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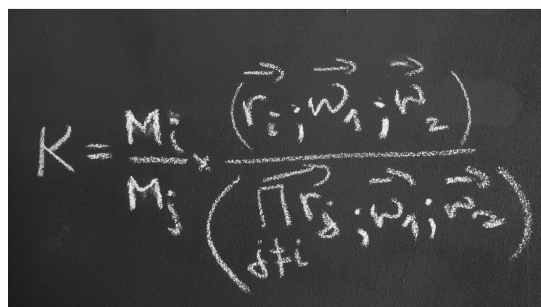
Calibration of isotope amount ratios by analysis of isotope mixtures

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Abstract. The question as to what constitutes a fully calibrated isotope amount ratio measurement still remains a topic of active research. For years, the definitive calibration approach has been by means of synthetic mixtures of highly enriched isotopes with known chemical purity to give gravimetrically defined ratios. This article outlines the core concepts and assumptions of this method and illustrates the recent developments in the practical metrology of isotope amount ratio measurements.


$$K = \frac{M_i}{M_j} \times \frac{(\vec{r}_i; \vec{w}_1; \vec{w}_2)}{(\prod_{i=1}^n \vec{r}_i; \vec{w}_1; \vec{w}_2)}$$

Keywords: metrology, mass spectrometry, isotope amount ratios

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1. Introduction

High-precision isotope amount ratio measurements play a significant role in science [1]. In fact, one of the most controversial questions posed by humankind was answered with this tool in the 1930s when lead and uranium isotope measurements revealed the advanced lower limit for the age of Earth [2]. Among other examples, direct determination of the Avogadro constant from near-perfect silicon crystal spheres requires measurement of the isotopic composition of silicon in those spheres [3], the 1972 discovery of a natural nuclear reactor in Gabon relied on high-precision measurements of uranium isotopic composition [4], and the historic 1932 discovery of deuterium hinged entirely on the fourth-digit discrepancy in the atomic weight of hydrogen [5]. Although isotope amount ratio measurements can be performed using techniques other than mass spectrometry (e.g., gravimetry, nuclear magnetic resonance, and infrared spectroscopy), mass spectrometry has become the de facto method for isotope amount ratio measurements. Not all mass spectrometry measurements, however, are calibrated. That is, the isotope amount ratios measured are not always free from the biases incurred during the measurement process. Even in the twenty-first century, calibrated isotope amount ratio measurements have never been performed for some 20 elements [6]. Hence, the need for calibration of isotope amount ratio measurements remains a state-of-the-art activity. Isotope ratio measurements often rely on the values compiled and evaluated by IUPAC in conjunction with various practical assumptions regarding the instrumental biases. This gives rise to popular methods such as internal normalization and double spike [7]. However, the question of how to obtain the primary values for isotopic composition remains.

2. Calibration

Calibration is set of operations that establish the link between the isotope amount ratio values indicated by a mass spectrometer and the corresponding values of standards. The metrological chain of measurement starts with a preparation of a primary calibrator (standard) with an assigned property value [8]. This is then used to calibrate the measuring system. So what constitutes a fully calibrated isotope amount ratio measurement in practice? For decades, the IUPAC Commission on Isotopic Abundances and Atomic Weights has recognized the approach pioneered by Alfred O. Nier in 1949 whereby isotope amount ratio measurements are calibrated by means of synthetic mixtures of highly enriched isotopes with known chemical purity to give gravimetrically defined ratios

[9]. The calibration is then performed from a direct analysis of such a mixture.

The assignment (synthesis) of the true isotope amount ratio values in synthetic isotope mixtures can be achieved from the mass measurements. In principle, when single crystals of pure isotopes are available, establishing the isotopic composition of the primary calibrator is a trivial matter of weighing the crystal samples in a desired proportion. As an example, a mixture of 28.98 g of ^{29}Si (1.000 mol) and 29.97 g of ^{30}Si (1.000 mol) yields the amount ratio $n(^{30}\text{Si})/n(^{29}\text{Si}) = 1.000 \text{ mol/mol}$.

