

Studies of Artificial Mass Bias in Isotopic Measurements by Inductively Coupled Plasma Mass Spectrometry

Henrik Andrén

Luleå University of Technology
Department of Chemical Engineering and Geosciences, Division of Chemistry

Abstract

Mass spectrometry, and especially inductively coupled plasma mass spectrometry (ICP-MS), suffers heavily from mass bias, or instrumental mass discrimination. The nett result of this effect is the preferential transmission, most often of heavier ions through the mass spectrometer. Most work regarding this phenomenon in ICP-MS dates back quite far, and has been interpreted in terms of the space-charge effect. This means that Coulombic forces acting on the beam of positively charged particles extracted from the ICP result in greater dissipation of lighter, and hence more mobile ions from the beam axis. In this work the importance of the space-charge effect as a universal explanation for mass bias is challenged by the results of high precision measurements of isotope ratios. Other than considering some commonly known sources of isotope ratio measurement bias, a not previously considered mechanism of isotopic fractionation has been investigated, i.e. diffusion in solution.

It was established that, indeed, diffusion does lead to isotopic fractionation in solution, and although this is a long term process, may contribute to the minor isotopic variations observed in certain aquatic environments. Furthermore it was established that spectral interferences of ArO^+ could be discerned from Fe^+ using high resolution ICP-MS, thus eliminating this potential source of artificial fractionation. Most significant was the discovery that the extent of mass bias varied throughout the volume of the plasma, and was further affected by sample characteristics, such as analyte concentration and acid strength. This identifies the plasma itself as the major source of instrumental mass discrimination. Varying the sampling position, i.e. the point at which ions are extracted from the plasma, not only affected the measured isotope ratios, but also the precision of such measurements. From these results, it is not recommended to measure at the sampling position providing maximum signal, since the variability in the isotope ratio is also at its' maximum there. Instead, the ions should be sampled from a point below the maximum, where the stability of the ratios will be better.

This thesis is based on the following papers that are hereafter referred to by their Roman numerals.

- I I. Rodushkin, A. Stenberg, H. Andrén, D. Malinovsky and D. C. Baxter. Isotopic fractionation during diffusion of transition metal ions in solution. *Anal. Chem.*, 2004, **76** (7), 2148-2151.
- II D. Malinovsky, A. Stenberg, I. Rodushkin, H. Andrén, J. Ingri, B. Öhlander and D. C. Baxter. Performance of high resolution MC-ICP-MS for Fe isotope ratio measurements in sedimentary geological material. *J. Anal. At. Spectrom.*, 2003, **18**, 687-695.
- III H. Andrén, I. Rodushkin, A. Stenberg, D. Malinovsky and D. C. Baxter. Sources of mass bias and isotope ratio variation in multi-collector ICP-MS: Optimization of instrumental parameters based on experimental observations. *J. Anal. At. Spectrom.*, 2004, **19**, 1217

The following papers have not been included in this thesis.

- A A. Stenberg, D. Malinovsky, I. Rodushkin, H. Andrén, C. Pontér, B. Öhlander and D. C. Baxter. Separation of Fe from whole blood matrix for precise isotopic ratio measurements by MC-ICP-MS: a comparison of different approaches. *J. Anal. At. Spectrom.*, 2003, **18**, 23-28.
- B A. Stenberg, H. Andrén, D. Malinovsky, E. Engström, I. Rodushkin and D. C. Baxter. Isotopic variations of Zn in biological materials. *Anal. Chem.*, 2004, **76**, 3971-3978

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1 Introduction

Despite the fact that mass spectrometry has been around for a little more than a century, far from everything is understood about the technique. From Sir J. J. Thomson's positive ray parabola mass spectrograph,¹⁻³ used in 1886 to discover the two main isotopes of neon, ²⁰Ne and ²²Ne, to modern multi collector (MC) mass spectrometers (MS), anomalies not fully accounted for exist, one of the most persistent being the mass bias.^{4,5} In the modern industrial uses of mass spectrometry⁶ (MS) which can generally be dealt with by careful calibration of the spectrometer, this sufficiently corrects for the mass bias effect. However when isotopic measurements are conducted, careful consideration of this effect is a necessity and, indeed, hard to avoid since it is inherent in the design of all mass spectrometers.

1.1 Ion sources

Mass spectrometers do not measure actual mass as we are accustomed, but rather the amounts of a certain isotopes of given mass. The only thing distinguishing different isotopes is the number of neutrons in the atomic core, i.e. the mass. Since mass m is directly proportional to kinetic energy E_k according to

$$E_k = \frac{mv^2}{2}$$

where v is the velocity, energy can be utilised to separate isotopes. One of the easier ways to manipulate single atoms are to ionise and then have a force applied to them. There exist a number of different methods to create ions, but this work centres on the plasma⁷ technique.

