td>
<td>1.41</td>
<td>0.68</td>
<td>0.71</td>
</tr>
<tr>
<td>66Zn:68Zn</td>
<td>-0.18</td>
<td>-0.05</td>
<td>-0.14</td>
<td>0.13</td>
<td>-0.28</td>
<td>-0.71</td>
</tr>
<tr>
<td>64Zn:70Zn</td>
<td>0.48</td>
<td>0.08</td>
<td>0.19</td>
<td>0.04</td>
<td>-0.72</td>
<td>0.74</td>
</tr>
<tr>
<td>64Zn:67Zn</td>
<td>0.64</td>
<td>0.72</td>
<td>0.58</td>
<td>1.21</td>
<td>0.39</td>
<td>1.19</td>
</tr>
<tr>
<td>66Zn:70Zn</td>
<td>-0.34</td>
<td>-0.74</td>
<td>-0.78</td>
<td>-1.21</td>
<td>-1.67</td>
<td>-0.68</td>
</tr>
<tr>
<td>66Zn:67Zn</td>
<td>-0.19</td>
<td>-0.11</td>
<td>-0.40</td>
<td>-0.08</td>
<td>-0.57</td>
<td>-0.24</td>
</tr>
</tbody>
</table>

* bias = (measured ratio - natural ratio) / natural ratio * 100

7.3.8 Summary of Zn isotopic ratio measurement
A short term measurement precision of 0.10 % RSD for the 64Zn:68Zn isotope ratio, 0.08 % for the 66Zn:68Zn isotope ratio, 0.35 % RSD for the 64Zn:70Zn isotope ratio, 0.31 % RSD for the 66Zn:67Zn isotope ratio, 0.35 % RSD for the 66Zn:70Zn isotope ratio and 0.26 % RSD for the 66Zn:67Zn isotope ratio has been obtained for a solution containing 500 ng ml⁻¹ of Zn. There is a little scope for further improvement of the precision of Zn isotopic ratios, as is indicated by Table 7.3, however, the limited number of dwell times available for the optimisation of noise reduction prevents further improvement to be made in practice. The accuracy of Zn isotopic ratio measurements was found to be good, following correction for dead time, mass bias and background interference effects, ratios were typically biased by between 0.2 and 10 %.

7.4 BORON ISOTOPE RATIO MEASUREMENT

7.4.1 Introduction
Boron has two naturally occurring isotopes 10B (~19 %) and 11B (~81 %). As a consequence of the high mobility of boron in the natural environment, relatively large isotopic fractionation occurs, which makes measurement of the 11B:10B isotope ratio useful in determining the origin and history of various geological sample types. For example, it is possible to deduce whether brines and evaporites are of marine or
non-marine origin, as sea water and marine evaporite borates are enriched in $^{11}\text{B}$ relative to those of non-marine origin.

The low mass and large relative mass difference between the two B isotopes, approximately 10%, cause instrumental mass bias factors for $^{11}\text{B}:^{10}\text{B}$ isotope ratio measurements made by ICP-MS to be large. Mass bias factors as large as 20% have been reported [10]. The accuracy of $^{11}\text{B}:^{10}\text{B}$ isotope ratios is also susceptible to bias due to B contamination, primarily from glassware. Boron contamination is best kept to a minimum by replacing glassware with plasticware wherever possible.

7.4.2 Data acquisition parameters and noise reduction
Boron isotope ratio measurement was made using a VG PlasmaQuad II+ instrument (FI Elemental, Winsford, Cheshire, UK). The data acquisition parameters selected for use in B isotope ratio measurement are summarised in Table 7.7. Peak jumping was utilised as it makes more efficient use of the available acquisition time than scanning (Table 5.1), and in doing so minimises the theoretical counting statistic. For each isotope, three measurement positions were utilised, these being located at the apex of the isotopic peak and at a distance of 0.05 u either side of the apex.

As for Zn isotope ratio measurement (Section 7.2), a dwell time of 10.24 ms was utilised, yielding a high frequency cut-off of 49 Hz (Equation 5.3). Use of three measurement positions per isotope gave an elapse time of 63.44 ms (Equation 5.1), hence, ratioing of the B isotopes occurred at a rate of 15.8 Hz, to provide attenuation of noise frequencies below 7.9 Hz. A ratioing frequency of 7.9 Hz ought to have been sufficient to minimise the detrimental influence of $1/f$ and peristaltic pump induced noise (Section 4.3)
Table 7.7: Data acquisition parameters for B isotope ratio measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition Mode</td>
<td>Peak Jumping</td>
</tr>
<tr>
<td>Quadrupole Rest Mass</td>
<td>9 u</td>
</tr>
<tr>
<td>Quadrupole Settle Time</td>
<td>2 ms</td>
</tr>
<tr>
<td>Detector Dead Time</td>
<td>24 ns</td>
</tr>
<tr>
<td>Number of Isotopes</td>
<td>2</td>
</tr>
<tr>
<td>Dwell Time per Channel</td>
<td>10.24 ms</td>
</tr>
<tr>
<td>Points per Peak</td>
<td>3</td>
</tr>
<tr>
<td>Acquisition Time</td>
<td>120 s</td>
</tr>
<tr>
<td>Replicate Measurements</td>
<td>5</td>
</tr>
</tbody>
</table>

Between the cut-off frequency associated with rationing of isotopes at 7.9 Hz, and the high cut-off frequency of the dwell time at 49 Hz, the summation of sweeps is effective in reducing noise with frequencies other than those in close proximity to the reciprocal of the sum of the elapse time and settle time, and its harmonics. Only noise frequencies in close proximity of 15.3 Hz (the reciprocal of 65.44 ms), 30.6 and 45.8 Hz are not attenuated. The summation of 916 sweeps reduces the width of the bandpass at these frequencies to 0.014 Hz (Equation 5.5).

The data acquisition parameters given in Table 7.7 were assessed for use in minimizing sample introduction and plasma noise by holding the quadrupole mass analyser at a fixed position upon the apex of the $^{10}$B isotopic peak, while the multi-channel analyser collected data in the six channels associated with the two B isotopes as normal. The measurement precision obtained for the B isotopic ratio should approximate the counting statistic, if the data acquisition parameters are appropriate for reduction of coherent noise. The measured precision for the isotope ratio was 0.10 % RSD, while the theoretical precision, obtained from counting statistics was 0.08 % RSD.

The measurement precision of the B isotope ratio, for a solution containing 25 ng ml$^{-1}$ of NIST SRM 951 ($^{11}$B:$^{10}$B = 4.0436), was measured for eight consecutive determinations, each consisting of five, 120 s integrations. The internal precision, within determinations,
averaged 0.20 % RSD, while the external precision over the eight
determinations was 0.29 % RSD.