In practice, however, before an isotope amount ratio can be assigned by gravimetric blending of isotopes, the enriched isotope materials must be evaluated for the presence of chemical impurities and for the presence of other minor isotopes. In particular, measurements of the isotopic composition of these materials raise circularity concerns since the results of these measurements cannot be calibrated yet. Hence, we arrive at the classic *catch-22* in metrology: how does one establish the primary standards?

Isotope amount ratio measurement results are expressed in the SI unit of moles per mole; hence, the preparation of a primary standard requires a primary realization of the mole. This can be done from the mass measurements since the (current) definition of the mole is related to the kilogram. Consider a two-isotope system of lithium. First, the isotopic composition, i.e., $n(^6\text{Li})/n(^7\text{Li})$, of lithium enriched in ^6Li is measured (r_A) and then the isotopic composition of lithium enriched in ^7Li is measured (r_B). Then, the isotopic composition of a mixture of these two materials is measured (r_{AB}). If the mass bias remains identical in all three measurements, then the true (mass-bias-corrected) isotopic composition of both enriched materials and their blend can be expressed as follows:

$$R_A = K r_A \quad (1)$$

$$R_B = K r_B \quad (2)$$

$$R_{AB} = K r_{AB} \quad (3)$$

Here R_A , R_B , and R_{AB} are the true isotope amount ratios (still unknown), r_A , r_B , and r_{AB} are the measured isotope amount ratios, and K is the bias in these measurement results (still unknown). At this point we have four unknown quantities (R_A , R_B , R_{AB} , and K) and only three equations relating them. Note, however, that R_{AB} depends on the isotopic composition of the enriched materials A and B:

$$R_{AB} = \frac{n(^6\text{Li}, A) + n(^6\text{Li}, B)}{n(^7\text{Li}, A) + n(^7\text{Li}, B)} \quad (4)$$

or

$$R_{AB} = \frac{x_{^6\text{Li}, A}(m_A/M_A) + x_{^6\text{Li}, B}(m_B/M_B)}{x_{^7\text{Li}, A}(m_A/M_A) + x_{^7\text{Li}, B}(m_B/M_B)} \quad (5)$$

where x and M are the (unknown) isotope abundances and the (unknown) molar masses of materials A and B, respectively. Isotope abundances can be expressed as isotope amount ratios. For example,

$$x_{6\text{Li},A} = \frac{n(^6\text{Li},A)}{n(\text{Li},A)} = \frac{R_A}{1 + R_A}, \text{ etc} \quad (6)$$

For the molar mass,

$$M_{\text{Li},A} = \frac{M_{6\text{Li}}R_A + M_{7\text{Li}}}{1 + R_A} \quad (7)$$

where $M_{6\text{Li}}$ and $M_{7\text{Li}}$ are the molar masses of ^6Li and ^7Li , respectively. Analogous expressions can be written for material B. Once the isotopic composition and molar masses of materials A and B have been expressed in terms of the (unknown) isotope amount ratios, Eq. (5) can be rewritten as follows:

$$R_{AB} = \frac{m_A R_A / (M_{6\text{Li}}R_A + M_{7\text{Li}}) + m_B R_B / (M_{6\text{Li}}R_B + M_{7\text{Li}})}{m_A / (M_{6\text{Li}}R_A + M_{7\text{Li}}) + m_B / (M_{6\text{Li}}R_B + M_{7\text{Li}})} \quad (8)$$

or

$$R_{AB} = \frac{n_A R_A (1 + R_A) + n_B R_B (1 + R_B)}{n_A (1 + R_A) + n_B (1 + R_B)} \quad (9)$$

We now have three equations (Eqs. (1), (2), and (8) or (9)) and three unknown quantities $-K$, R_A , and R_B . Traditionally, this system of expressions is solved using iterative algebra [10]. In the first iteration K is set to one ($K = 1$) and the values of R_A and R_B (obtained from r_A , r_B , and Eqs. (1), (2)) are used to calculate R_{AB} as per Eq. (8) or (9). Then, the “new” value of K is calculated from Eq. (3), i.e., $K = R_{AB}/r_{AB}$. This procedure is repeated until the value of K no longer diverges between the iterations. Note that both mass and the amount of substance can serve as the primary input quantities (Eqs. (8), (9)). The former can be obtained from the mass measurements of pure substances [11], whereas the latter can be established from chemical equivalent measurements by coulometry [12, 13].