1.1.1 Inductively coupled plasma

The inductively coupled plasma (ICP) works by heating a gas to about 10000K, thereby ionising it.⁸⁻¹⁰ This is done by injecting gas, predominately Ar, although experiments have been performed with other noble gases, like He^{11,12} or Ne^{13,14} into the centre of a conductive spool inside the torch (see Fig. 1), predominately made out of quartz, a so called load coil. The spool, commonly known as load coil, has a high current quickly alternating through it at a frequency of 2.72 MHz, creating an oscillating magnetic field. A spark ignites the gas by creating charges of both electrons and ions, set in motion by the electric field. Those charges heats up the rest of the gas primarily via collisions to a plasma, with electron atom collisions being the primary mechanism for ionisation. To protect the torch, as well as making the plasma toroidal instead of spherical, a high flow cooling gas is blown around it, creating a cooler interface region between the plasma and the torch. This also helps by forcing the plasma to roll into itself, creating a passage through the middle of the ball, giving the characteristic doughnut shape.

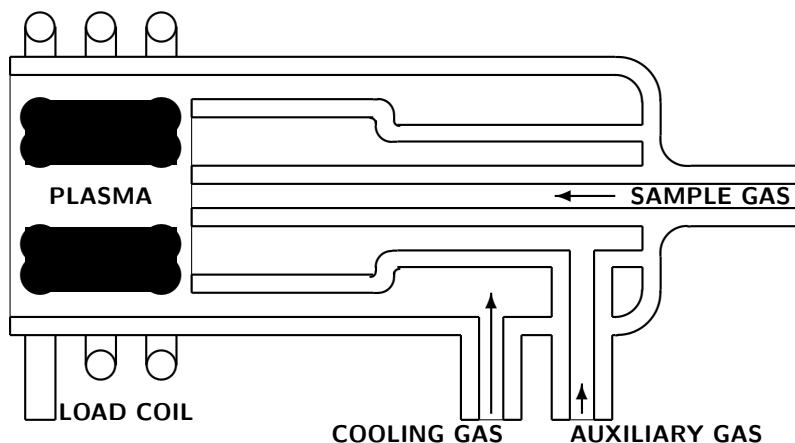


Figure 1: A very crude picture of the design of a plasma torch, showing the arrangement of concentric quartz tubes and load coil. The relatively slow moving auxiliary gas (see Table 1) creates the bulk of the actual plasma. The very high flow of cooling gas in the tight passage gives the plasma a toroidal shape for the sample gas to flow through in the slightly cooler ($\approx 6000\text{K}$) centre of the plasma.

Through this passage the analyte is then injected, in the form of an aerosol.^{15,16} The high temperature dries the aerosol, vaporises the constituent material and dissociates it into atoms, which are then ionised, most often by removal of a single electron. As an ICP is operated at atmospheric pressure and the mass spectrometer must be maintained under vacuum conditions, a differentially pumped region is required to interface these two system components. The interface is equipped with a set of cones,¹⁷ a sampler and a skimmer, both being water cooled, due to the proximity of the plasma, and the tips have orifice diameters of about a millimetre. A potential field is used to accelerate the positive ions through the cones and into the mass spectrometer.

The ICP is considered one of the most stable and efficient ionisation methods there are, the only one that can compete is the thermal ionisation (TI) source, being capable of higher efficiency for easily ionised elements.^{18,19}

1.1.2 Thermal ionisation mass spectrometry

Thermal ionisation²⁰ is carried out in a completely evacuated system. A thin filament of heat resistant material, predominantly Pt or Re, is loaded with the analyte in gel like form. When heated up inside a chamber, the ions produced are drawn through a potential field into the mass spectrometer.

Unlike in an ICP, where material is lost during sample introduction, dispersion in the plasma and non-quantitative transfer through the interface, most of the actual sample is utilised in a measurement by TIMS. This contributes to the very high precision that can be attained for easily ionised elements, but also that each sampling takes longer time. Sample preparation for a TIMS measurement is also generally more tedious procedure and modern multi collector inductively coupled plasma mass spectrometry (MC-ICP-MS) provides competing levels of accuracy and precision to TIMS. Also, the high ionisation potential of the Ar allows for more efficient sampling of the hard to ionise elements with ICP than TI.

1.2 Mass separation

To measure the different elements and their isotopes in the ion beam, they have to be separated according to mass, or rather as above by momentum. Actually, it is on a mass to charge (m/z) that ions are separated, since electromagnetic force is directly proportional to the discrete elemental charge of the ion. The quadrupole (see Fig. 2) is the most primitive method of doing this. It consists of four rods, with alternating potential fields applied between each other.

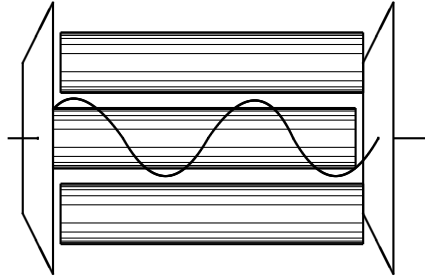


Figure 2: An illustration of a quadrupole, the foremost pole having been cut away to allow viewing of the beam, moving in a helical trajectory from the entrance to the exit slit. Only a narrow range of (m/z)-values (usually corresponding to 0.3-0.8 atomic mass units) will have stable trajectories at given frequencies and potentials and thus be transmitted through the mass filter.