7.4.3 Mass calibration
Where possible mass calibration should be undertaken using elements
in close proximity to the isotopes of interest. The skipped mass regions
of 11.5 to 23.5 u and 27.5 to 41.5 u, necessary to prevent detector
saturation from C, N, O and Ar species, somewhat limits the isotopes
of low mass available for use in mass calibration of B. A mass
calibration solution containing 100 ng ml\(^{-1}\) of Li, Be, Mg, Al, Mn and
Co, in addition to B, was used NIST SRM 951, which is supplied as
H\(_3\)BO\(_4\), and has a certified value of the \(^{11}\)B:\(^{10}\)B isotope ratio of 4.0436,
was used in preparation of the mass calibration solution. The isotopes
utilised in mass calibration were \(^7\)Li, \(^9\)Be, \(^{10}\)B, \(^{11}\)B, \(^{24}\)Mg, \(^{27}\)Al, \(^{55}\)Mn
and \(^{59}\)Co.

7.4.4 Dead time correction
Of the two methods for determination of the dead time detailed in
Section 6.4, only that involving measurement of one or more ratios at a
number of analyte concentrations was considered useful for B isotope
ratio measurement. As B is highly vulnerable to mass bias, with
instrumental mass bias factors of 20 % having been reported [10],
determination of the correct dead time, as that which provides
equivalent mass bias factors for two or more solutions of B of known
isotopic composition was considered to be inappropriate.

A series of solutions containing B (NIST SRM 951), at concentrations
of 1, 2.5, 5, 10 and 25 ng ml\(^{-1}\), were analysed using the data acquisition
parameters given in Table 7.7. To prevent error in selection of the dead
time, arising from instrumental drift during analysis, the series of
solutions were ordered 5, 1, 10, 2.5 and 25 ng ml\(^{-1}\). The \(^{11}\)B:\(^{10}\)B isotopic ratios were calculated for dead times of 20, 30, 35, 40, 45 and
50 ns, the results of which are shown in Figure 7.3. The measured
\(^{11}\)B:\(^{10}\)B isotope ratio for the three highest analyte concentrations (5, 10
and 25 ng ml\(^{-1}\)) were found to converge at a dead time of
approximately 24 ns. For B concentrations of 1 and 2.5 ng ml\(^{-1}\), the
measured B isotope ratio is believed to have been influenced by
background interference from B contamination, as is suggested by the
Figure 7.3: Dependence of observed mass bias for the $^{11}$B:$^{10}$B isotope ratio, at varying B concentrations, upon the dead time used in dead time correction.
bias observed in the mass bias and dead time corrected isotopic ratios given in Table 7.8. To ensure that the dead time correction applied to samples was accurate, their B concentration was adjusted to around 25 ng ml\(^{-1}\) prior to isotopic ratio analysis.

Table 7.8. Influence of analyte concentration upon B isotope ratio

<table>
<thead>
<tr>
<th>Concentration of NIST SRM 951 (ng ml(^{-1}))</th>
<th>Bias* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-0.57**</td>
</tr>
<tr>
<td>1.0</td>
<td>-0.21</td>
</tr>
<tr>
<td>2.5</td>
<td>-0.17</td>
</tr>
<tr>
<td>5.0</td>
<td>-0.02</td>
</tr>
<tr>
<td>10.0</td>
<td>-0.01</td>
</tr>
<tr>
<td>25.0</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

* bias = \(\frac{\text{measured ratio} - 4.0436}{4.0436} \times 100\) for mass bias and dead time corrected B isotope ratios

** reflects ratio of B contamination observed in blank

7.4.5 Mass bias correction
As mentioned in Section 7.4.1, large mass bias factors are a common occurrence in determination of B isotopic ratios by ICP-MS. As B has only two isotopes and the non-linear nature of the mass response curve below 10 u is likely to preclude use of Li as an internal isotopic reference, the only feasible means for mass bias correction involves use of an external isotopic reference. At least two B isotopic reference materials of natural abundance are commercially available, NIST SRM 951 \((^{11}\text{B}:^{10}\text{B} = 4.0436)\) and CBNM IRM 011 \((^{11}\text{B}:^{10}\text{B} = 4.1576)\), for use as primary standards in mass bias correction.

NIST SRM 951 was utilised, herein, as an external isotopic reference for determination of the instrumental mass bias. To monitor mass bias shift, a solution containing 25 ng ml\(^{-1}\) of NIST SRM 951 was run following each fourth sample, equivalent to an interval of approximately 1.5 h. Across nine such measurements, extending to
almost 16 h, the observed mass bias for the $^{11}\text{B}:{^{10}\text{B}}$ isotope ratio was found to vary between 7.6 and 8.4%. The mass bias factor utilised in mass bias correction (Equation 6.4), assuming mass bias to be a linear function of mass, was based upon that measured for the first and fifth determinations of the value of the $^{11}\text{B}:{^{10}\text{B}}$ isotope ratio for NIST SRM 951.

7.4.6 Interference effects

No correction for isobaric interference is necessary for B, however, spectral overlap of $^{11}\text{B}$ and $^{12}\text{C}$ can occur, if high levels of C are present in samples. However, the groundwater samples analysed herein had a low C content. Non-spectroscopic interference caused by high concentrations of matrix elements are at their most severe for light elements such as B. To remove matrix elements (Mg, Ca, K, and particularly Na) Amberlite IRA 743 anion exchange resin was utilised, which also allowed pre-concentration of B where necessary.

Contamination is the most probable form of interference likely to be experienced in B isotopic ratio measurement. Boron contamination may occur during sample preparation or introduction, as a result of adsorption or desorption on glass surfaces, particularly those of the nebuliser. The $^{11}\text{B}:{^{10}\text{B}}$ isotope ratio for the procedural blank was found to have a value of 4.021, which is consistent with that for B of natural isotopic abundance. To identify the source of B contamination, reagents utilised in pre-concentration and preparation of water samples were analysed to determine their B content. Ammonium hydroxide, used in adjusting the pH of water samples to 8.0, prior to anion exchange, was found to be the primary source of B contamination, containing several ng ml$^{-1}$ of B, some thirty times that present in 18 MΩ water. Passing NH$_4$OH through Amberlite IRA 743 anion exchange resin was found to give a six-fold reduction in B concentration.

To minimise B contamination resulting from memory effects a time study was made of the wash-out time necessary for the $^{11}\text{B}$ signal intensity to return to the blank level. Decay of the $^{11}\text{B}$ signal intensity was found to extend to almost 8 min. As a 2 min delay existed between commencement of sample uptake and attainment of a steady state signal, a wash-out time of 6 min was considered to be adequate.
Measurement of the value of the $^{11}\text{B} : ^{10}\text{B}$ isotope ratio was undertaken for a solution containing 25 ng ml$^{-1}$ of NIST SRM 951 in 1 M HNO$_3$ and for a similar solution which had first undergone sample preparation, involving anion exchange, to determine whether B contamination was problematic. Three determinations, each consisting of five integrations, for the solution having been treated as a ground water, gave a mean value for the $^{11}\text{B} : ^{10}\text{B}$ isotope ratio of $4.035 \pm 0.009$ (0.27 % RSD), while that for the untreated reference standard was $4.037 \pm 0.011$ (0.22 % RSD). The difference between these values is statistically insignificant, thus, it may be concluded that, for samples with a B concentration in the region of 25 ng ml$^{-1}$, analyte contamination did not make a significant contribution to offset of the measured ratio.

