Atomic Spectrometry Update – Atomic Mass Spectrometry

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The review this year is dominated by the large number of publications on AMS, ICP–MS and SIMS. The increasing number of new AMS installations bears witness to the increasing interest in the technique now that smaller and simpler systems are becoming more widely available. Although high–energy systems still have an important role to play, each of the new systems was compact and of relatively low–energy. The development of ion sources that can accept gaseous samples has lowered the sample size requirement such that it is now approaching the background level. Contamination therefore has become a major issue. The numerous papers on improvements to SIMS analysis demonstrate the important role the technique plays in materials science. Unlike for most of the techniques covered, fundamental studies on

SIMS analysis abound with particular attention being paid to understanding the ionization processes and the representativeness of the measured ion beam. Quantum chemistry calculations have been used to determine the fundamental processes occurring in cell-ICP-MS. This approach contrasted with the empirical studies that are normally undertaken. Although many applications are still being published using collision and/or reaction cell ICP-MS, there were fewer novel or fundamental studies than in previous years. This suggests that cell-ICP-MS is becoming a more routine method of analysis. The same can probably also be said of hyphenated ICP-MS methods for speciation, which continues to grow in importance but which is very much at the applied end of the spectrum. Speciation is notable in that it cuts across a number of MS techniques and conventional organic MS techniques are increasingly being investigated for structure determination of organometallic species. Each year seems to find further expansion of MC-ICP-MS into 'non-traditional' isotope analysis. This was the year for Ti isotope analysis.

This Update is the 21st and last annual review on atomic mass spectrometry and follows the same format as last year’s[1]. Although an attempt is made to consider all relevant refereed papers, conference abstracts, reports, book chapters and patents for inclusion, the content of the review is highly selective. The selection of papers is based on criteria applied to focus sharply on the most significant developments in instrumentation and methodology or improved understanding of the fundamental phenomena involved in the MS process. The main ruling criterion for all speciation papers is that the work should involve or be intended for the study of natural systems. For example, the study of synthetic metal clusters is generally not included whereas the determination of organometallic compounds in environmental samples is.

Applications of atomic MS are not covered in this Update and readers are referred to the Updates on Industrial Analysis: Metals, Chemicals and Advanced Materials[2], Environmental Analysis[3] and Clinical and Biological Materials, Food and Beverages[4]. Other, fundamental, reviews appear on X-ray fluorescence spectrometry[5] and atomic emission, absorption and fluorescence spectrometries[6].

Throughout this review, the term molecular ion will be restricted to denote only the positive or negative radical ion formed by removal or capture, respectively, of an electron. In contrast, addition of a proton or cation to a neutral molecule gives molecular adduct ions. Deprotonated molecules are considered as fragments.

Although reproducibility or precision is a key figure of merit in MS, there is no agreed format for quoting it. The reader can assume that values of precision given in this Update as a percentage correspond to the RSD unless otherwise specified. For isotope ratios, however, values of precision are generally given as the SD of a permil value.

It is a widespread phenomenon that analytical techniques in general and MS in particular spawn a large number of abbreviations and acronyms. A glossary of all abbreviations used in this Update appears at the end of the review. Most abbreviations are not defined in the text but those which are unlikely to be commonly known are defined in the text when used first and again in the glossary.

The writing team would welcome feedback from readers of this review and invite you to complete the Atomic Spectrometry Updates questionnaire on http://www.asureviews.org.

1. Accelerator mass spectrometry (AMS)

1.1. Reviews

The excellent review by McNichol and Aluwihare[7] on *radiocarbon in biogeochemical studies* provided a clear introduction to the terms and definitions used in such studies, the fundamentals of AMS analysis and radiocarbon in the environment. A perceived dearth of educational opportunities and training tools for teaching AMS methods to new investigators prompted Getachew *et al.* [8]to write a much needed and detailed description of the methods used to convert C in urine, faeces, tissue and blood into graphite for AMS analysis. The extensive detail were such that tables listed all the equipment, chemicals and other supplies used in the preparation of graphite together with the names of suppliers (in the USA) and their catalogue numbers.

1.2. New facilities

An indication of the expanding use of AMS is the number of *new systems* being commissioned or developed. Details of seven new facilities have been reported[9-15]. In addition, new compact instruments have been built in existing facilities[16, 17] and by a commercial manufacturer[18]. It is of note that not one of these new systems had an accelerating voltage >3 MV and that compact low–energy instruments are increasingly being developed. Although all of the new systems were commercial designs, each was unique and custom made.

The *3 MV AMS system* installed in Xi'an, China, was the first of the new generation of instruments to be designed for the analysis of elements other than carbon[14]. The facility, tested for the analysis of ^{26}Al, ^{10}Be and ^{14}C, gave precisions for ^{14}C using sequential injection as good as those obtained by simultaneous injection. The locally made sample preparation system was the weak link in the analysis and required further improvement. An as–yet–unexplained phenomenon observed with the new radiocarbon facility at Saclay, France, was a decrease in measured ^{14}C:^{12}C ratios with increasing CH^{-} output from the targets[15].

Most of the new generation of *low–energy systems* have acceleration voltages of only 0.5–1 MV but retain the tandem accelerators used in larger systems. The performance of the first of these commercial instruments has now been fully assessed[18]. Measurements on processed graphite indicated that it was possible to keep the background intensity at *m/z* 14 to ~1–5 × 10^{-15} of that at *m/z* 12 by using the 1+ charge state, a terminal voltage of 600 kV and a stripper gas density of ~1.2 μg cm^{-2}. An improved transmission was obtained without compromising the suppression of polyatomic interferences by increasing the terminal voltage to 1 MV, reducing the stripper gas density to below 4 μg cm^{-2} and using the 2+ charge state. The 1 MV system had the flexibility to switch between different charge states and allowed heavy ions such as ^{129}I and Pu to be measured. A stripper gas pressure of 6 mTorr was optimum for giving lowest background and highest transmission in a 500 kV radiocarbon system[11]. The pressure had to be high enough to dissociate polyatomic interferences but not so high as to reduce transmission through scattering effects. Whereas the 600 kV system at Peking University[12] gave a ^{14}C accuracy better than 0.4% and a machine background of <0.03 pMC (Percent Modern Carbon), the 500 kV system in Seattle[9] delivered a ^{14}C accuracy of 0.3% and a machine background of ~0.004 pMC. The latter system was able to handle samples with ^{14}C concentrations ranging over six orders of magnitude without any measurable cross–contamination.