Iterative calculations are often used when analytical solutions are hard to obtain. Early developments of the double spike and internal normalization methods for isotope ratio measurements [14], as well as the double spiking isotope dilution for quantitation of interconverting analytes, such as Cr(III) and Cr(VI), are examples of this [15]. Although they are useful, iterative solutions lack the mathematical rigor and are difficult to utilize in uncertainty propagation calculations. Analytical solutions are therefore an invaluable resource and such a solution of Eqs. (1), (2), and (8)

(or Eq. (9)) is as follows [16]:

$$K = \frac{M_{7\text{Li}}}{M_{6\text{Li}}} \frac{m_A(r_{AB} - r_A) + m_B(r_{AB} - r_B)}{m_A r_B(r_A - r_{AB}) + m_B r_A(r_B - r_{AB})} \quad (10)$$

or

$$K = \frac{n_A(r_{AB} - r_A) + n_B(r_{AB} - r_B)}{n_A r_B(r_A - r_{AB}) + n_B r_A(r_B - r_{AB})} \quad (11)$$

This, when multiplied by r_A or r_B , gives the calibrated isotopic composition of materials A and B. Although Eq. (11) (or Eq. (10)) was only presented recently [16], it can be derived by direct inversion of the traditional isotope dilution equation,

$$K = n_B \frac{r_{AB} - r_B}{r_A - r_{AB}} \frac{1 + K r_A}{1 + K r_B} \quad (12)$$

with respect to K . This demonstrates the kinship between the method of isotope dilution and the method of isotope ratio calibration by means of synthetic mixtures of isotopes.

3. General aspects

The primary calibration of isotope amount ratios from the analysis of isotope mixtures can be performed in a variety of conceptual variations. For example, the classical “one-mixture” strategy to calibrate a two-isotope system could be modified so that more blends are analyzed in order to avoid the analysis of enriched isotope materials. In addition, this method can be applied to elements with more than two isotopes, or it can be extended to instrumental platforms that measure complex molecular ions, such as CO_2^+ . All these adaptations follow the conceptual framework of two-isotope systems; however, the complexity of the corresponding mathematics rises sharply. Hence, simplifications often lurk even in “absolute” isotope amount ratio determinations.

3.1. More isotope mixtures

Primary calibration of a two-isotope system involves a system of three unknown variables (R_A , R_B , K) if identical instrumental bias can be maintained during the experiment. Hence, measurements of three distinct materials are necessary. Traditionally this has been achieved in its simplest form –by separately measuring both isotopically enriched materials and one blend of the two [10, 17]. However, only one of the enriched isotope materials has to be measured directly if two distinct blends are made. Moreover, three different blends can be made. Such variation in the experimental design offers the choice (convenience) of bypassing measurements of highly enriched isotope materials. This is attained at the cost of elevated uncertainty of the resulting calibration factor.

Consider two isotopically distinct materials (A and B) of a bi-isotopic element such as lithium, silver, or thallium. Three different blends are prepared from these two parent materials, and the isotope amount ratio $R_{i/j} = n(^i\text{E})/n(^j\text{E})$ is measured in each of the three blends. The measured isotope ratios in these blends are denoted as r_1 , r_2 , and r_3 , respectively. Given a perfect proportionality (linearity) between the observed ion currents and isotope amount ratios, and a constant instrumental bias during all measurements, the true isotope amount ratios, R_i , and the measured isotope amount ratios, r_i , are all related to a single isotope ratio calibration factor K , i.e., $R_i = Kr_i$, where $i = 1, 2, 3$. Since the isotope amount ratio in any blend depends on the isotopic composition of the two enriched materials as per Eq. (8) or (9), one can establish such expressions for each isotope blend. The resulting system of these three equations allows one to calculate the three unknown quantities: R_A , R_B , and K . The calibration factor for the isotope amount ratios, K , can be expressed in a single master equation:

$$K_{i/j} = \frac{M_j}{M_i} \frac{\begin{vmatrix} r_1 & r_2 & r_3 \\ w_{A1} & w_{A2} & w_{A3} \\ w_{B1} & w_{B2} & w_{B3} \end{vmatrix}}{\begin{vmatrix} r_2 r_3 & r_1 r_3 & r_1 r_2 \\ w_{A1} & w_{A2} & w_{A3} \\ w_{B1} & w_{B2} & w_{B3} \end{vmatrix}} \quad (13)$$

where w_A and w_B are the mass fractions of the parent materials A and B in each of the three blends and M_i and M_j are the corresponding molar masses with accounting for the gravimetric form of the analyte (as an example, when Li_2CO_3 is weighed, $M_i = 2M_{\text{Li}} + M_{\text{CO}_3}$, etc.). A similar equation can be obtained in terms of the amount fractions of the materials, x_A and x_B :

$$K_{i/j} = \frac{\begin{vmatrix} r_1 & r_2 & r_3 \\ x_{A1} & x_{A2} & x_{A3} \\ x_{B1} & x_{B2} & x_{B3} \end{vmatrix}}{\begin{vmatrix} r_2 r_3 & r_1 r_3 & r_1 r_2 \\ x_{A1} & x_{A2} & x_{A3} \\ x_{B1} & x_{B2} & x_{B3} \end{vmatrix}} \quad (14)$$

All calibration experiments as per Eqs. (13) and (14) fall into one of the three strategies shown in Table 1. Of these, only the first strategy has been utilized in practice and it involves measurements of both enriched parent materials along with a single blend of the two. In this case $\{w_{A1}, w_{B1}\} = \{1, 0\}$, $\{w_{A2}, w_{B2}\} = \{0, 1\}$, and Eq. (13) reduces to Eq. (10):

Table 1. Primary calibration of isotope amount ratios in a two-isotope system.

Strategy	Material 1	Material 2	Material 3
1	A	B	A + B
2	A or B	A + B	A + B
3	A + B	A + B	A + B

$$K_{i/j} = \frac{M_j}{M_i} \frac{\begin{vmatrix} r_A & r_B & r_{AB} \\ 1 & 0 & w_A \\ 0 & 1 & w_B \end{vmatrix}}{\begin{vmatrix} r_B r_{AB} & r_A r_{AB} & r_A r_B \\ 1 & 0 & w_A \\ 0 & 1 & w_B \end{vmatrix}} = \frac{M_j}{M_i} \frac{w_A(r_A - r_B) + (r_B - r_{AB})}{w_A(r_B - r_A)r_{AB} + (r_{AB} - r_B)r_A} \quad (15)$$

The equation for this particular calibration design is equivalent to that given recently by Mana *et al* [16]. Eq. (13) can also be rewritten for the true isotopic composition of the enriched materials A and B:

$$R_X = K_{i/j} \frac{\begin{vmatrix} r_2 r_3 w'_{X1} & r_1 r_3 w'_{X2} & r_1 r_2 w'_{X3} \\ w_{A1} & w_{A2} & w_{A3} \\ w_{B1} & w_{B2} & w_{B3} \end{vmatrix}}{\begin{vmatrix} r_1 w'_{X1} & r_2 w'_{X2} & r_3 w'_{X3} \\ w_{A1} & w_{A2} & w_{A3} \\ w_{B1} & w_{B2} & w_{B3} \end{vmatrix}} \quad (16)$$

where X denotes either A or B and $w'_X = (1 - w_X)$. Experimental design with $\{w_{A1}, w_{B1}\} = \{1, 0\}$, $\{w_{A2}, w_{B2}\} = \{0, 1\}$ reduces Eq. (16) to Eqs. (1), (2), and (3), i.e., $R_X = Kr_X$. The utility of Eq. (16) becomes relevant when dealing with systems of large isotope amount ratios. There, the isotopic composition measurements are often limited by the signal-to-noise ratio due to the minor isotopes. In this vein, Eq. (16) offers an alternative to direct measurement of R_A (via the route $R_A = Kr_A$).