### 7.4.7 Accuracy

The accuracy of the measured B isotope ratio for five determinations of a solution containing 25 mg ml$^{-1}$ of NIST SRM 951, expressed as a percentage bias from the certified value is given in Table 7.9. The measured $^{11}\text{B} : ^{10}\text{B}$ isotope ratios, determined over almost 10 h, are shown to deviate from their certified value by between -0.67 and +0.23 %. The accuracy of the overall method, including sample preparation, given by NIST SRM 951, which had been treated as a ground water sample and undergone anion exchange, was found to be similar, at between -0.43 and -0.04 % ($n = 3$).
7.5 LEAD ISOTOPE RATIO MEASUREMENT

7.5.1 Introduction

Interest in Pb isotope ratio measurement, in geochemistry and related disciplines, stems from the radioactive decay of $^{238}\text{U}$ to $^{206}\text{Pb}$, $^{235}\text{U}$ to $^{207}\text{Pb}$ and $^{232}\text{Th}$ to $^{208}\text{Pb}$, as was shown in Figure 2.1. Only $^{204}\text{Pb}$ is non-radiogenic and has remained unchanged through time. As such, $^{204}\text{Pb}$ is crucial in providing information about the genesis of rocks and magmas and in radiometric age determination. The low abundance of $^{204}\text{Pb}$, in natural samples, generally limits the measurement precision of Pb isotopic ratios in which it is involved. The $^{204}\text{Pb}$ isotope also suffers from an isobaric overlap with $^{204}\text{Hg}$. Having a natural abundance...
approximately five times that of $^{204}\text{Pb}$, $^{204}\text{Hg}$, poses a threat to the accuracy of Pb isotope ratios, even where Hg is only present at trace level. The high mass and wide range of natural abundance of the Pb isotopes can also complicate high accuracy measurement of Pb isotopic ratios.

7.5.2 Data acquisition parameters and noise reduction
The data acquisition parameters selected for high accuracy Pb isotope ratio measurement are summarised in Table 7.10. Data acquisition was once again undertaken in the peak jumping mode. A dwell time of 10.24 ms being favoured, for all isotopes, independent of their isotopic abundance, to give a high frequency cut-off of 49 Hz (Equation 53). The narrow mass range being studied allowed use of a 2 ms settle time, as opposed to the standard of 10 ms.

Three acquisition points per peak were utilised because it provided a crude method of identifying mass shift, and hence, suspect isotopic data. Additionally, three points per peak allowed the maximum accumulated count to approximate $48 \times 10^6$ ion counts, thrice that attainable using a single point per peak, since the multi-channel analyser limits the maximum count per channel to $16 \times 10^6$ ion counts. Use of three points per peak was necessary to attain a sizeable count for $^{204}\text{Pb}$, which with a natural abundance of just 1.4 %, is a primary restriction to the theoretical counting statistic.

Table 7.10: Data acquisition parameters for Pb isotope ratio measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition Mode</td>
<td>Peak Jumping</td>
</tr>
<tr>
<td>Quadrupole Rest Mass</td>
<td>200 u</td>
</tr>
<tr>
<td>Quadrupole Settle Time</td>
<td>2 ms</td>
</tr>
<tr>
<td>Detector Dead Time</td>
<td>32.5 ns</td>
</tr>
<tr>
<td>Discriminator Level</td>
<td>40</td>
</tr>
<tr>
<td>Number of Isotopes</td>
<td>4</td>
</tr>
<tr>
<td>Dwell Time per Channel</td>
<td>10.24 ms</td>
</tr>
<tr>
<td>Points per Peak</td>
<td>3</td>
</tr>
<tr>
<td>Acquisition Time</td>
<td>120 s</td>
</tr>
<tr>
<td>Replicate Measurements</td>
<td>10</td>
</tr>
</tbody>
</table>

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To permit internal mass bias correction it was necessary to include the thallium isotopes (\(^{203}\text{Tl}\) and \(^{205}\text{Tl}\)) in the data acquisition procedure. The number of isotopes to be measured increased from four to six, or seven if the nature of the sample material had necessitated correction for isobaric interference from \(^{204}\text{Hg}\) on the minor Pb isotope. Utilising three acquisition points per peak and a dwell time of 10.24 ms, sequential measurement of six isotopes proved to be ineffective in minimisation of instrumental noise. With an elapse time, as defined in Section 5.3.2, of 195 ms, the ratioing of isotopes is inadequate for reduction of low frequency noise, as the band-pass extends to frequencies as low as 2.6 Hz.

To attain measurement precision approaching counting statistic levels for Tl mass bias corrected Pb isotopic ratios it was found necessary to measure the Pb isotope ratios on an individual basis. Hence, both Tl isotopes and two of the four Pb isotopes were measured within any given data acquisition procedure. The elapse time was, therefore, reduced to 129 ms. For both the \(^{205}\text{Tl}:^{203}\text{Tl}\) and Pb isotope ratios noise reduction extended to a frequency of 5.2 Hz.

Between the lower and upper cut-off frequencies given by ratioing of isotopes and the dwell time, respectively, noise reduction occurs as a result of the comb filter effect given by the summation of sweeps. Only noise frequencies in close proximity to the reciprocal of 130.88 ms and associated harmonics (7.64, 15.28, 22.92, 30.56, 38.20 and 45.84 Hz) are not attenuated. A total of 916 sweeps were acquired and summed in the multi-channel analyser during the acquisition time. As a result, the width of the bandpass at the above frequencies was just 0.007 Hz (Equation 5.5).

Using the data acquisition parameters given in Table 7.10, the measurement precision for the Tl and Pb isotope ratios, obtained for a fixed mass position upon the apex of the \(^{206}\text{Pb}\) isotopic peak, averaged 0.08 % RSD for \(^{205}\text{Tl}:^{203}\text{Tl}\) and 0.06 % RSD for \(^{207}\text{Pb}:^{206}\text{Pb}\) (n = 3). These compared favourably with the theoretical counting statistic, which for the first determination had a value of 0.05 % RSD. The RSDs of 10 replicate integrations forming a determination, for normal operation were somewhat higher, averaging 0.12 % RSD for \(^{205}\text{Tl}:^{203}\text{Tl}\) and 0.13 % RSD for \(^{207}\text{Pb}:^{206}\text{Pb}\) (n = 5).
7.5.3 Mass calibration
Lying at the upper end of the mass range, the Pb isotopes are susceptible to mass scale shift resulting from instability of the quadrupole mass analyser (see Figure 6.3). As mentioned in Section 7.5.2, use of three data acquisition points per isotope allowed mass scale shift to be monitored, but did not provide a means for correction. However, in instances where mass shift was suspected, re-calibration of the mass scale was undertaken prior to analysis of the sample which followed. The isotopes utilised in mass calibration were $^{203}\text{Tl}$, $^{205}\text{Tl}$, $^{206}\text{Pb}$, $^{207}\text{Pb}$, and $^{208}\text{Pb}$.