The use of *ultra–low energies* at 200–250 kV terminal voltages has allowed very compact instruments to be constructed. The tabletop system designed at Zurich, which retained the tandem accelerator concept yet had a footprint of only 2.5 × 3 m^{2}, was novel in that a vacuum–insulated high voltage platform was used[16]. Neither a pressure vessel to insulate the high voltage terminal nor acceleration tubes were needed. A feature of the ion source box was that samples were held in a linear 21–position magazine located in a separate vacuum chamber outside the ion box. Transfer of cathodes took only 10–20 s. Both graphite and CO_2 samples could be analysed directly. Background resulting from molecular break–up products was a limitation on performance and further development was needed to eliminate it. A contrasting approach to the design of an ultra–low energy system was the open–air, single–stage system installed at Lund[17]. The machine operated at 250 kV with the gas stripper, high–energy magnet and detector mounted on a high voltage deck and with the injector at ground potential. One advantage of the single stage accelerator was that charge exchanges in the residual gas of the second acceleration step were avoided. No SF_6 insulation gas was needed and the simpler system reduced costs by about 30% when compared to those of a 500 kV system. Two ion sources were used so that one could be dedicated to radiocarbon dating and the second used for the analysis of other elements. In this way, cross–contamination was reduced. The reported performances for the two ultra–low energy systems were very similar with a dating precision of 0.5–0.6%, equivalent to ±50 radiocarbon years.

1.3. Status Reports

It is common practice within the AMS community to provide regular status reports in which improvements and developments in the design and operation of facilities are given. That for the *East Kilbride facility* provided a general discussion on the operation and management of an AMS facility and as such could prove to be of use to new users[19]. Problems of spark damage to the accelerator tube supports were reduced by changing their design and material. Helium was used as carrier gas in a gas ion source because the alternative (argon) reduced the source output. Ion detection and evaluation were improved through the use of thinner (50 nm) silicon nitride membranes as detector entrance windows and a more powerful on–line data analysis system.

Because the 40–sample ion source on the *University of California Irvine* instrument suffered initially from severe problems of arcing, poor serviceability and low output, it has been subject to a major programme of improvements[20]. Replacement of the extractor and pre–acceleration assemblies with more–open structures gave a threefold improvement in pumping conductance and quicker sample wheel changes. The standard conical ionizer and Cs focus electrode were replaced with a new spherical ionizer assembly and negative ion immersion lens at cathode potential. This improved markedly the focusing of the Cs ion beam and led to major gains in ion source efficiency and negative–ion–beam quality. Source efficiencies for small samples (5–10 µg C) were sufficiently high (>10%) to give precise measurement of the ^{14}C content. Better confinement of Cs within the new ionizer assembly resulted in lower Cs consumption and reduced arcing problems. Similar improvements to a larger 134–sample source were being contemplated.

The main focus of improvements to the *Erlangen* facility were the automation of sample preparation, development of new sample preparation techniques and development of an efficient automated gas feeding system for a gas ion source[21]. These allowed an elemental analyser to be coupled directly to the ion source for the fast and automated analysis of samples down to a few µg without the laborious production of solid samples. Such a system offers new possibilities for the analysis of biomedical and environmental samples.

The need to measure traces of heavy elements in complex matrices, such as high–purity substrates exposed to the solar wind for the determination of elemental and isotopic composition of the sun, motivated the *Naval Research Laboratory (Washington DC)* to couple a commercial SIMS instrument to an AMS instrument[22, 23]. The combined instrument was effectively operated as a SIMS instrument with the detector replaced by the AMS facility. The SIMS analysis benefited from interference–free analysis and the use of ultra–low–background nuclear–physics–based particle detectors used in AMS. In contrast to other attempts at trace element AMS analysis, the new instrument was able to accept elements simultaneously over a wide mass range. This led, however, to a number of new problems not usually experienced in AMS systems that inject elements over only a narrow mass range. There was a much greater possibility of interferences from the break–up of molecules and increased background resulting from charge changing effects after acceleration. These observations highlighted the need for good vacuum in the high–energy accelerator tubes. The appropriate use of energy detectors overcame the limitations and the procedure was considered to be a large improvement on SIMS analysis.

A "molecular pilot beam" method that stabilized the terminal voltage with an accuracy of 0.1% improved measurement of ^{26}Al, ^{14}C, ^{36}Cl and ^{129}I at the *University of Tsukuba* facility[24]. Ions of the long–lived radionuclide and a molecular pilot beam with the same particle mass were extracted from the ion source and injected into the accelerator simultaneously. The determination of ^{26}Al was improved by extracting AlO^- ions which produced a more intense beam than Al^- ions used previously. The Al_2O_3 targets were mixed with $^{26}MgO_2$ to produce a pilot beam of $^{26}MgO^-$ ions which was used to control the terminal voltage. A LOD of better than 5×10^{-15} for the ^{26}Al:^{27}Al ratio was obtained when using complete stripping of the ions. For the determination of ^{36}Cl, a pilot beam of $^{12}C_3^-$ was used. The terminal voltage was increased from 9 to 10 MV to produce a $^{36}Cl^{9+}$ beam of 100 MeV energy. This increased the yield of $^{36}Cl^{9+}$ ions by 1.5 times and provided better separation between ^{36}Cl and ^{36}S in the new ΔE–E detector. The LOD for ^{36}Cl:^{35}Cl was better than 2.0×10^{-14}. A $^{97}Mo^{16}O_2$ pilot beam method controlled the acceleration voltage (12 MV) to within 0.1% for several days and the $^{129}I^{26+}$ ions were detected with no strong interferences[25]. The yield of $^{129}I^{26+}$ ions after passing through the 10 µg cm^{-2} second stripper foil was only about 20% so the overall ^{129}I ion transmission to the detector of only ~0.8% limited the efficiency of analysis. The "sensitivity" of $\sim 1 \times 10^{-13}$ was considered, however, to be excellent.