The calibration uncertainty, $u(K_{i/j})$, from Eqs. (13) and (14) increases significantly as the three blends become more similar. However, the corresponding decrease in the range of the measured isotope amount ratios can outweigh this effect. Consider two materials: 99.9 % ^6Li (A) and 99.9 % ^7Li (B). Primary isotope amount ratio calibration as per strategy 1 (Table 1) entails measurements of both of these materials with $R_A \approx 1/1000$ and $R_B \approx 1000$ in addition to their 1 : 1 mixture ($R_{AB} \approx 1$). Strategy 3, with mixtures of $R_{AB} \approx 10$, $R_{AB} \approx 1$, and $R_{AB} \approx 1/10$, on the other hand, offers a two orders of magnitude reduction in the range of measured isotope amount ratios at the fair cost of a twofold increase in the calibration uncertainty. This is illustrated in Figure 1.

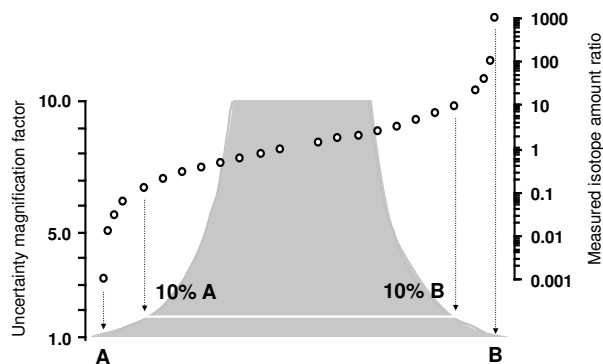


Figure 1. Calibration of isotope ratio measurements in a two-isotope system. Comparison of two primary calibration strategies as per Eq. (13). Strategy 1 consists in measuring pure materials A and B and their 1 : 1 mixture, whereas strategy 2 consists in measuring 1 : 10, 1 : 1, and 10 : 1 mixtures of materials A and B ($R_A = 1/1000$ and $R_B = 1000$).

The strength of the general expressions above (Eqs. (13), (14)) is in enabling the calibration of isotope amount ratios with complete control over the measured isotope amount ratios. Such control can be useful, for example, to verify the linearity of the isotope ratio response or to avoid practical complications when measuring materials of highly enriched isotopes.

Equation (14) describes the entire metrological landscape of a two-isotope system. Regarding the *synthesis* of isotope ratios, this equation shows all possible pathways for calibration (Table 1). Conversely, the inversion of this expression leads to a generic equation for *analysis*, commonly known as the method of isotope dilution. It was shown earlier how Eq. (11) leads to a standard short-form isotope dilution equation (Eq. (12)). Model equations for complex isotope dilution methods can also be derived. As an example, consider double isotope dilution analysis [18], which consists of two analyses: (1) analysis of a mixture of a (natural) standard and an isotopic spike and (2) analysis of a mixture of the isotopic spike and the sample. If constant mass bias can be maintained during the two analyses and if the isotopic composition of the analyte is taken from other sources, such as IUPAC, this experiment can be translated into the following model equation:

$$K = \frac{\begin{vmatrix} r_1 & r_2 & r_A \\ n_{st}/(n_{st}+n_{B1}) & n_A/(n_A+n_{B2}) & 1 \\ n_{B1}/(n_{st}+n_{B1}) & n_{B2}/(n_A+n_{B2}) & 0 \end{vmatrix}}{\begin{vmatrix} r_2 r_A & r_1 r_A & r_1 r_2 \\ n_{st}/(n_{st}+n_{B1}) & n_A/(n_A+n_{B2}) & 1 \\ n_{B1}/(n_{st}+n_{B1}) & n_{B2}/(n_A+n_{B2}) & 0 \end{vmatrix}} \quad (17)$$