The nature of mass scale shift is such that the larger the difference in mass of the measured isotopes, the greater the influence upon the isotope ratio, as was shown in Figure 6.3 For this reason, the lightest and heaviest isotopes being measured have been ratioed to give a monitor ratio for correction of mass scale shift. Any integration which gave a monitor ratio outwith two standard deviations of the mean value, for integrations within the determination were rejected as outliers. This test was undertaken iteratively, never more than twice, until all remaining monitor ratios occurred within two standard deviations. Statistical outliers were found in the monitor ratio ($^{203}\text{Tl}$-$^{208}\text{Pb}$) where no outliers were observed in either the Tl or Pb isotopic ratios.

7.5.4 Dead time correction
The instrumental dead time was determined by calculation of the observed mass bias for the $^{205}\text{Tl}$:$^{203}\text{Tl}$ and $^{208}\text{Pb}$:$^{207}\text{Pb}$ isotope ratios. These isotopic ratios were chosen as they have similar values, $^{205}\text{Tl}$$^{203}\text{Tl}$ = 2.3871 and $^{208}\text{Pb}$$^{207}\text{Pb}$ = 2.3704 for NIST SRM 981 The data acquisition parameters, with the exception of the dead time, given in Table 7.10 for minimisation of instrumental noise were utilised. The observed mass bias factors for the $^{205}\text{Tl}$:$^{203}\text{Tl}$ and $^{208}\text{Pb}$:$^{207}\text{Pb}$ isotopic ratios were found to converge at a dead time of approximately 32.5 ns, as shown in Figure 7.4.

7.5.5 Mass bias correction
Mass bias corrections were performed using the thallium correction method, validated by Ketterer et al. [11], by spiking each of the Pb samples with Tl to a concentration of 1000 ng ml$^{-1}$. The $^{205}\text{Tl}$:$^{203}\text{Tl}$ isotope ratio has a fixed and known value of 2.3871. Measured mass bias factors for both the $^{205}\text{Tl}$:$^{203}\text{Tl}$ isotope ratio and the $^{207}\text{Pb}$:$^{206}\text{Pb}$
Figure 7.4: Dependence of observed mass bias for the $^{205}$Tl:$^{203}$Tl and $^{208}$Pb:$^{206}$Pb isotope ratios upon the dead time used in dead time correction.
isotope ratio for NIST SRM 981, having a certified value of 0.91464, may be seen from Table 7.11 to be of the order of 0.73 % u⁻¹. To attain equivalent mass bias factors for both isotopic ratios it was first necessary to accurately correct for detector dead time.

### 7.5.6 Interference effects

As mentioned above and in Chapter 3, Pb suffers from only one isobaric interference, ²⁰⁴Pb being overlapped by ²⁰⁴Hg. Working solutions of NIST SRM 981 were found to contain Hg in insufficient quantities to necessitate measurement of ²⁰²Hg for correction of ²⁰⁴Hg on ²⁰⁴Pb. The ion count observed on masses 202 and 203 u were comparable for a solution containing 1000 ng ml⁻¹ of NIST SRM 981.

<table>
<thead>
<tr>
<th>Sample</th>
<th>²⁰⁵Tl ²⁰³Tl</th>
<th>²⁰⁷Pb ²⁰⁶Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.66</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>0.69</td>
<td>0.78</td>
</tr>
<tr>
<td>3</td>
<td>0.74</td>
<td>0.69</td>
</tr>
<tr>
<td>4</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>5</td>
<td>0.77</td>
<td>0.70</td>
</tr>
<tr>
<td>Mean</td>
<td>0.72</td>
<td>0.73</td>
</tr>
<tr>
<td>RSD* (%)</td>
<td>0.087</td>
<td>0.038</td>
</tr>
</tbody>
</table>

* calculated for 1 standard deviation

### 7.5.7 Accuracy

Isotopic data obtained for five samples, each containing 1000 ng ml⁻¹ of NIST SRM 981, are given in Table 7.12. Each of the Pb isotopic ratios were measured individually using the optimum data acquisition parameters as detailed in Table 7.10 The measured isotopic ratios for NIST SRM 981 are shown to be in good agreement with the certified ratios, following correction for mass bias and mass scale shift. The measured precision (RSD) for the Pb isotopic ratios, given in Table 7.12, is that obtained for one standard deviation of the mean of the five replicate determinations. The counting statistic, however, represents the uncertainty associated with measurement for a single integration.
7.5.8 Summary of Pb isotopic ratio measurement

An external measurement precision of 0.12 % RSD was obtained for the $^{207}\text{Pb}:^{206}\text{Pb}$ isotope ratio without correction for mass dependent drift effects. Following mass scale and mass bias correction, an improved external measurement precision of 0.038 % RSD was realised. The acquisition parameters required for reduction of instrumental noise limited the number of Pb isotopic ratios which may be simultaneously measured to one. The use of one point per peak as opposed to three may permit measurement of up to seven isotopes without incurring significant reduction in measurement precision. The mean values of the measured Pb isotope ratios, given in Table 7.12, all lie within 0.3 % of their certified value.

Table 7.12 Accuracy and precision of Pb isotope ratios for NIST SRM 981

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{204}\text{Pb}$</th>
<th>$^{206}\text{Pb}$</th>
<th>$^{207}\text{Pb}$</th>
<th>$^{206}\text{Pb}$</th>
<th>$^{208}\text{Pb}$</th>
<th>$^{206}\text{Pb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0593</td>
<td>0.9153</td>
<td>2.1706</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.0591</td>
<td>0.9149</td>
<td>2.1715</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.0592</td>
<td>0.9143</td>
<td>2.1715</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.0593</td>
<td>0.9146</td>
<td>2.1698</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.0593</td>
<td>0.9148</td>
<td>2.1712</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean: 0.0592  0.9148  2.1709

RSD* (%): 0.12  0.038  0.033

Counting Stat (%): 0.15  0.048  0.041

Certified Value: 0.059042  0.91464  2.1681

2 Sigma: 0.000037  0.00033  0.0008

* calculated for 1 standard deviation
References
CHAPTER EIGHT
CONCLUSIONS

8.1 CONCLUSIONS

8.1.1 Introduction
In this chapter the results presented in the preceding chapters will be discussed, problems experienced and instrumental limitations highlighted and conclusions drawn.