The rapid alternations destabilise most of the ions in the beam, only one target mass being able to achieve a stable trajectory. The frequency or more commonly the amplitudes of the applied potential are then alternated to let different masses through.

Time of flight (TOF)^{21,22} is a more trivial method of mass separation, but technically advanced. Here an electronic shutter admits a sub- μ s ion pulse and then accelerates it in a potential field. Acceleration a is mass m dependent as

$$a = \frac{F}{m}$$

where F depends on the potential field and the ion charge z , generally being negative one elemental charge. Acceleration is then integrated over time to get a velocity v as

$$v = \int a \, dt = \int \frac{f}{m} \, dt = \frac{f}{m}t,$$

and then the distance s is divided by the velocity to get a time t . The lesser the time, the lighter the element. Since the force f is constant in the field, this means a separation of all particles in the pulse that is inversely proportional to mass. For lighter isotopes this varies a lot, but heavier isotopes like ^{234}U and ^{235}U the difference in time is very narrow. A longer flightpath helps with this, but since the beam is positively charged, it will deteriorate due to space charge effects and other phenomena in its' path.

The third method is to divide the beam according to m/z . If an equal force is applied perpendicularly to the flight path, the ions will deviate according to

$$r = \frac{mv^2}{F},$$

where r is the radius, depending on the force F , mass m and velocity v squared. Due to the direct mass relation, lighter isotopes will deviate with a smaller radius than heavier ones.

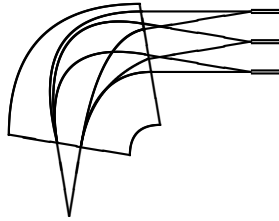


Figure 3: A cut out of a magnetic sector. Three distinct masses present in the ion beam deviate differently in the magnetic field and are individually brought to focus in separate detectors. A correct setting of ion lenses before the magnet is crucial to have the correct focal depth to the plane of the detectors.

This is done by letting the ion beam pass through a magnet. A moving charge in a magnetic field will experience a force applied to it according to

$$F = zvB,$$

giving our circular deviation as above. The force F is dependent on the charge z (one elemental charge for singly ionised elements), the velocity v and magnetic field strength B . The magnet (see Fig. 3) generally covers a $35^\circ - 130^\circ$ arc. The actual mass being observed may be altered by changing either the accelerating potential or the magnetic field strength to bring the ion of interest into the detector, which is generally referred to as a collector. A common type is the secondary electron multiplier (SEM)(see Fig. 4), also known as an ion counter. Each ion colliding with the sensor releases a couple of electrons from a dynode, which are accelerated to a second dynode, where even more electrons are emitted, finally generating a measurable pulse of current.

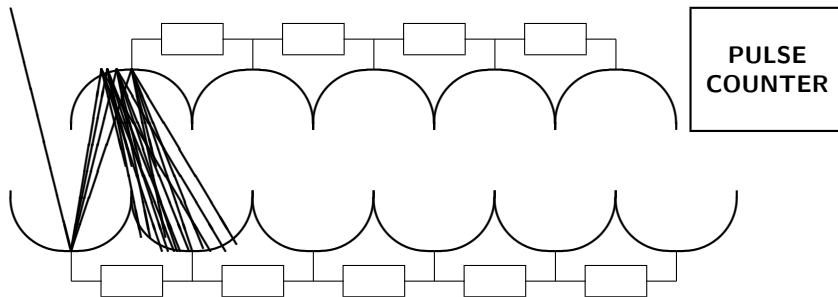


Figure 4: A sketch of a secondary electron multiplier. The impact of an ion at the first dynode release a few electrons from the surface. These are then drawn to the second dynode, accelerated by a great potential between them, where they release further electrons that are then accelerated to another dynode, creating a shower of electrons finally being accounted for by a pulse discriminator at the end of the dynode chain.

Another means of detection is to use a so called Faraday cup, a graphite box working like a black body, collecting the positive ions by neutralising them with electrons from its'

conductive surface. The current is then amplified and measured, giving a value for the intensity of the ion beam. This works best with thousand-fold higher intensities than the ion counter is used for.

For isotopic measurements, the magnetic force and potential field are generally held stable, and many collectors are used instead. These are arranged along the focal plane in an array to catch the beams of one isotope each (see Fig. 3), and with careful positioning this can be used to get rid of unwanted interferences.²³

1.3 Instrumentation

Most measurements for this research were conducted on a Thermo Finnigan Neptune MC-ICP-MS instrument. It was most often equipped with a double-pass Scott-type spray chamber, but for some experiments a low-volume dual cyclonic-Scott type spray chamber was used as well. The sample is fed through polypropylene tubing and injected with Ar gas at the base of the spray chamber with a micro concentric PFA nebuliser. The cyclotron inside separates the larger droplets by letting them collide with the chamber walls,¹⁵ to be drained by the same peristaltic pump used to inject the analyte. Self aspiration, i.e. letting the suction of the spray chamber itself draw the analyte through the tubing, was seldom used. A spray chamber serves to moderate the size and speed of the droplets in the aerosol. The spray chamber is directly linked to the Fassel torch, working with the typical gas flowrates seen in Table 1.