In the case of exact-matching double isotope dilution,

$r_1 = r_2$, which leads to

$$n_A = n_{st} \frac{n_{B2}}{n_{B1}} \quad (18)$$

This expression illustrates the benefits of exact-matching double isotope dilution, where mass spectrometry serves the purpose of a null-point indicator. One still has to ensure that the instrumental bias remains the same during both isotope ratio measurements, which is the only way to enjoy the benefits of Eq. (18).

3.2. Extension to more isotopes

The gravimetric strategy towards primary calibration of isotope amount ratios has recently been extended to three isotope systems [19, 20]. To avoid any assumptions regarding the interrelationship between the calibration factors, an experimental design is required that involves as many isotopically distinct materials as there are stable isotopes [21]. As an example, primary calibration of silicon isotopic composition can be established by measuring three enriched materials (^{28}Si , ^{29}Si , and ^{30}Si) and two of their pairwise blends, such as ^{28}Si plus ^{29}Si and ^{29}Si plus ^{30}Si [20]. In practice, however, simplifications are introduced to obtain the gravimetrically defined isotope amount ratios. Using silicon as an example, this is akin to obtaining the gravimetrically defined ratio $n(^{28}\text{Si})/n(^{29}\text{Si})$ from the isotopic analyses of ^{28}Si and ^{29}Si and their blend ^{28}Si plus ^{29}Si . For this simplified approach to work, further concessions are required for the calibration factors of the disregarded ^{30}Si isotope ratio. In other words, to obtain $K_{28/29}$, the isotope ratio calibration factor $K_{30/29}$ has to be made a dependent variable by using a mass-dependent discrimination model. For example, $K_{30/29} \approx (2 - K_{28/29})$, or otherwise.

If the isotope ratio calibration factors are close to $K = 1$, as is typical in thermal ionization mass spectrometry or molecular leak inlet mass spectrometry, the two-isotope mixing is justified and helpful. In fact, this simplification underlies most available isotopic reference materials where a single isotope amount ratio is obtained by gravimetric blending of two highly enriched isotopes. Hence, isotopic analysis of multi-isotopic elements can be done without having as many distinct isotopic materials as there are stable isotopes at the cost of using mass-dependent discrimination models. If the measurement process is well understood however, high-quality isotope amount ratio measurements can be achieved without pure isotope standards. This has been exemplified at the IRMM using a mass spectrometer with molecular leak sample introduction [22].

In inductively coupled mass spectrometry (ICPMS), the instrumental discrimination is considerably larger and, in addition, large mass-independent discrimination can occur. The most “disturbing” behavior is the discrimination behavior of ^{73}Ge and ^{204}Pb , where deviations from the exponential fractionation model can reach 0.5 % [23]. This means that primary isotope ratio calibration using the simplified two-isotope mixing scheme is not well suited for ICPMS. In this vein, a less-demanding modern alternative to establish calibrated isotope amount ratios for multi-isotopic elements is the regression model, which relies on the correlated temporal isotope ratio drift in ICPMS [24–26]. Using this model, one can commute a known isotope amount ratio value to any other isotope amount ratio, belonging to either the same or a different element. This secondary calibration method revives one of the salient features of the classical “Harvard method”, a network of relationships among the isotopic composition of various elements [27].