8.1.2 Noise sources and their reduction
Noise spectra obtained for monitoring of both ion current and pulse counting data were found to be 'coloured' by a number of excess noise components. Discrete frequency noise components arising from rotation of the peristaltic pump head and 1/f noise were observed in low frequency noise spectra (extending to 5 Hz). In noise spectra for the frequency range 0 to 400 Hz, prominent discrete frequency noise components were associated with the a.c line frequency and the ICP discharge. With the exception of the weak discrete noise components observed at approximately 475, 525 and 575 Hz, all noise sources were similar to those described elsewhere for ICP-MS and/or ICP-AES.

The instability for ion current signals was calculated as being composed by approximately 40% white noise, 40% 1/f noise and 20% frequency dependent noise. Further breakdown revealed that the counting statistic accounted for some 60% of white noise.

The ICP has generally been regarded as the major source of instrumental noise in ICP-MS instruments, causing measurement precision (RSD) for isotopic ratios to be well above that given by the theoretical counting statistic. It was shown in Chapter 5 that noise components inherent to both isotopes, e.g. noise derived from the ICP and sample introduction processes, can be virtually eliminated upon ratiotting. Optimisation of data acquisition parameters for the reduction of noise has been based upon information obtained from noise power spectra. The success of noise reduction has been due to filter effects provided by the peak jumping mode of data collection in conjunction with the use of a multi-channel averager. Data collection parameters
were chosen, so as to provide filtering effects, which precluded discrete noise components from entering the isotopic ratios.

8.1.3 Accuracy and precision of isotopic ratio measurements

The external measurement precision for isotopic ratios, determined using optimised data acquisition parameters, was found to exceed the theoretical counting statistic. External precision was poorer than internal precision, as very low frequency noise was influencing isotopic ratios measured across several determinations. For a fixed mass position, the measurement precision and theoretical counting statistic were found to be equivalent (Table 6.1). The absence of residual noise for a fixed mass position proves that instabilities observed between determinations arose from the quadrupole mass analyser or ion optics. Forms of instrumental instability which show a dependence upon mass, e.g. mass scale and mass bias, were found to cause decrease in the reproducibility of isotopic ratio measurements.

It was shown, in Chapter 7, that the magnitude of the various sources of inaccuracy which combine to offset the measured ratio from its 'true' value, are largely dependent upon the mass and abundances of the isotopes of the element under investigation. For instance, mass scale shift and dead time correction are more problematic in accurate measurement of Pb than B isotopic ratios. There is no one definitive method for the correction of bias applicable to all elements, instead, it is necessary to assess and select correction procedures on an individual basis. Various methods for correction of dead time, mass bias, mass shift and interference effects were detailed in Chapters 6 and 7. The most appropriate of these methods were chosen for measurement of B, Zn and Pb isotopic ratios to achieve high accuracy and precision.

The accuracy and precision obtained for Pb isotopic ratio measurement of common Pb, reference material NIST SRM 981, was given in Table 7.12. The $^{207}$Pb:$^{206}$Pb isotope ratio was measured as $0.9148 \pm 0.0004$ (mean $\pm$ standard deviation), compared with a certified value of 0.91464. The bias from the certified value is 0.013 %, well within the one standard deviation (RSD = 0.043 %). The precision and bias of $^{207}$Pb,$^{206}$Pb isotope ratio measurements, for NIST SRM 981, taken from the literature were given in Table 2.1. Only measurements made
using a multiple collector, magnetic sector based ICP-MS instrument are of a superior accuracy and precision [1,2]. Utilising a standard nebuliser and spray chamber configuration, the multiple-collector ICP-MS instrument gave a precision of 0.011 % RSD and bias of -0.058 % [1]. These are not far removed from the accuracy and precision given herein. In both studies the Pb concentration was 1000 ng ml⁻¹.

The bias, expressed as a percentage difference from the certified value, for the \(^{208}\text{Pb}:^{206}\text{Pb}\) and \(^{204}\text{Pb}:^{206}\text{Pb}\) isotope ratios, given in Table 7.12, was 0.13 % and 0.30 % (n = 5), respectively. Certified values for NIST SRM 981 are 2.1681 for \(^{208}\text{Pb}:^{206}\text{Pb}\) and 0.059042 for \(^{204}\text{Pb}:^{206}\text{Pb}\). As is the case for these Pb isotope ratios, accuracy generally decreases as the true value of the isotope ratio extends from unity.

Accuracy has been investigated in absolute terms, in order to identify bias, arising during sample preparation and/or analysis. Although the accuracy of isotopic ratios determined by ICP-MS is almost exclusively expressed in absolute terms, this is not always necessary, in fact, absolute accuracy is probably only necessary in a minority of instances. Absolute accuracy is paramount for geochronology, but in tracer studies and environmental monitoring it is unnecessary. To know how the isotopic ratio of samples relates to a base value is often sufficient, e.g. the natural value of the Zn isotope ratio(s) if studying Zn absorption by administration of an enriched stable isotope, or identifying Pb pollution relative to the background isotopic signature.

In stable isotope mass spectrometry, of the light elements (H, C, N, O and S), the abundance of the minor isotope, e.g. \(^{13}\text{C}\), is expressed as a parts per thousand (‰) difference from a standard. Thus, for the oxygen composition of a sample \(x\):

\[ \delta^{18}\text{O} = \left( \frac{^{18}\text{O} \cdot ^{16}\text{O}_x}{^{18}\text{O} \cdot ^{16}\text{O}_{\text{standard}}} - 1 \right) \times 1000 \quad (8.1)[3] \]

The standard, as defined in Equation 8.1, may be an actual reference material, e.g. NIST SRM 981 (common Pb), or a natural abundance material, if undertaking a tracer study using one or more enriched isotopes.
Expressing isotopic ratios obtained by ICP-MS as a difference from a traceable standard may be more useful and appropriate in many instances. The corrected Zn isotopic ratios for meat digests, given in Table 7.6, were biased by as much as -1.67 and 1.41 %. These bias factors exceed the measurement precision, which was ≤ 0.35 % RSD for all six measured Zn isotopic ratios. It ought to be possible to reproducibly measure isotopic ratios, relative to a reference material, to within the precision of the data. The standard and sample x would require to be of equivalent concentration and have been prepared for analysis using the same method.

If two or more isotopic reference materials were available, each with a distinct isotopic ratio, preferably spanning the range likely to be measured in samples, the measured and certified difference(s) between these materials may used to provide a linear regression correction method for offset in samples. A similar technique is used in H and O isotopic ratio measurement of water samples, two reference materials are available, the first being the standard as defined in Equation 8.1 and the second being highly depleted compared with natural abundance samples [3]. A third reference water (intercomparison material) having an isotopic ratio, relative to the standard, of approximately half that of the second reference material, can be used to check the fit of the linear correction. Unfortunately, at present there are few metallic elements for which two or more isotopic reference materials exist, however, many laboratories will possess materials of well known isotopic composition in sufficient quantity for this purpose.