Three major upgrades have been carried out at the *Lower Hutt Facility*, New Zealand[26]. Conversion of the tandem accelerator from a belt–driven charging system to a Pelletron (chain–driven) system reduced fluctuations on the terminal voltage by at least one order of magnitude. Construction of a new beamline featuring a Wien velocity filter made interference–free detection of $^{26}Al^{7+}$ possible and reduced the backgrounds in the determination of $^{10}Be^{3+}$ and $^{14}C^{4+}$. Computer control of about half of all the parameters along the beamlines was implemented though a distributed network built from a combination of electronic interfaces either bought off–the–shelf or built in–house.

Automatic scanning of the target position with respect to the Cs–sputter beam was made possible at the *VERA laboratory* (Vienna) by replacing the stepper motor drive with a pneumatic sample changer and by motorizing the adjustment collar for the vertical target wheel position[27]. To hold the negative ion output constant, a control computer regulated the Cs–capillary heater while keeping the Cs-oven heater power supply constant. Replacement of the original conical ionizer with a spherical one and enlargement of the Cs–focus lens diameter doubled the source output. A section of the paper that could be very useful to other laboratories was a collection of the lessons learned from ten years of operating the ion source.

1.4 Instrumentation

A feasibility study concluded that a *radio frequency quadrupole* (RFQ) accelerator would be suitable for AMS ^{14}C measurements[28]. Compared to tandem and single–staged AMS systems, a RFQ–based system would have several advantages. The acceptance of a high beam load meant that ^{12}C beam currents of several mA could be accelerated and simultaneous injection realized without an injection magnet. The stripper, used to eliminate polyatomic interferences, could be placed after the RFQ at ground potential. No insulation gas system would be needed. Several major disadvantages were also predicted, however. The energy spread of the RFQ would be too high for particle identification in AMS detectors, there would be difficulty in measuring ^{12}C and ^{13}C on the high energy side of the accelerator and the cost and power consumption of the rf transmitter would be problematical. It was considered that a well–designed RFQ of <1 m length could have low energy spread and good isotopic selection but this had yet to be tested. A contrasting use of a RFQ would be to decelerate the anions from a standard sputter ion source to eV energies and then separate atomic and polyatomic isobars by very low energy collisions with a gas prior to injection into the accelerator[29]. The advantages of using low energies were that ionic reactions in gases could be isobar–specific and the multiple scattering of eV ions could be controlled in linear rf multipoles. It was considered that Cl^- and S^- isobars could be separated by using NO_2 as reaction cell gas but this had yet to be demonstrated.

Not many facilities have until now developed gas ion sources because of their complexity, poor reliability, high running costs and low ion currents (<15 µA C^-). However, the suitability of these sources for the measurement of very small samples, thereby removing the need for graphitization of small amounts, has made them increasingly important. Samples of CO_2 containing as little as 10 µg C could be analysed by directly injecting the gas into a He carrier[30]. Stable and reproducible C^- currents of up to 12 µA were achieved at an optimal gas flow of 1.5±0.5 µl min^{-1}. Precisions of better than 0.5% and 1% could be obtained for >200 µg C and 10–200 µg C, respectively. Performance was limited by the volume of the manifold in the gas handling system and a planned redesign would make analysis of samples containing as little as 1 µg C possible. A gas handling system for the introduction of CO_2 samples (1 µg to 1 mg C) into an AMS ion source was designed for complete automation and optimized for coupling an elemental analyser (EA) to the ion source[31]. The system was based on cryogenic isolation of the CO_2 followed by introduction into the ion source under the pressure difference between the CO_2 reservoir and the ion source. The sputtering of solid targets remained preferable for samples with >200 µg C because of the better precision and lower background. Also designed with the long–term aim of a fully automated EA–AMS system, a gas feeding system intended for a low-energy (200 MV acceleration voltage) system was based on CO_2 being mixed in a syringe with He and then introduced at a constant flow rate into the ion source[32]. Stable but relatively low ion currents of 3–6 µA C^- were produced with an efficiency of 3–6% for samples containing 3–30 µg C. A major limitation was the significant fractionation observed when carbon deposition occurred as a result of CO_2 being introduced too quickly into the source.

A system under construction was to utilize a combination of a 2.45 GHz *microwave ion source* and a magnesium–vapour charge exchange canal to produce C^- ions from a continuously flowing CO_2 stream[33, 34]. Positive ions would be produced in the microwave source and converted into negative ions by passage through the charge exchanger located at the exit of the ion source. Drawbacks of such sources include large emittance and energy spread of the beam. Electromagnetic field modelling and ion optics calculations were used to redesign each element in the high energy beamline for acceptance of large energy spreads. An existing source unit was redesigned to achieve higher efficiency, doubled energy and halved energy spread. A 10 mm diameter opening would be required for high–efficiency transmission through the stripper canal at the accelerator terminal.

The basic concept of an *electron–transfer gas ion source*, based on resonant transfer from a primary beam to a gas, was validated with Cu^- primary ions and ICl gas target[35]. The use of ICl has potential in ^{36}Cl studies because the sulphur analogue (S_2I_2) is unstable at room temperature. The Cu^- primary beam was chosen because it reacted resonantly with the ICl gas to produce a good Cl^- current with minimal production of S^-. The 20 keV primary beam was mass analysed by a 90° double focussing magnet before passing into the ion source which consisted of a gas cell at the entrance and a series of electrodes along its length to extract the secondary ions. A secondary beam of 8–10 keV Cl^- ions was obtained with one Cl^- secondary ion produced for about five incident Cu^- ions. Although the feasibility of such a source was demonstrated, further development was required to improve the extraction of the secondary ions.