Table 1: The different ranges of parameters during typical cool (650 W), warm (1200 W) and hot (1500 W) plasma conditions.

Acc. volt.	-10000 V		
Ion lens	Optimised for maximum intensity and stability		
Sampler	Ni 1.1 mm diameter		
Skimmer	Ni 0.8 mm diameter		
RF power	650 W	1200 W	1500 W
	Argon gas flow rates (l/min):		
Sample	0.80-0.95	1.09-1.45	0.94-1.52
Coolant		15.8	
Auxiliary		0.3-1.5	

A guard electrode²⁴ is placed around the torch, and can be set floating (off) or grounded (on). This is to avoid spontaneous discharges between the cones and the electron cloud surrounding the plasma, with remarkable effects on signal intensity when activated. After passing the skimmer cone, the beam enters a set of ion lenses, plates and cylinders with different potentials. These shape the beam and assure that the focus at the collectors is set. To get this right mostly requires training, since the effect of the settings are almost unforeseeable. They also have to be adjusted each time the machine is started, since what holds for one day generally is not true the day after.

The Neptune is a double focusing mass spectrometer, meaning it is equipped with both magnetic sector and an electrostatic analyser (ESA). The latter is a 90° channel consisting of two potential plates, only letting ions of a specific kinetic energy through, as above, since anything going too fast will deviate too little and hit the outer plate and anything going too slowly will collide with the inner plate. The ESA is equipped with an aperture that can be set to one of three fixed widths to operate in high, medium and low resolution modes. In low

resolution mode with the widest aperture, Naturally this increases the intensity, generally by a factor of two between high and medium resolution, and another five between medium and low resolution. The drawback is that, as the beam becomes wider, interferences are harder to sort out. Then we have the focus quadrupole, a very important part of the lens system, making sure the beams entering the magnet stay on focus, as they still have a certain energy spread. After this comes the actual magnet, separating the ions according to energy. Finally a dispersion quad helps with the placement of the cups, by pressing the beams together or spreading them out. If two mass ranges are measured it can be used to alter the beam geometry without having to change the cup positions. Since the beams are tighter together at higher masses, it can also be used to spread them to expand cup spacing, or to press them together, to fit even lighter elements inside the limited mass range of the focal plane.

The Neptune in this work is fitted with nine Faraday cups, the central one being fixed on the axis and the other movable. The axial beam can also be deviated past the central cup into a SEM (see Fig 4) for precise measurements of low intensity beams.

The magnet and collectors are kept at a high vacuum of about 10^{-6} Pa, whereas the interface region is maintained at about 10^{-4} Pa. This pressure is maintained by turbo molecular pumps, and when the plasma is off, by shutters separating both the interface region and the high vacuum regions.

1.4 Isotope measurements

For determinations of element concentrations in most samples there is no need to consider isotope deviations as they are generally too small to have any significant impact on the measurements. When it comes to the question of isotopic fractionation, most fractionation mechanisms are chemical in nature,^{25,26} even though the isotopes of a given element have almost identical chemical properties. Bond strengths differ much more between elements than the minor effects cause by the slight alteration of mass for different isotopes. Measurements have already revealed the isotopic fractionation for lighter elements, such as O and N and man made fractionation has been accomplished with for example U. MS-ICP-MS has the potential to perform analogous studies of the heavier elements, complementing TIMS in situations where the latter technique is less efficient, e.g. for the large number of samples or for analytes that are difficult to ionise.^{25,26}

1.4.1 Spectral interferences

Isotopes of different elements can have the same mass number, for example ^{54}Cr and ^{54}Fe . This makes an analysis much more difficult, but also polyatomic molecular ions can survive the plasma or form in the region after the sampling cone, and species such as $^{40}\text{Ar}^{16}\text{O}^+$ are not uncommon, disturbing measurement of $^{56}\text{Fe}^+$.^{27,28} Although $^{56}\text{Fe}^+$ and $^{40}\text{Ar}^{16}\text{O}^+$ has the same mass number, they actually differ slightly in exact mass. This is a consequence of the fact that the sum of the masses of the elementary particles present in an atomic core is not the same as the actual mass of the nucleus. Increased density and bond strength between the nucleons means a measurable decrease in mass, i.e. a reduction in energy as required for the nucleus to be more stable than the isolated constituents. This mass defect, the deviation of the atomic mass from the sum of its' elementary particles, is different for each combination of neutrons and protons. For example, Fe has the greatest mass defect per nucleon, making it the most stable element there is. It is the same bond strength that only makes it possible for a limited number of different isotopes to exist.