8.1.4 Overcoming instrumental limitations

The stability of quadrupole mass analysers places a fundamental limitation upon the accuracy and precision for isotopic ratio measurements made by quadrupole based ICP-MS instruments. The precision of measurements made by quadrupole mass analysers is fundamentally limited to approximately 0.02 % RSD [4]. However, for isotopic ratio measurement the fundamental limit may never be met as the theoretical counting statistic may be greater. This is especially true for isotopic ratios with values remote from unity.
The method for the collection and storage of data utilised by the ICP-MS instruments used herein is far from ideal for isotope ratio measurement. A single integration involves sweeping the selected isotopes or mass range several thousand times. Each of these sweeps is begun at the lowest mass position. Between sweeps the mass analyser is rapidly returned to the first mass position. The ability to transverse the mass range in both ascending and descending order, if it were available, would increase the efficiency of data collection. There would no longer be any need for a settle time between sweeps, hence, the duration of the cycle time would be trimmed. The length of the settle time between isotopes could also be reduced to a few tenths of a millisecond, since the largest mass skip would have been cut from perhaps 6 u to no more than 2 u. The settle time necessary for stabilisation of the mass analyser is directly dependent upon the width of the mass skip. By removing a potential source of mass instability, sweeping of the mass range in both ascending and descending order is also likely to improve the precision of isotopic ratio measurements.

The limited choice of available dwell times provides the user with only three practical choices for isotope ratio measurement in the peak jumping mode (5.12, 10.24 and 20.48 ms). A wider selection of dwell times would provide greater flexibility and allow for more effective use of the available acquisition time and sample volume. Although the mass difference between adjacent isotopes may vary greatly, for instance when requiring to measure both U and Pb isotopic ratios in geochronological age determination, the same settle time is used following each skip. It would be advantageous if the settle time between isotopes could be defined on an individual basis, to prevent loss of stability during large mass skips or waste of precious acquisition time during skips of just 1 u.

To increase the precision of isotopic ratios involving a isotope of low abundance, e.g. $^{70}$Zn or $^{204}$Pb, it is necessary to increase the accumulated count. As sample volume may be limited it will not always be practical to raise the accumulated count to the required level by increasing the data acquisition time. Increasing the transportation efficiency at one or more points in the ICP-MS system will raise the count rate on not just the minor isotopes, but all isotopes. Unless the
Linearity of ion counting at high count rates can be extended, improvement in transportation efficiency will increase bias in measured isotopic ratios, as well as providing improved measurement precision. If a detection system were available which could count at several MHz without counting fatigue, it would be useful if accumulated counts of up to $100 \times 10^6$ could be stored in a single data channel.

It would be of great benefit, not only in isotope ratio measurement, but generally, if steps were made to provide intelligent software which could reduce the scope for error in parameters such as the dead time, detector gain and discriminator level, which are currently user definable. Automated methods of checking the detector gain and discriminator values would reduce the probability of offset arising from pulse pile-up. As would a fully automated means for calculation of the dead time. It may be feasible to utilise species such as Ar dimer, Xe or ArO as 'analytes' and vary their intensities by automated detuning of an ion lens, hence providing a range of apparent concentrations from which the dead time, to be subsequently used in dead time correction, could be determined.

There are a few instrumental modifications, currently available, which may provide a small but significant improvement in the accuracy of isotopic ratio measurements, beyond that given herein. Recent advances in interface geometry, which reduce instrumental mass bias by flattening of the mass response curve, if suitably robust, may go some way towards removing mass bias as a contributing factor in offsetting the measured isotope ratio from its true value (see Figure 7.1). Discrete dynode-electron multipliers give lower background counts than continuous-dynode detector systems and increased counting logic efficiency, reducing dead times to several nanoseconds. Discrete dynode-electron multipliers are likely to reduce the influence of concentration upon pulse-pile up and, hence, pulse pile-up upon offset.

8.1.5 Further work
The ICP remains the most robust of methods, used in analytical chemistry, for ion production of metallic elements. The ICP is as appropriate a source for isotopic ratio measurement as thermal
ionisation, as has been shown by isotopic ratio measurements made at a fixed mass and by multiple-collector, magnetic sector ICP-MS [1,2]. The high cost of magnetic sector based instruments will continue to make the use of quadrupole based ICP-MS instruments attractive in measurement of isotopic ratios, for which a measurement precision of ≥ 0.05 % RSD is acceptable.

Hyphenated systems such as HPLC-ICP-MS, LA-ICP-MS and CE-ICP-MS are increasingly being used in separation of metallic species. The low volumes of eluting species obtained from HPLC and CE may necessitate use of more recently developed methods for introduction of samples into the ICP, such as direct injection nebulisation (DIN), or desolvation devices such as Mistral (FI Elemental, Winsford, Cheshire, UK). Introduction of liquid samples by nebulisation has been shown herein to make a significant contribution to the overall instability. Little is known about the nature and magnitude of instrumental noise added by the use of hyphenated systems, whether or not alternative methods of nebulisation are utilised. If hyphenated systems are to be utilised most effectively in determination of isotopic ratios, then characterisation of instrumental noise and optimisation of data acquisition parameters requires to be undertaken. Attainment of high precision isotopic ratio measurement for hyphenated ICP-MS systems, and in particular for LA-ICP-MS, may be realised by adoption of the noise reduction techniques used herein. Utilising noise spectral analysis, additional sources of instrumental noise can be identified and data acquisition parameters selected which minimise their detrimental influence upon measurement precision.

The various forms of offset, discussed in Chapters 6 and 7, are likely to be even more problematic in hyphenated ICP-MS systems than for ICP-MS. In HPLC-ICP-MS and CE-ICP-MS where analytes and standards are time displaced and chromatographic peaks may be of varied height and width, the influences of mass bias, background and pulse pile-up upon measured isotopic ratios are likely to be considerable. In LA-ICP-MS mass bias resulting from high concentrations of matrix elements is likely to significantly offset measured isotopic ratios from their true value. Use of the protocol developed in Chapter 7 for minimisation of bias in isotopic ratio
measurement ought to be helpful in overcoming these offsets. Optimised conditions may provide improved accuracy and precision, which would be useful in areas such as human pathology of Fe, Cu or Zn bioavailability, permitting identification of the chelates or species involved by stable isotope tracer study.
References
APPENDIX

COMPUTER PROGRAMS FOR NOISE SPECTRAL ANALYSIS
(ASYST v.3.1)

Collection of low frequency range noise spectra

FORGET.ALL \ Reset system
DAS20 \ Configure A/D converter
STACK CLEAR

TOKEN DATA.BUFFER \ Allocate memory space
EXP.MEM> DATA.BUFFER \ for data array

INTEGER SCALAR AQU.POINTS \ Define acquisition
\ parameters
INTEGER SCALAR START CHNL
INTEGER SCALAR END CHNL
INTEGER SCALAR AQU.GAIN
REAL SCALAR AQU.RATE