Modification of a 40–sample ion source with a new Cs oven and direct introduction of a vacuum–insulated Cs feed tube had been reported previously to provide better confinement of the Cs than in the standard setup[36]. Such a design would be unsuitable for a 134–sample source because the area directly below the ionizer assembly is inaccessible so a modified geometry with the delivery tube entering the source body via the source end flange was tested on a 40–sample source[37]. Although the design proved successful for the 40–sample source, it has not yet been tested for a 134–sample source. A second beam profile monitor was installed in the injection line to make on–line source emittance measurements. At full output (150 µA C^- at 55 keV), the emittance of the source at 8 KV sputtering voltage was ~40π mm mrad. This value was considered to be only a first estimate as factors such as space charge effects were not taken into account in the calculations. Computer simulation of the original and modified sources showed that the modified source provided a more intense and better focused Cs^+ beam at the cathode target resulting in higher negative ion production[38]. The primary Cs^+ beam was simulated as space–charge limited emission from the ionizer surface. The secondary negative ion beam was simulated in the presence of space–charge induced by both the primary and secondary beam.

The *carbon ionization efficiency of a modified high–intensity* Cs^+ *sputter source* was redetermined to ensure that the very high output levels achieved did not result in low ionization efficiency[39]. There had been some concern that the high–intensity beam would burn through small samples before adequate data could be acquired. The ion source operated at ~33% C^- ionization efficiency which allowed the overall system to operate at an efficiency of >15%.

In order to increase versatility, a proposal has been made for a new design of *dual injection system* for either simultaneous injection (for radiocarbon analysis) or sequential injection (for all other radioisotopes). [40]A pulsed voltage applied to a Wien filter, placed between the ion source and recombinator, would give sequential injection. With the pulsing voltage and magnetic field turned off, the filter would act as field–free drift space and simultaneous injection would occur.

When using medium–sized accelerators (5 MV), the isobaric separation of heavy nuclei ($M \geq 36$) by a gas ionization chamber is limited by energy straggling and detector resolution. A $\geq 10^5$ suppression of ^{36}S was obtained in the measurement of ^{36}Cl by using a *gas–filled magnet* (2 mbar N_2 gas pressure) combined with a gas ionization detector[41]. A terminal voltage of 4.6 MV, gas–foil stripping and a 37 MeV $^{36}Cl^{7+}$ ion beam were used. Samples containing ≤5 ppm S and with ^{36}Cl:Cl ratios $\geq 10^{-15}$ could be analysed successfully. For ion beam currents of 1–5 µA, the ^{36}Cl count rate in the detector was ~5 Hz for a ^{36}Cl:Cl ratio of 5×10^{-12} so 10% precision could be reached within an acquisition time of ~ 3 h for ratios of 10^{-14}.

Previous attempts at using a *gas–filled TOF detector system* for isobaric identification have not proved successful for the measurement of ^{36}Cl. A new system achieved improved time resolution by using a thinner entrance window (Mylar foil of 0.9 µm thickness), an optimum flight length (50 cm long gas–filled chamber with a 16 mm diameter entrance window) and a low–resistance surface barrier detector[42]. The chamber was filled with argon containing 10% methane. It was possible to separate ^{36}Cl from ^{36}S at ion energies of 33, 49 and 64 MeV. Calculations showed that the optimal residual energy was about one fifth of the incidence energy. The efficiency of the detector was only about 40% of that of the ΔE–E method so further improvements were still required, in particular in time resolution.

As a step towards the development of multi–isotope AMS facilities at low energies (0.3–3MeV), significant improvements in the performance of *special gas ionization detectors* were obtained by using thin silicon nitride foils as entrance windows and low–noise preamplifiers[43]. Electronic noise was reduced by a compact design which minimized cable length and input capacitance. For heavier ions, the resolution was limited by the statistical nature of the ionization process in the counter gas. For lighter elements, the electronic noise was the dominant limitation on resolution. Good separation of ^{10}Be and ^{10}B was achieved in the 0.3–0.8 MeV energy range.

A simple *CO_2 trapping device* was coupled between an EA and the inlet manifold of a SIRMS instrument in order to collect samples for AMS analysis[44]. In this way a single combustion step provided samples for the determination of both δ^{13}C, required to correct for fractionation in the AMS analysis, and ^{14}C by SIRMS and AMS, respectively. The system, capable of batch combustion and isotope analysis of up to 40 samples, was fully automated under the control of the SIRMS software. Only a minor amount of contaminant C was added during the EA combustion, CO_2 trapping or graphitization.

1.5. Data handling

Reliable estimates of uncertainties are of crucial importance in AMS analysis. In a new *Bayesian model* developed for the analysis of AMS radiocarbon data, a first–order continuous autoregressive process was used to model instrument drift and measurement uncertainties were assumed to be Gaussian[45, 46]. Uncertainty from the ^{14}C counting statistics was used for individual measurements. The method was sufficiently robust to provide reliable uncertainties even when the number of measurements was small. The long computational time meant, however, that the model was not suitable for routine use. The model was further improved by representing the AMS instrumental drift with hidden variables instead of assuming a normal distribution for the measurement error and marginalizing over the trend[47]. The use of hidden variables allowed a more realistic Poisson distribution to be used for the measurement error. In comparison to the commonly used mean–based method, the inclusion of Poisson–distributed measurement error improved the analysis of very old or very small samples.

A detailed explanation has been given for the method used to quantify *measurement uncertainty* for all isotopes measured at the Arizona facility[48]. The error analysis served both to quantify measurement error and to provide diagnostic information about machine performance. The method addressed the situation when the machine was functioning properly, i.e. when the random machine error (RME), a measure of instrumental uncertainty in an AMS measurement, was <0.3%. The RME was monitored daily through measurements on multiple standards. When repeat measurements failed to achieve the 0.3% RME target, the accelerator was shut down, the faults diagnosed and repairs made.