1.4.2 Mass bias

All the advanced ion lenses and extraction devices of course add their own mass dependencies to the transmission of ions through the instrument. The beam itself is strictly positively charged, and thus works with a repelling force on the particles present. This is known as the space charge effect and obviously the lighter elements in the beam will deviate with more ease from the beam axis than the heavier ones. Furthermore, every part of the machine affects the composition of the result in some way. The composite effect is known as mass bias or mass discrimination, since the only thing separating isotopes apart, in any physical way, is the mass. This effect can be measured and calibrated as well as corrected for by comparison with isotopic standards.^{29,30} Of course, the accuracy of such determinations can never be better than the standard itself. These materials also have to be standardised in some way, and generally this is done by inter-laboratory comparison of TIMS measurements of a selected pure standard. The best average of these results, minus outliers, is then assumed to represent the true isotopic composition of this standard. Naturally this makes them very expensive, and when the standard has been consumed there is no more of that exact composition available. Another way to create a standard is to blend together mono isotopically enriched materials into a known composition, but that is even more costly. Such materials are used to calibrate TIMS equipment used for the determinant of absolute isotopic standards.

To make things even more complicated, the mass bias varies depending on the composition of the materials containing the analyte, the so called matrix, and may even exhibit time dependent and random fluctuations. The short term fluctuations are so rapid that a lot of the uncertainty from single collector come from the alternations of the plasma between sequential measurements, something that multi collectors deal with. Fewer parameters change during multi collection as well, meaning that mass bias is more stable. Still, measuring a standard every third or fourth sample is good practise, to observe how mass bias fluctuates in the long run.

2 Theory

2.1 Plasma physics

A plasma is an ionised gas, with such a high percentage of ionised bodies that they have significant impact on the behaviour of the gas.³¹ What distinguishes a plasma from a gas, where the predominant interactions between particles are kinetic, is that the charges experiences Coulombic forces, turbulences create positively and negatively charged areas, and currents flow between these. The currents create magnetic fields that further affect the plasma, and creates what is known as plasma turbulence.

There is no sharp boundary for when a gas becomes a plasma, unlike for example a solid and a liquid. Rather a gas can be considered a plasma when the electromagnetic forces become dominant over the purely kinetic forces. This is easiest to achieve in a low density, high temperature chamber, which is the common state of most experimental plasmas. For analytical purposes on the other hand, the low density means too little analyte, and therefore the plasma is formed at atmospheric pressure, meaning a density factor of some 10^9 times greater in comparison with a normal low pressure plasma.

The most common way of describing the level of ionisation in a plasma is by using the Saha equation,³¹⁻³³

$$\frac{n_i}{n_n} \approx \frac{2Q_i(T)}{Q_a(T)} \left(\frac{\pi m_e K}{h} \right)^{3/2} \frac{T^{3/2}}{n_e} e^{-\frac{U_i}{KT}} \quad (1)$$

giving the ratio of ions n_i to neutral atoms n_n as a function of the amount of electrons n_e . Here T is the gas temperature in K, K is Boltzmann's constant and U_i is the ionisation energy of the ions in question in J, not electron volts, m_e is the electron mass in kg and h is Planck's constant. Q_i and Q_a are the statistical weights of ions and atoms, commonly assumed to be $1/2$.³³ The first ionisation energy is the energy required for the atom in question to release the outermost electron, that is, the minimum energy to ionise it. Of course the Saha equation is just an approximation at best, but it can help to further understand a plasma in an open atmosphere.

Of course neither n_i nor n_e is generally known, but the total number of particles n per cubic meter should be equal to $n = n_i + n_e + n_n$, n_e and n_i are assumed to be equal and n can be deduced from the ideal gas law

$$pV = nRT.$$

At one atmosphere the pressure p would be some 101 325 Pa, R is the universal gas constant and V is 1 since n is a density rather than an amount. The temperature T is of course dependent on the plasma itself.

Considering a Fe plasma at a pressure of one atmosphere, solving³⁴ the Saha equation for n_i gives us a maximum at around 12000 K (see Fig 5). This is because the increase in temperature decreases the particle density according to the ideal gas law. This is a simplification though, since most of the plasma consists of Ar of a much higher ionisation potential. Naturally reality is considerably more complicated since a plasma is heavily turbulent, very compressible and experiences a number of other forces on it as it passes the load coil, but still, this gives a little understanding of why the temperature is optimal around 10000 K.