8192 AQU POINTS := \ Allocate values to
\ acquisition parameters
0 START.CHNL :=
0 END CHNL :=
1 AQU GAIN :=
50 AQU.RATE :=

INTEGER DIM[ AQU POINTS ] ARRAY DATA BUFFER \ Define data array

20 STRING FILENAME
START CHNL END CHNL A/D TEMPLATE DEMO.TEMPLATE \ Select to collect data from
\ channel 0
AQU.POINTS TEMPLATE.REPEAT \ Set number of data points
\ to 8192

DATA.BUFFER TEMPLATE.BUFFER
CYCLIC
AQU RATE CONVERSION.DELAY \ Set sampling rate to 20
\ points per second
AQU.GAIN A/D.GAIN \ Set input range to +/- 10 \ volts
A/D.INIT \ Initialise A/D converter
A/D.IN>ARRAY \ Collect data

FILE.TEMPLATE \ Define datafile format
3 COMMENTS
INTEGER DIM[ AQU.POINTS ] SUBFILE
END

: DATA STORE \ Subroutine for storage of \ datafile
SCREEN.CLEAR
CR. " ENTER FILE NAME (INCLUDING DIRECTORY) : "
"INPUT FILENAME "="
FILENAME DEFER> FILE.CREATE
FILENAME DEFER> FILE.OPEN
" SINGLE CHANNEL "
1 >COMMENT
" 8192 POINTS "
2 >COMMENT
" 20 POINTS/SEC "
3 >COMMENT
1 SUBFILE
DATA.BUFFER ARRAY>FILE
FILE CLOSE
;

DATA.STORE \ Save datafile on disk
Collection of audible frequency range noise spectra

FORGET.ALL \ Reset system
DAS20 \ Configure A/D converter
STACK CLEAR

TOKEN DATA.BUFFER \ Allocate memory space
EXP.MEM> DATA.BUFFER \ for data array

INTEGER SCALAR AQU.POINTS \ Define acquisition parameters
INTEGER SCALAR START.CHNL
INTEGER SCALAR END CHNL
INTEGER SCALAR AQU.GAIN
REAL SCALAR AQU.RATE

24576 AQU.POINTS.:= \ Allocate values to acquisition parameters
0 START.CHNL.:=
0 END.CHNL.:=
5 AQU.GAIN.:=
1 AQU.RATE.:=

INTEGER DIM[ AQU.POINTS ] ARRAY DATA.BUFFER \ Define data array

20 STRING FILENAME

START CHNL END.CHNL A/D.TEMPLATE DEMO.TEMPLATE \ Select to collect data from channel 0
AQU.POINTS TEMPLATE.REPEAT \ Set number of data points to 24576
DATA BUFFER TEMPLATE.BUFFER CYCLIC
AQU.RATE CONVERSION.DELAY \ Set sampling rate to 1000 points per second
AQU.GAIN A/D.GAIN \ Set input range to +/- 0.5 volts
A/D INIT \ Initialise A/D converter
A/D IN>ARRAY \ Collect data
FILE TEMPLATE \ Define datafile format
3 COMMENTS
INTEGER DIM[ AQU POINTS ] SUBFILE
END

: DATA STORE \ Subroutine for storage of
datafile
SCRREEN.CLEAR
CR." ENTER FILE NAME (INCLUDING DIRECTORY) : "
"INPUT FILENAME ":=
FILENAME DEFER> FILE.CREAE
FILENAME DEFER> FILE OPEN
" SINGLE CHANNEL ":
1 >COMMENT
" 24576 POINTS ":
2 >COMMENT
" 1000 POINTS/SEC ":
3 >COMMENT
1 SUBFILE
DATA BUFFER ARRAY>FILE
FILE.CLOSE
;

DATA.STORE \ Save datafile on disk
Calculation of low frequency range noise spectra

FORGET.ALL \ Reset system
STACK.CLEAR

TOKEN SINGCHNL.DATA \ Allocate memory
EXP.MEM> SINGCHNL DATA \ for experimental data

TOKEN POWERSPEC \ Allocate memory
EXP.MEM> POWERSPEC \ for transformed data

TOKEN TIME SCALE \ Allocate memory
EXP.MEM> TIME.SCALE \ for time

TOKEN FREQ.SCALE \ Allocate memory
EXP.MEM> FREQ.SCALE \ for frequency

INTEGER DIM[ 10 ] ARRAY FREQ.INTGRS

INTEGER SCALAR AQU.POINTS \ Define variables
INTEGER SCALAR AQU.RATE
INTEGER SCALAR COUNT
INTEGER SCALAR 8TH AQU POINTS
INTEGER SCALAR POSN.IN.ARRAY
REAL SCALAR SIGNAL.AMPLITUDE

20 STRING FILENAME
20 STRING 123.FILENAME

8192 AQU POINTS := \ Allocate values to variables
20 AQU RATE := \ representative of acquisition
AQU.POINTS 8 / 8TH AQU POINTS := \ parameters

: FILE.RETRIEVAL \ Subroutine for the retrieval of experimental data
SCREEN.CLEAR \ stored on disk
CR ." ENTER FILE NAME (INCLUDING DIRECTORY) . "
"INPUT FILENAME ":=
FILENAME DEFER> FILE OPEN
1 SUBFILE
FILE>UNNAMED ARRAY \ Place retrieved data
BECOMES> SINGCHNL.DATA
FILE.CLOSE
;

FOURIER

\begin{verbatim}
COUNT := 80 DO
SINGCHNL.DATA
SUB[ COUNT, 8TH.AQU.POINTS, 1 ]
FFT ZMAG

POWERSPEC +
BECOMES> POWERSPEC
COUNT 8TH.AQU.POINTS +
COUNT :=
LOOP
POWERSPEC
8 /
BECOMES> POWERSPEC
POWERSPEC [ 1 ] SIGNAL.AMPLITUDE :=
SUB[ 2, 8TH.AQU.POINTS 2 /, 1 ]
SIGNAL.AMPLITUDE / LOG
20 *
BECOMES> POWERSPEC
;
\end{verbatim}

TIME.AXIS.CREATION
TIME.SCALE
8TH.AQU.POINTS REAL RAMP 1 -
AQU.RATE /
BECOMES> TIME.SCALE
;

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: FREQ.AXIS.CREATION
FREQ.SCALE
8TH AQU.POINTS REAL RAMP 1 -
AQU RATE *
8TH AQU.POINTS /
SUB[ 2 , 8TH.AQU.POINTS 2 / , 1 ]
BECOMES> FREQ.SCALE
;

: INTEGER.TO.FREQ
1 COUNT :
10 0 DO
FREQ.INTGRS [ COUNT ]
POSN IN.ARRAY :=
FREQ.SCALE [ POSN.IN.ARRAY ]
CR
COUNT 1 +
COUNT =
LOOP
;

: FREQ COMPONENT.ANALYSIS
3 SET #.POINTS
10 SET.# OPTIMA
POWERSPEC LOCAL MAXIMA
SWAP
FREQ.INTGRS :=
INTEGER.TO.FREQ
;