The LOD of AMS, in particular for the heavy nuclides, is often limited by interferences. In order to solve the problem of high background, a *simulation code* was used to model the AMS spectra of heavy nuclides[49]. The simulated spectrum was produced by considering almost all sources of background ions. Interfering nuclides could be identified easily by comparing the simulated spectra with the measured spectra.

1.6. Developments in radiocarbon analysis

The increasing need for the analysis of small samples focused attention on the *graphitization* process. Two new sample preparation lines, described in detail, were designed with special attention placed on reducing the background contamination[50]. Whereas a line based on muffle combustion produced samples characterized by negligible fractionation effects and low background, a line based on zinc reduction delivered poor precision. An evaluation of the purity and behaviour of 14 iron powders and one cobalt powder used to catalyse the reduction of CO_2 identified just three powders that met the requirements for rapid graphitization, homogeneity, lack of sintering of the catalyst–C mixture and low contamination[51]. The sealed tube zinc reduction method for converting CO_2 to graphite was modified by carefully controlling the amounts of reagents (zinc, titanium hydride and cobalt or iron catalyst) and by using the simultaneously measured AMS $\delta^{13}C$ for correction of isotopic fractionation during graphitization[52]. Precisions of 2–3‰ and relatively low background of 5×10^4 radiocarbon years were obtained routinely on 1 mg samples. Although the method was rapid, convenient and cheap and gave acceptable performance, the background was higher than that obtained using the H_2 reduction method and prevented application to small samples. In addition, strong fractionation occurred. The memory effect in a graphitization reactor was gratifyingly low at 0.035% of the preceding sample but this could be substantial in the analysis of small samples[53]. A relatively long or harsh reactor pretreatment was required to eliminate or mask the memory effect.

Although the development of gas ion sources is generally seen as the way forward for handling small (25–100 µg C) and ultra–small (<25 µg C) samples, some attention has also been paid to *ultra–small–scale graphitization*. An overview of radiocarbon sample preparation discussed experiences of handling small and ultra–small samples[54]. Precisions of 0.2–0.3 and 1% were obtained routinely for samples containing 1 and 0.1 mg C, respectively. Analyses of samples containing as little as 10 µg C with a precision approaching 1% were also considered possible. The graphite yield of the reduction reaction (CO_2 reduced by H_2 over pre–baked iron powder catalyst in ~3.1 cm^3 reactors) increased from ~60 to 90–100% for samples containing 6–20μg C when a reaction temperature of 450°C was used instead of the 550°C used for larger samples[55]. A reduction in the reactor volume to ~1.6 cm^3 improved the yield further to ~100% for samples containing <6 μg C. High–performance measurements on small samples were made possible by use of a modified source which gave C^- currents of 1 μA per μg C for samples in the range 2–10 μg C. On–line measurements of ^{12}C and ^{13}C allowed machine–induced isotopic fractionation to be corrected. Two components to background were identified – 0.2–1 μg modern C and 0.1–0.5 μg dead C. Ultra–small samples of 2–10 μg C could be measured with an accuracy and precision of a few percent. The effect of N_2O, produced during the oxidation of CH_4 in air samples, upon the graphitization of small samples was investigated because it is known that nitrogen–containing species can retard the reaction[56]. No effect on the reduction reaction was found for levels of N_2O up to 9.3% by volume of the CO_2. Improved water trapping resulted in faster reaction rates thereby reducing the risk of contamination through air leaks.

The development of methods to analyse small samples is accompanied by the need to understand the *sources of contamination* better. In a study on the ^{14}C content of individual biomarkers in ocean water, the carbon blank was considered to be composed of three components[57]. One was proportional to sample mass, one was constant (e.g. from the closed–tube combustion) and the third was variable and difficult to quantify (e.g. contaminants from the vacuum line). The uncertainty for microscale measurements was derived mostly from unavoidable sample processing blanks, in particular the combustion blank. That for larger samples was determined primarily by factors associated with sample graphitization, counting statistics and tuning and stability parameters inherent to the instrumentation. Ultra–small samples required meticulous assessment of all contributions of exogenous C followed by careful propagation of associated uncertainties. The equations used to calculate these uncertainities were presented in full. As the total propagated uncertainty gave a practical sample size limit of 5 μg, new approaches to sample combustion or oxidation were considered necessary for ultra–small samples. The analysis of natural diamonds, of great geological age and to which molecular species do not adhere, was used to assess whether ion source memory could be reduced[58]. Although the experiment was successful and gave ages of 65000 to 80000 years, it was unclear whether conversion of samples into a diamond matrix was a feasible idea. A useful table presented seven potential sources of pseudo–^{14}C signal in AMS measurements. A stringent combustion procedure, which employed step combustion with only the highest temperature (880°C) fraction being retained, and graphitization in a vacuum line dedicated to old samples were measures taken in the analysis of ancient wood samples in order to extend the radiocarbon calibration curve to older dates[59]. Only the α–cellulose fraction of wood was analysed as washing procedures were not fully effective in removing contamination. The need to eliminate completely ^{13}CH ions and other polyatomic fragments with mass 14 necessitated the use of an accelerator operating at >2 MV and a charge state of 3^+ or higher. Every step in the processing of ice samples has been assessed for contamination[60]. The blank for the complete filtration procedure (1.3±0.3 μg C) was not substantially greater than the 0.9±0.6 μg C contribution from freshly baked unused quartz filters. The iron catalyst used in the graphitization process contributed 0.5 μg C to the blank and was targeted for further reductions in the overall blank.