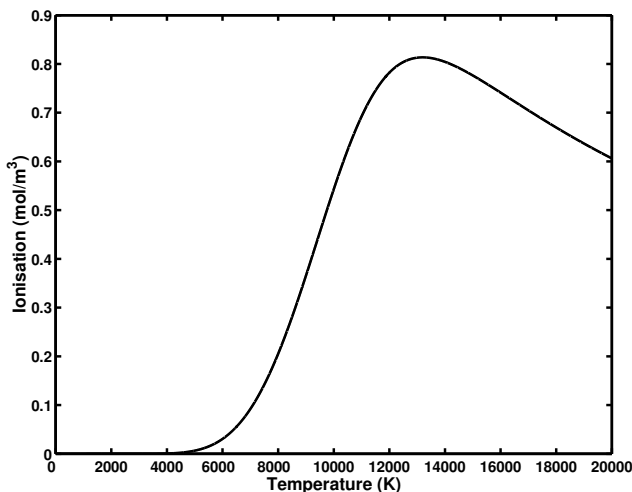


Figure 5: A display of the Fe^+ density of an atmospheric pressure plasma. The peak in density is the overlap of thermal expansion of the gas in corollary with the average ionisation of Fe at that temperature.

2.2 Mathematics

2.2.1 Splines

A spline interpolation is a piecewise fitting of data points,³⁵ considering the derivatives to assure smoothness of the function. Between each data point a cubic polynomial (third degree, $a_0 + a_1x + a_2x^2 + a_3x^3$) is fitted to match the data points as well as the first and second derivatives of its' neighbouring piecewise interpolants.

Example 2.1 *Interpolating a set of four data points, $p_1 = (x_1, y_1)$, $p_2 = (x_2, y_2)$, $p_3 = (x_3, y_3)$ and $p_4 = (x_4, y_4)$ gives the following equations*

$$\begin{aligned} p_1 &\rightarrow a_0 + a_1x_1 + a_2x_1^2 + a_3x_1^3 = y_1, \\ p_2 &\rightarrow a_0 + a_1x_2 + a_2x_2^2 + a_3x_2^3 = b_0 + b_1x_2 + b_2x_2^2 + b_3x_2^3 = y_2, \\ p_3 &\rightarrow b_0 + b_1x_3 + b_2x_3^2 + b_3x_3^3 = c_0 + c_1x_3 + c_2x_3^2 + c_3x_3^3 = y_3, \\ p_4 &\rightarrow c_0 + c_1x_4 + c_2x_4^2 + c_3x_4^3 = y_4, \end{aligned}$$

as well as the first and second order derivatives

$$\begin{aligned} p_2 &\rightarrow a_1 + 2a_2x_2 + 3a_3x_2^2 = b_1 + 2b_2x_2 + 3b_3x_2, \\ p_2 &\rightarrow 2a_2 + 6a_3x_2 = 2b_2 + 6b_3x_2. \\ p_3 &\rightarrow b_1 + 2b_2x_3 + 3b_3x_3^2 = c_1 + 2c_2x_3 + 3c_3x_3^2, \\ p_3 &\rightarrow 2b_2 + 6b_3x_3 = 2c_2 + 6c_3x_3. \end{aligned}$$

This leaves us with twelve unknowns and ten equations. To ensure a unique solution, the second derivatives of the endpoints can be set to equal zero, like

$$\begin{aligned} p_1 &\rightarrow 2a_3 + 6a_4x_1 = 0, \\ p_4 &\rightarrow 2c_3 + 6c_4x_4 = 0, \end{aligned}$$

giving us what is referred to as a natural spline, and a uniquely solvable system.

Cubic splines give a smoother fit of the data than polynomial approximations and they are also much better at fitting data that is not polynomial in its' behaviour, like Gaussian functions. The piecewise construction also means that slight errors do not propagate through the function and create unrealistic solutions for non data points.

2.2.2 Non-linear programming

Non-linear programming is a numerical optimisation method.³⁶ For a stated n dimensional problem, a starting point is given. Then the n dimensional derivative (gradient) of this point is numerically calculated, much like Newtons method for finding roots. This derivative points in the direction that the function increases the most, going in the opposite direction would, hopefully, lead us to the functional minimum. The crucial point is choosing the length of this movement, too far and the minimum will be missed, too short and you will never reach it.

There are numerous different softwares that can do this, in this research ordinary non linear programming packages of Matlab were used to minimise the weighted difference between a sloped Gaussian function and the research data. As weight a perfect Gaussian, centred more firmly over the maximum intensity point, was used.

In this work non-linear programming was employed to find a minimal deviation between measured values and a sloping normal distribution,

$$f(m) = he^{\frac{(x-\mu)^2}{(2\sigma)^2 + s(x)}}$$

where

$$s(x) = \begin{cases} t_l(\mu - x)^p & x \leq \mu \\ t_r(x - \mu)^p & x > \mu \end{cases},$$

μ is the position of the top of the peak, σ is the standard deviation, i.e. proportional to the width of the peak and h is the peak height. What distinguishes this from an ordinary normal distribution is $s(x)$, the slope function, because the tailing of the measured values is much more severe than in a normal distribution. Also, since the tailing before and after the peak is different, two coefficients were used t_l and t_r , as well as a specified power of tailing p .