· FILE.CREATION
SCREEN CLEAR
CR ." ENTER 123-FILE NAME (EXTN. WKS) : "
"INPUT 123.FILENAME " =
123 FILENAME DEFER> 123FILE.CREATE
123 FILENAME DEFER> 123FILE OPEN
3 1 123WRITE.DOWN
FREQ SCALE ARRAY>123FILE
3 2 123WRITE.DOWN
POWERSPEC ARRAY>123FILE
123FILE CLOSES
FILE RETRIEVAL

\ Retrieve experimental data

FOURIER

\ Create power spectrum

TIME.AXIS.CREATION

\ Create time axis

FREQ.AXIS.CREATION

\ Create frequency axis

FILE CREATE

\ Save power spectrum

GRAPHICS.DISPLAY

\ Create graphics window

VUPORT.CLEAR

VUPORT UPPER

VUPORT LOWER

UPPER

0.2 0 6 VUPORT.ORIG

0.8 0 4 VUPORT.SIZE

LOWER

0.2 0 2 VUPORT.ORIG

0.8 0.4 VUPORT.SIZE

TIME SCALE

SINGCHNL.DATA

SUB[ 1 , 8TH.AQU.POINTS , 1 ]

UPPER XY.AUTO PLOT

\ Plot experimental data vs time

FREQ.SCALE

POWERSPEC

LOWER XY.AUTO PLOT

\ Plot power spectrum vs frequency

FREQ COMPONENT ANALYSIS

\ Locate discrete frequency components
Calculation of audible frequency range noise spectra

FORGET.ALL
STACK CLEAR

TOKEN SINGCHNL.DATA
EXP.MEM> SINGCHNL.DATA

TOKEN POWERSPEC
EXP.MEM> POWERSPEC

TOKEN TIME.SCALE
EXP.MEM> TIME.SCALE

TOKEN FREQ.SCALE
EXP.MEM> FREQ SCALE

INTEGER DIM[10] ARRAY FREQ.INTGRS

INTEGER SCALAR AQU.POINTS
INTEGER SCALAR AQU RATE
INTEGER SCALAR COUNT
INTEGER SCALAR 24TH.AQU POINTS
INTEGER SCALAR POSN.IN.ARRAY
REAL SCALAR SIGNAL.AMPLITUDE

20 STRING FILENAME
20 STRING 123.FILENAME

24576 AQU POINTS :=
1000 AQU.RATE =
AQU.POINTS 24 / 24TH AQU POINTS =

: FILE.RETRIEVAL
SCREEN.CLEAR
CR ." ENTER FILE NAME (INCLUDING DIRECTORY) : ":
"INPUT FILENAME ":=
FILENAME DEFER> FILE.OPEN
1 SUBFILE
FILE>UNNAMED.ARRAY

\ Reset system
\ Allocate memory
\ for experimental data
\ Allocate memory
\ for transformed data
\ Allocate memory
\ for time
\ Allocate memory
\ for frequency
\ Define variables
\ Allocate values to variables
\ representative of acquisition parameters
\ Subroutine for the retrieval of experimental data stored on disk
\ Place retrieved data
BECOMES> SINGCHNL.DATA \ in allocated memory
FILE.CLOSE
;

: FOURIER \ Subroutine for
\ transformation to the
\ frequency domain &
\ conversion to a
\ power spectrum

1 COUNT :=
24 0 DO
SINGCHNL.DATA
SUB[ COUNT , 24TH AQU.POINTS , 1 ] \ Select a 1 Kbyte
FFT ZMAG \ slice of data
POWERSPEC + \ Fourier transform &
BECOMES> POWERSPEC \ take the magnitude
\ of the complex array
POWERSPEC + \ Add transformed
BECOMES> POWERSPEC \ data with that for the
\ previous 1 Kbyte
COUNT 24TH AQU.POINTS + \ slices
COUNT :=
LOOP \ Repeat for all
POWERSPEC \ 1 Kbyte slices
24 /
BECOMES> POWERSPEC \ Obtain mean slice
POWERSPEC [ 1 ] SIGNAL AMPLITUDE = \ from combined
SUB[ 2 , 24TH AQU POINTS 2 / , 1 ] \ data slices
SIGNAL.AMPLITUDE / LOG \ Scale transformed
20 *
BECOMES> POWERSPEC \ data in decibels
;

: TIME.AXIS.CREATION \ Subroutine for
\ generation of
\ time axis
TIME SCALE
24TH.AQU.POINTS REAL RAMP 1 -
AQU.RATE /
BECOMES> TIME.SCALE
;

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FREQ_AXIS_CREATION
FREQ_SCALE
24TH_AQU_POINTS_REAL_RAMP 1 -
AQU_RATE *
24TH_AQU_POINTS /
SUB[2, 24TH_AQU_POINTS 2 /, 1]
BECOMES > FREQ_SCALE
;

INTEGER_TO_FREQ
1 COUNT :
10 0 DO
FREQ_INTGRS [ COUNT ]
POSN_IN_ARRAY :=
FREQ_SCALE [ POSN_IN_ARRAY ]
CR
COUNT 1 +
COUNT :=
LOOP
;

FREQ_COMPONENT_ANALYSIS
3 SET # POINTS
10 SET #.OPTIMA
POWERSPEC LOCAL.MAXIMA
SWAP
FREQ_INTGRS :=
INTEGER TO FREQ
,
,

FILE_CREATE
SCREEN.CLEAR
CR ." ENTER 123-FILE NAME (EXTN WKS) : "
"INPUT 123.FILENAME ":=
123.FILENAME DEFER > 123FILE.CREATE
123.FILENAME DEFER > 123FILE.OPEN
3 1 123WRITE DOWN
FREQ_SCALE_ARRAY > 123FILE
3 2 123WRITE DOWN
POWERSPEC ARRAY > 123FILE
123FILE.CLOSES

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FILE.RETRIEVAL \ Retrieve experimental data
FOURIER \ Create power spectrum
TIME.AXIS.CREATION \ Create time axis
FREQ.AXIS.CREATION \ Create frequency axis
FILE.CREATE \ Save power spectrum
GRAPHICS.DISPLAY \ Create graphics window
VUPORT.CLEAR
VUPORT UPPER
VUPORT LOWER
UPPER
0 2 0.6 VUPORT ORIG
0 8 0.4 VUPORT.SIZE
LOWER
0 2 0.2 VUPORT.ORIG
0 8 0.4 VUPORT.SIZE
TIME.SCALE
SINGCHNL.DATA
SUB[ 1 , 24TH AQU POINTS , 1 ]
UPPER XY.AUTO.PLOT \ Plot experimental data vs. time
FREQ SCALE
POWERSPEC
LOWER XY.AUTO.PLOT \ Plot power spectrum vs. frequency
FREQ.COMponent.ANALYSIS \ Locate discrete frequency components