The analysis of *old bones* presents particular problems of contamination. Ultrafiltration of bone collagen is used by some laboratories to reduce contamination from soil–derived amino acids and to remove degraded collagen and other short–chain proteins but problems of contamination from the filters themselves has been reported[61]. A humectant (glycerol), applied by the manufacturers to prevent the membrane drying out, had to be removed prior to analysis. Details were given of the cleaning procedure, more rigorous than that recommended by the manufacturer, and of the quality assurance scheme used to demonstrate the effectiveness of the decontamination. The latter included monitoring the level of C remaining in cleaned filters and dating bones of known age with each batch of samples. Redating of some samples has been necessary to remove anomalies in data obtained before ultrafiltration was adopted. Testing of the ultrafiltration method revealed that, although there was no significant contamination of the >30 kD fraction, a significant contamination remained in the <30 kD fraction[62]. It was considered that the >30 kD could also still contain small amounts of young C and the authors recommended caution in the use of ultrafiltration. A modified Longin method in which acid–soluble gelatine was separated from bone collagen for dating gave older and more reliable dates than direct dating of the collagen from mammoth bones[63]. A protocol based on FTIR spectroscopy in the attenuated total reflection mode made it possible to identify the presence of collagen in bone samples and to determine the suitability of the bones for AMS analysis[64]. A cleaning procedure based on extraction with five solvents (acetone, methanol, trichloroethylene, xylene and petroleum ether) in sequence was used to remove conservation chemicals from preserved bones[65].

Measurements of atmospheric ^{14}C require *high precision (<2‰) AMS analysis* for studies of global and regional carbon cycles. Specific changes made to standard procedures included selection of an iron catalyst that produced fine, loose graphite to reduce inhomogeneity in the sample target; accurate weighing of the iron catalyst to provide a consistent graphite:iron ratio; use of magnesium perchlorate in the graphitization reactors instead of dry ice–isopropanol cold traps to lower the water vapour pressure; use of a specific pressure to compact graphite samples; reduction in the number of samples analysed in each batch from 55 to 24 to reduce the level of instrument drift; and matching of the weight of standards to that of the samples[66]. By collecting 1×10^6 counts on replicate CO_2 samples (n=36, measured in several batches) extracted from a cylinder of air, a SD of 1.7‰ was achieved. An alternative approach was to measure each batch of samples twice, without removing the samples from the ion source chamber, to give two fully independent measurements[67]. In this way AMS drifts and variability became more recognizable and averaged out. The measurement plan, error sources and a calibration scheme involving two RM were described in detail. The major part of the scatter in $\delta^{13}C$ measured by AMS could be corrected for and use of individual AMS $\delta^{13}C$ measurements for fractionation instead of a SIRMS value improved the final data quality significantly. Using this procedure, high–quality measurements with a combined uncertainty of better than 3‰ could be made.

Knowledge about *particulate carbon* (separated into elemental and organic fractions) trapped in ice cores can give us a better understanding of the effects of the particulates on climate. A procedure for the measurement of µg amounts of particulate ^{14}C in ice samples was successfully developed from an existing method for the analysis of recent aerosol samples[68]. Improvements were made to the graphitization step and $\delta^{13}C$ was determined independently by SIRMS. Details were given for the filtering of melted ice samples, the combustion of µg amounts of water–insoluble carbonaceous particles, and graphitization of the CO_2 produced. The procedural blanks per filter were 1.3±0.6 and 0.3±0.1 μg C for organic and elemental C, respectively.

The combined use of capillary GC and off–line AMS for *compound–specific radiocarbon analysis* (CSRA) can be considered still to be highly experimental and far from robust. The CSRA results obtained by two independent laboratories for a fossil standard after sample cleanup, GC and AMS were in good agreement and showed no sign of contamination from ^{14}C–labelled or natural abundance compounds[69]. Analysis of a modern RM indicated the absence of significant contamination from fossil carbon. Distinct isotopic fractionation of ^{13}C:^{12}C and ^{14}C:^{12}C ratios was observed in the capillary GC but this could be corrected mathematically by using a data processing procedure (normalization of radiocarbon results to a δ^{13}C value of -25‰) commonly applied to avoid incorrect radiocarbon ages. Nevertheless, using the whole chromatographic peak to obtain the isotope ratio was preferred.

A general protocol for measuring the incorporation of ^{14}C–labelled 2'–deoxynucleosides into *DNA* gave attomole absolute LOD and ^{14}C:C LOD in the 1×10^{-11} to 1×10^{-12} range[70]. The method was based on a commercial extractor kit but a key change was the use of the chaotropic salt NaI as antioxidant during the DNA isolation to prevent artifactual DNA oxidation.

1.7. Developments in the measurement of elements other than carbon

The *use of BeF_2* instead of BeO as target material and injection of BeF^- to suppress interference from B made it possible to get a ^{10}Be:^{9}Be background sensitivity of 2×10^{-14} with a 600 kV accelerator[71]. Use of a new high–resolution gas ionization detector with a thin silicon–nitride entrance window and special preamplifier design was essential to achieve this sensitivity. The BeF^- currents were limited to a few hundred nA in order not to exceed the maximum count rate accepted by the detector and this led to extended measurement times. The hydroscopic nature of BeF_2 was overcome elsewhere by using $BaBeF_4$ as target for producing BeF^- ions[72]. As a fine precipitate, $BaBeF_4$ was less hazardous to handle than the commonly used BeO which can become an airborne dust. The production efficiency of BeF^- was low, however, whereas that for BeF_3^- ions was 5–10 times higher and could potentially be used for direct measurement of ^7Be. The co–precipitation of BeF_2 with a fixed quantity of CaF_2 was discussed as a possible sample preparation method not requiring a Be carrier. A systematic study of the strong fluoride anions BF_4^-, $BeF_3^-$and LiF_2^-, which belong to a class of molecules known as super–halogens, showed that they all produced strong ion beams[73]. The direct measurement of $^7Be^{2+}$ using $^7BeF_3^-$ at low terminal voltage with little ^7Li interference was feasible because LiF_3^- was unstable.