Since it was the intensity peak that was of interest, the fitting was also weighted according to a weight function

$$w(x) = e^{-\frac{(x-\mu)^2}{\sigma^2}},$$

that is, much more narrow than the original function, to concentrate on the peak centre. The actual problem solved was

$$\min \left(\left(h(x_n) - h e^{-\frac{(x_n-\mu)^2}{(2\sigma)^2 + s(x_n)}} \right) w(x_n) \right) \text{ over } \mu, \sigma, t_l, t_r, p \quad \text{where } n = 1, \dots, m,$$

i.e. a five dimensional problem over the measurement points x_1, x_2, \dots, x_m .

2.3 Isotope ratios

The deviations of isotopic compositions are naturally very small from any reference values. The International Union of Pure and Applied Chemistry (IUPAC) releases a standardisation document about what isotope ratios can be considered natural³⁰ on a fairly regular basis. A deviation from this is generally quite small, unless there are radioactive elements involved. Therefore a good measure of such deviations has to be used, one common unit being the so called δ -value, defined as

$$\delta \frac{m}{n} = \left(\frac{\frac{m}{n} \text{M}}{\frac{m}{n} \text{A}} - 1 \right) \times 1000 \text{‰}$$

where M is the measured abundance of isotope n or m respectively, and A is the natural or reference abundance of the same isotope. Per mil is a good unit and all too commonly not even written out; care has also to be taken to note if heavier over lighter ($m > n$) or lighter over heavier ($m < n$) notation is used. The natural ratios do not have to follow the IUPAC recommendations, and are more generally the ratios of the isotopic standard the measurements are being compared to.

2.3.1 Mass bias correction

To be able to compensate for mass bias it has to be measured, since the phenomenon as manifested in ICP-MS is far from well understood. All elements in all manner of matrices behave slightly differently,³⁷ so regular calibration is preferable.^{5,25,38,39} Generally the calibrations are done with carefully TIMS measured isotopic standards, and the output of the ICP-MS analysis is then corrected to correlate with those values. Since ICP-MS succumbs to temporal variations in the plasma and therefore also mass bias, it should be calibrated many times during the day. Therefore, bracketing standards are recommended, every third or fourth measurement or so being an isotopic standard to keep the data on track. Furthermore, an internal standard is recommended, i.e. an element close in behaviour and mass to the analyte, but preferably not interfering with the actual measurement. This

internal standard can then be measured by MC-ICP-MS together with their analyte and used for on line correction of the measurements.

There are some different expressions for the mass bias, the most commonly exploited and at the moment most accurate being the exponential model^{4,25,39} that states that

$$\frac{{}^m\text{A}}{{}^n\text{A}} \approx \frac{{}^m\text{E}}{{}^n\text{E}} = \frac{{}^m\text{M}}{{}^n\text{M}} \left(\frac{n}{m} \right)^f,$$

where A is the true abundance of isotope with mass number m or n , E is the expected abundance from isotopic measurements of the element and M is the measured abundance. Since E is considered known when an isotopic standard is measured f , known as the mass bias factor, can be calculated via

$$f = \frac{\log\left(\frac{{}^m\text{E}}{{}^n\text{E}}\right)}{\log\left(\frac{{}^m\text{M}}{{}^n\text{M}} \left(\frac{n}{m}\right)\right)}.$$

Both the isotopic standard and the measured samples are spiked with an internal standard. From all bracketing standards measured during the day a relation between the mass bias factor of the isotopic standard, f_{ist} , and the spike, f_{spi} , can be observed,

$$f_{ist} = a f_{spi} + m.$$

It is then assumed that the spike and the analyte behave in the same way in the samples, thus a relation between the mass bias factor of the analyte f_{ana} and the spike can be established. Generally the behaviour is linear, thus

$$f_{ana} = a f_{spi} + m,$$

where f_{spi} now is the mass bias factor of the sample measured. Then f_{ana} can be considered known and used to calculate the expected ratio E from M as above.

2.3.2 Three isotope plots

A common evaluation tool for mass bias corrected data is a three isotope plot²⁶ (see Fig 6 drawn using the δ -values for two pairs of isotopes, sharing one common denominator. If the points do not form a straight line it is an indication that some of the isotopic measurements are not wholly correct. In such small intervals mass bias should deviate linearly depending on the mass difference between the isotopes. Most isotopic-selective processes seem to follow this behaviour.

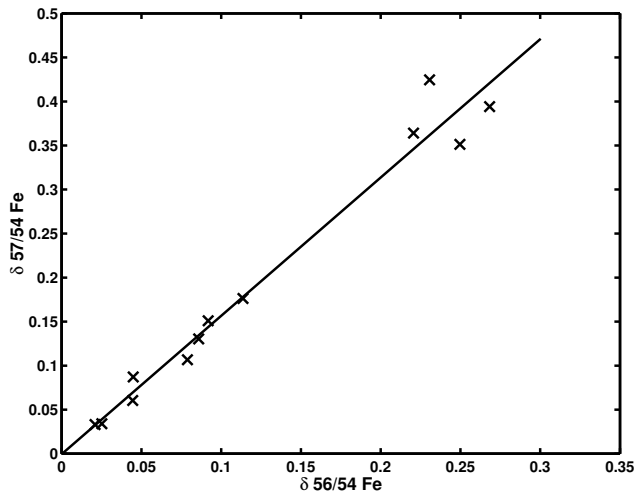


Figure 6: A normal three isotope plot, in this case of the main isotopes of Fe. The values in the upper right hand corner of the graph seems to deviate, perhaps as a result of spectral interferences, whereas the values in the lower left hand corner seem very consistent.