3.3. Extension to molecular mass spectrometry

The principle of isotope mixture deconvolution can and has been extended to molecular mass spectrometry, where the isotopic composition of complex atom clusters is measured. As an example, in the analysis of carbon dioxide with electron impact ionization the CO_2^+ ion is formed. Therefore, determination of the carbon isotope amount ratio $n(^{13}\text{C})/n(^{12}\text{C})$ with this method involves the isotopic composition of oxygen. Measurements of three isotope amount ratios (corresponding to mass numbers 45/44, 46/44, and 47/44) in two isotopically distinct materials of CO_2 in addition to measurements of these isotope ratios in a mixture of these two materials is sufficient to yield the calibrated isotopic composition of carbon and oxygen [28]. The difficulty that arises when the isotope mixture deconvolution model is applied to molecular systems is the polynomial conversion between the isotope amount ratios of atoms and isotopologues. For CO_2 , this involves solving a set of three equations for $R_{13/12}$ (R_{13}), $R_{17/16}$ (R_{17}), and $R_{18/16}$ (R_{18}),

$$\begin{cases} R_{45/44} = R_{13} + 2R_{17} \\ R_{46/44} = 2R_{13}R_{17} + 2R_{18} + R_{17}^2 \\ R_{47/44} = 2R_{18}(R_{13} + R_{17}) + R_{17}^2R_{13} \end{cases} \quad (19)$$

which results in a cubic equation of the variables $R_{45/44}$, $R_{46/44}$, and $R_{47/44}$ with respect to R_{13} .

4. Outlook

Primary calibration of isotope amount ratios is a topic of renewed interest. In particular, recent isotope measurements of argon and silicon have played a

vital role in the determination of the Boltzmann and Avogadro constants for the implementation of the new SI. In geosciences, the isotope amount ratios underpin the estimates of geological age and decay constants of isotopes. Owing to the lack of high-quality primary standards, conventional values, such as $n(^{146}\text{Nd})/n(^{144}\text{Nd}) = 0.7219$, are often used for calibration purposes. It is hoped that the progress in absolute isotope ratio measurements will abate the reliance on conventions. Likewise, the demonstrated mass-independent deviations from the traditional mass-bias correction models employed in ICPMS raise questions for the veracity of popular methods, such as the double spike, which rely on mass-dependent models. In this vein, it can be foreseen that the supremacy of the double spike method will fade once more appropriate methods for secondary calibration are established. However, one cannot achieve any of the above mentioned advances without high-quality primary isotope amount ratios at hand.

References

- [1] de Laeter J R 1998 *Mass Spectrom. Rev.* **17** 97–125 URL [http://dx.doi.org/10.1002/\(SICI\)1098-2787\(1998\)17:2<97::AID-MAS2>3.0.CO;2-J](http://dx.doi.org/10.1002/(SICI)1098-2787(1998)17:2<97::AID-MAS2>3.0.CO;2-J)
- [2] Nier A O 1939 *Phys. Rev.* **55** 153–163 URL <http://dx.doi.org/10.1103/PhysRev.55.153>
- [3] Becker P and Bettin H 2011 *Philos. Trans. Roy. Soc A* **369** 3925–3935 URL <http://dx.doi.org/10.1098/rsta.2011.0222>
- [4] Laeter J D 2011 *Mass Spectrom. Rev.* 757–771 URL <http://dx.doi.org/10.1002/mas.20300>
- [5] Urey H C 1966 *Nobel Lectures, Chemistry 1922–1941* (Elsevier) chap Some thermodynamic properties of hydrogen and deuterium, pp 339–354
- [6] de Laeter J R, Böhlke J K, Bièvre P D, Hidaka H, Peiser H S, Rosman K J R and Taylor P D P 2003 *Pure Appl. Chem.* **75** 683–800 URL <http://dx.doi.org/10.1351/pac200375060683>
- [7] Rudge J F, Reynolds B C and Bourdon B 2009 *Chem. Geol.* **265** 420–431 URL <http://dx.doi.org/10.1016/j.chemgeo.2009.05.010>
- [8] Bièvre P D, Dybkær R, Fajgelj A and Hibbert D B 2011 *Pure Appl. Chem.* **83** 1873–1935 URL <http://dx.doi.org/10.1351/PAC-REP-07-09-39>
- [9] Nier A O 1950 *Phys. Rev.* **77** 789–793 URL <http://dx.doi.org/10.1103/PhysRev.77.789>
- [10] Qi H P, Berglund M, Taylor P D P, Hendrickx F, Verbruggen A and Bièvre P D 1998 *Fres. J. Anal. Chem.* **361** 767–773 URL <http://dx.doi.org/10.1007/s002160051013>
- [11] Shields W R, Murphy T J and Garner E L 1964 *J. Res. Natl. Bur. Stan.* **68A** 589–592 URL <http://dx.doi.org/10.6028/jres.068A.056>
- [12] Catanzaro E J, Murphy T J, Garner E L and Shields W R 1964 *J. Res. Natl. Bur. Stan.* **68A** 593–599 URL <http://dx.doi.org/10.6028/jres.068A.057>
- [13] Shields W R, Murphy T J, Catanzaro E J and Garner E L 1966 *J. Res. Natl. Bur. Stan.* **70A** 193–197 URL <http://dx.doi.org/10.6028/jres.070A.016>
- [14] Gale N 1970 *Chem. Geol.* **6** 305–310 URL [http://dx.doi.org/10.1016/0009-2541\(70\)90031-8](http://dx.doi.org/10.1016/0009-2541(70)90031-8)
- [15] Meija J, Yang L, Caruso J A and Mester Z 2006 *J. Anal.*