A survey and intercomparison of several *^{26}Al and ^{10}Be RM* revealed that a new set of RM from the University of California gave excellent systematic reproducibility and internal consistency but that minor deviations occurred for other RM[74]. It was suggested that the University of California RM should be adopted by the global AMS community in order to set international standards for the measurement of ^{26}Al and ^{10}Be.

The low beam currents (100–500 nA) of *$^{26}Al^-$* produced from Al_2O_3 have inhibited the use of Al for exposure–dating applications even though Al has advantages of higher *in situ* production rate and lower background over the much more commonly used ^{10}Be. The Al^- ion beam currents produced from Al_2O_3 were found to be affected by the metal matrix in which the Al_2O_3 was dispersed, by the matrix–Al_2O_3 mixing ratio and, in some cases, by the depth of sample[75]. An attempt was made to identify matrix systems with the potential to enhance ^{26}Al ion currents but it was concluded that the use of novel matrix systems had no advantage over the commonly used equimolar mixture of Al_2O_3 and Ag. It was suggested that a method to produce cathodes of Al metal was needed. Use of the AlO^- ion, produced 20 times more efficiently than Al^-, gave counting statistics comparable to those given by ^{10}Be analysis as long as a gas–filled magnet (N_2 gas, 8 mbar) was used to reduce the intense flux of ^{26}Mg ions at the detector[76]. A new multi–element gas ionization detector provided excellent discrimination between ^{26}Al ions and the residual flux of ^{26}Mg ions.

High energies are generally needed to remove the isobaric interference of ^{36}S in the measurement of *^{36}Cl*. In a systematic evaluation of the performance of the Oak Ridge facility with the aim of defining the limits of analysis, ^{36}Cl:Cl ratios as low as 10^{-16} were measured in seawater samples[77]. This sensitivity, sufficient to use ^{36}Cl as a tracer in oceanographic studies, was claimed to be the best achievable in the world for this isotope and resulted mainly from use of the highest operating voltage in the world (25 MV) and of a folded geometry with a 180° magnet in the terminal. The high energy allowed a large proportion of ions up to 50 amu to be completely stripped. The folded geometry provided an early magnetic filter to suppress contaminant polyatomic fragments and therefore resulted in an unparalleled clean background. A Monte Carlo simulation of the trajectories and profiles of ^{36}Cl and ^{36}S in a gas–filled magnet revealed that the central trajectories of ions in the magnet were almost spiral and that most of the ^{36}S ions collided with the interior wall[78]. These findings led to improved analytical conditions and resulted in the background ^{36}Cl:Cl ratio being lowered to 10^{-15}. The calculation code could be applied to any ion in the magnet and so should prove to be a powerful tool for improving analysis. Sufficient suppression of ^{36}S for routine analysis was obtained on a 5 MV system by using an argon stripper gas to produce 5+ ions[79]. The background for ^{36}Cl:Cl was 3×10^{-15}.

A beam line for the *measurement of ^{129}I* has been rebuilt with a gas–ionization detector because the TOF detector used previously had a low detection efficiency due mainly to beam spread at the foil of the TOF start counter[80]. The ^{129}I:I background of $<3 \times 10^{-14}$, achieved using a 4 MV terminal voltage and the 7+ charge state, was well below levels found in soils (10^{-10} – 10^{-7}) or natural pre–1950 levels (1.5×10^{-12}). A sample preparation procedure based on combustion of soil samples was also presented. A background of $\sim 10^{-14}$ has also been obtained using the 3+ charge state which is not usually considered for analysis because of the risk of severe ployatomic interferences[81]. Production of 3+ ions is several fold more efficient than the more commonly used production of 5+ ions and so would be suitable for low energy systems. Surprisingly few polyatomic ions were observed and these were readily suppressed with the argon gas stripper operated at normal thickness. It was considered that the 3+ charge state could be used as long as high–purity samples were prepared and as a consequence ^{129}I could be determined on small systems with low terminal voltages (1 MV). In a study to determine the lower mass limit at which reliable determinations of ^{129}I:I could be made, ion currents were constant for masses above 0.3 mg but decreased markedly for smaller masses[82]. This suggested that masses <0.1 mg did not produce sustainable currents. The measured isotope ratios were independent of sample mass but the uncertainty increased for masses <0.3 mg. As currently 1 mg samples are generally used for analysis, the prospect of producing reliable data for samples as small as 0.1 mg AgI widens considerably the range of viable applications.

Particular attention is being paid to the *sample preparation for ^{129}I determination* in environmental studies. In a combustion procedure, stepwise heating and continuous warming of the whole system were critical for achieving relatively satisfactory yields of I from small (≤1.5 g) samples[83]. The procedural background (^{129}I:I ~5×10^{-13}) was too poor for analysis of natural samples and limited application to anthropogenic I. A new method to extract iodine following combustion, based on use of an anion exchange resin disk, was simpler and faster than traditional methods such as solvent extraction and ion exchange but application of the method was limited because the disks had a tendency to clog[84]. The method was suitable for soil but not for milk or seaweed. A carrier–free method to extract μg amounts of I from marine sediments was developed for the dating of old (>1×10^4 years) sediments and for the detection of ^{129}I from a purported supernova explosion about 2.8×10^6 years ago[85]. The sediment was washed in a hydroxylamine hydrochloride – acetic acid mixture and iodine extracted with tetramethylammonium hydroxide, purified by anion exchange chromatography and co–precipitated as AgI–Ag_2O. Contamination placed an upper limit of 1.4×10^{-12} for ^{129}I:I in reagent blanks of 50 μg I. Large discrepancies were revealed between theoretical calculations and experimental data for the pre–anthropogenic ^{129}I:I ratio in marine sediments.