3 Causes of artificial mass fractionation

In this work we have encountered two of the more traditional sources of artificial mass fractionation, as well as encountering and quantifying a not so well known kind. Foremost, careful handling of the samples is of utmost importance, as any contamination is undesirable, and special care has to be taken to avoid inadvertent addition of any analyte. But also such things as careful consideration of matrix, both able to sustain the analyte in solution and preferably keep it in atomic solution.

3.1 Dissipation

No matter how carefully the solution is prepared, it can be understood from paper I that diffusion occurs, and has a mass bias effect. There both Fe and Zn were present in high initial concentrations, and then allowed to diffuse into clean solutions. By sampling the liquid at decreasing distances from the initial boundary between concentrated and analyte-free solutions, a mass bias was identified due to isotope specific rates of dissipation. Therefore samples should be prepared as late as possible and always shaken to homogeneity, otherwise artificial mass bias might be induced.

3.2 Spectral interferences

Another well explored but difficult to deal with source of artificial mass bias and general problems in measurement is spectral interferences. Isobaric overlaps, when elements close to one another have isotopes of the same mass number, are the hardest to deal with. The resolution of modern instrumentation is not capable of resolving such interferences. Instead, measurement of the interferent concentration using another one of its' isotopes and subtraction has to be done, or the sample has to be purified to a level where it is negligible. Careful considerations of the method then has to be taken, so as not to alter the isotopic composition

of the analyte. Another elemental overlap that is less common, but can still be disturbing is that of doubly charged species. They will be transmitted through the magnet as if they had half the mass, thus interfering with measurements far from their own mass range. Generally doubly and triply charged species are uncommon, but some elements have quite low second ionisation potentials and are thus candidates for this kind of interference. Generally the mass defect makes this resolvable, at least at the highest resolutions. Polyatomic interferences can also force you to run at higher resolution, like in paper II, where high resolution is used to be able to measure ^{56}Fe despite the interference of $^{40}\text{Ar}^{16}\text{O}^+$. Nevertheless, tailing of the interfering beam can still upset the measurement, since the beams are so close to one another and are not so compact as you might wish, but rather have a distribution not too far from Gaussian. This means that the edges still overlap to some extent with the part of the beam being analysed. Even if this just accounts for a very small portion of the signal it can become severe if the interfering signal is many times that of the analyte signal.

3.3 Plasma

The state of the plasma is not only paramount for the production of interfering species when it comes to mass bias, it produces its' own. Matrix effects are readily seen, as they suppress and enhance the signals in the plasma, also affecting mass bias and interferences. It can also be noted that different elements achieve maximum ion densities at different axial distances from the point of sample introduction in the plasma.⁴¹ What is harder to realise is that isotopes of the same element also peaks at different positions in the plasma. Paper III covers this to some extent, explaining what measures should be taken to obtain more stable and precise measurements.

Since it is not feasible to get rid of the mass bias in ICP-MS, the goal should be to make the bias as predictable and stable as possible, making it easier to calibrate for and correct. There is already a lot of knowledge in how to process samples, purify them to reduce interferences and how this affects mass bias. For spectral overlapping, a little more can be done. Blank subtraction methods have been long used to remove contributions from the always present elements, but the introduction of collision cell technology and high resolution capabilities in MC-ICP-MS instruments will allow many of the most problematic interferences to be eliminated.

4 Conclusions

Mass bias is something that will continue to plague ICP-MS measurements, but a greater understanding of why this phenomenon occurs and how to lessen the severity of its' effects is under way. Greater understanding of how an open air plasma works is essential for this, as well as all the rest of the strange and interesting matrix and solution problems that have been observed. It is this authors opinion that a greater collaboration between plasma physicists and plasma chemists would be most beneficial for both parties.

The technique of MC-ICP-MS has long been considered inferior to TIMS when it comes to accuracy and precision, but the latest generations of both are of comparable analytical power even for isotopic measurements. Research has already begun to come out of MC-ICP-MS equipped laboratories in such diverse fields as geological dating and medical examinations, even if the latter are only beginning to be explored researched, not commonly practised.

Nevertheless there is a high possibility that materials with specific isotope enrichment will become more widely used instead of radioactive tracers for the analysis of processes in the human body, identification of wear and tear in machines or for forensic science. So far

the equipment and sample handling costs require and the analysis of isotopic ratios are too high for common practise of the technique, but as with everything else the price decreases as the efficiency goes up, and single collectors for elemental analysis are already widespread in industry.

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