- At. Spectrom.* **21** 1294–1297 URL <http://dx.doi.org/10.1039/B607823K>
- [16] Mana G, Massa E, Valkiers S and Willenberg G D 2010 *Intl. J. Mass Spectrom.* **289** 6–10 URL <http://dx.doi.org/10.1016/j.ijms.2009.09.005>
- [17] Powell L, Murphy T and Gramlich J 1982 *J. Res. Natl. Bur. Stan.* **87** 9–19 URL <http://dx.doi.org/10.6028/jres.087.002>
- [18] Henrion A 1994 *Fres. J. Anal. Chem.* **350** 657–658 URL <http://dx.doi.org/10.1007/BF00323658>
- [19] Valkiers S, Vendelbo D, Berglund M and de Podesta M 2010 *Intl. J. Mass Spectrom.* **291** 41–47 URL <http://dx.doi.org/10.1016/j.ijms.2010.01.004>
- [20] Rienitz O, Pramann A and Schiel D 2010 *Intl. J. Mass Spectrom.* **289** 47–53 URL <http://dx.doi.org/10.1016/j.ijms.2009.09.010>
- [21] Mana G and Rienitz O 2010 *Intl. J. Mass Spectrom.* **291** 55–60 URL <http://dx.doi.org/10.1016/j.ijms.2010.01.008>
- [22] vre P D B, Valkiers S, Peiser H S, Taylor P D P and Hansen P 1996 *Metrologia* **33** 447–455 URL <http://dx.doi.org/10.1088/0026-1394/33/5/3>
- [23] Yang L, Mester Z, Zhou L, Gao S, Sturgeon R E and Meija J 2011 *Anal. Chem.* **83** 8999–9004 URL <http://dx.doi.org/10.1021/ac201795v>
- [24] Maréchal C N, Télouk P and Albarède F 1999 *Chem. Geol.* **156** 251–273 URL [http://dx.doi.org/10.1016/S0009-2541\(98\)00191-0](http://dx.doi.org/10.1016/S0009-2541(98)00191-0)
- [25] Meija J, Yang L, Sturgeon R and Mester Z 2009 *Anal. Chem.* **81** 6774–6778 URL <http://dx.doi.org/10.1021/ac9008435>
- [26] Yang L and Meija J 2010 *Anal. Chem.* **82** 4188–4193 URL <http://dx.doi.org/10.1021/ac100439j>
- [27] Yang L, Sturgeon R E, Mester Z and Meija J 2010 *Anal. Chem.* **82** 8978–8982 URL <http://dx.doi.org/10.1021/ac1019396>
- [28] Valkiers S, Varlam M, Ruße K, Berglund M, Taylor P, Wang J, Milton M and Bièvre P D 2007 *Intl. J. Mass Spectrom.* **264** 10–21 URL <http://dx.doi.org/10.1016/j.ijms.2007.03.012>