Interest is growing in the use of *^{182}Hf*, an extinct radionuclide which is only produced in supernova explosions in nature, as an indicator of such explosions in the vicinity of the earth within the last 100 million years. Although several papers have speculated on how the analysis may be undertaken, in particular separation of ^{182}Hf from ^{182}W, only one working system have been reported, simultaneously in two almost identical papers[86, 87]. The two prerequisites for AMS measurement of ^{182}Hf were high mass resolution (for separation from ^{180}Hf) and isobar separation from

^{182}W. Because the energy of <100 MeV at the high–energy side of the 13 MV instrument was insufficient to separate ^{182}W from ^{182}Hf, a chemical procedure based on anion exchange was used to reduce the ^{182}W:W ratio to 10^{-9}. For production of ^{182}Hf^{9+}ions, the maximum useable terminal voltage was 8.5 MV, corresponding to a final energy of 82.1 MeV. A carbon foil of 3 µg cm^{-2} thickness was used to produce the ions. The ^{182}Hf ions were detected by a gold–silicon surface barrier detector for energy determination and a 2 m TOF detector for isotope identification. The LOD for ^{182}Hf:^{180}Hf ratio of 4.15×10^{-11} was limited by the intense ^{180}Hf beam which, although greatly suppressed, still interfered in the measurement of ^{182}Hf. Further improvements to the detector system were being planned. Attempts to use an optimized projectile X–ray AMS (PXAMS) system to separate ^{182}Hf from ^{182}W proved unsuccessful because of the low (1.2%) efficiency[88]. Although this efficiency was better than previously reported for PXAMS systems, it was insufficient to detect the supernova signature of ^{182}Hf. The optimum ^{182}Hf^{11+} energy was 150 MeV. As an alternative approach, the use of an absorber foil to measure differences in energy loss of the ^{182}Hf and ^{182}W ions was being investigated for measurement of the ^{182}Hf:^{180}Hf ratio at the 10^{-13} level[89]. Details of progress in the use of "ΔTOF detection" for the measurement of ^{182}Hf have been reported but a fully operational system was not yet in operation[90]. The ΔTOF detector was based on the use of a stack of energy degrader foils (highly homogeneous carbon and silicon nitride) followed by a high–resolution TOF analyser. Isobars lost different energies in the foils giving them different velocities and TOF. In addition to optimization of the detector, improvement to the low transmission through the 14 MV tandem accelerator was needed.

A method for the determination of *^{53}Mn*, a cosmogenic radionuclide produced by spallation of iron in surface rocks, involved the preparation of test RM by using a heavy–ion fusion–evaporation reaction, the development of a chemistry protocol based on anion exchange to reduce the levels of the intense interference ^{53}Cr, and the use of a gas–filled magnet and gas–ionization detector to discriminate ^{53}Mn from the remaining ^{53}Cr background[91]. Further improvements intended were an increase in the path length of ions in the gas that was within the magnetic field, currently only 55% of the full path length, and a reduction in the background ^{53}Cr flux.

The development of *improved detection techniques* has made it possible to determine ^{41}Ca and ^{55}Fe on a small (3 MV) system[92]. Use of ΔTOF detection made it possible to determine ^{41}Ca:Ca ratios at the 10^{-13} level. By using the system in its standard configuration, high–precision (1%) measurements of ^{55}Fe:Fe were possible with a background level of $\sim 10^{-14}$. By using an additional magnet (the heavy ion beamline setup), very low isotope ratios (10^{-15} range) could be measured but with a trade off of slightly poorer precision.

A novel aspect of a procedure for determining *^{244}Pu* in marine sediments was the use of $^{97}\mathrm{Mo}^{2+}$ and $^{98}\mathrm{Mo}^{2+}$ (formed from the injection of $^{97}\mathrm{Mo_2O_4}^{-}$ and $^{98}\mathrm{Mo_2O_4}^{-}$, respectively) as pilot beams[93]. In this way the system could be tuned for the various Pu isotopes without using enriched–Pu RM and the risk of contamination was minimized. Use of a 2.26 MV terminal voltage gave an efficiency of better than 10^{-5} and a LOD of $<10^{4}$ atoms of ^{244}Pu per g sediment.

In order to measure *^{239}Pu and ^{236}U in the same uranium ore sample*, a new preparation protocol was developed to ensure efficient extraction of both elements and isotopic equilibrium between the ^{239}Pu in the ore and a ^{242}Pu spike[94]. After HF dissolution, the uranium was separated from the supernatant by chromatography on uranium tetravalent specific resin. A Pu/Th fraction was further purified by anion exchange to produce a purified Pu fraction. Plutonium was injected into the 14 MV accelerator as the PuO^- ion and the 5+ charge state selected.

The first AMS determination of *^{231}Pa*, used for U–series disequilibrium dating and as a tracer in paleoceanography, has been reported[95]. Concentrations in natural samples of 1–4 pg g^{-1} could be measured on a compact (300 kV) system with a reproducibility of better than 2% and an LOD in the low fg range. All samples were spiked with the short–lived ($t_{½}$=27 days) ^{233}Pa isotope prior to chemical purification in order to determine the yield. Purified Pa samples were baked with $Fe(NO_3)_3$ and the oxidized sample mixed with aluminium powder to form targets. The Pa isotopes were extracted from the sputter source as PaO^- ions which were stripped with Ar gas to the Pa^{3+} ions. An interesting consequence of using ^{233}Pa as spike was that ^{233}U was produced rapidly in the samples and a $^{233}UO^-$ ion beam was extracted together with the $^{233}PaO^-$ beam. The enhancement factor of UO^- over PaO^- had to be determined for each individual run by measuring additional ^{233}U–spiked RM.

The extraction of TcC^- ions from the ion source instead of TcO^- in a 12 MV system was considered a way of reducing the ^{99}Ru background that otherwise limited the current LOD for the *anthropogenic radionuclide ^{99}Tc* to 1×10^8 atoms[96]. The use of higher–purity chemicals could also reduce the background because the ^{99}Ru was derived primarily from the Nb_2O_5 matrix. Good linearity was obtained for ^{99}Tc:^{93}Nb in the 10^{-7}–10^{-10} range either by using a gas–ionization detector or by mathematically correcting for the presence of ^{99}Ru by measuring ^{101}Ru. At lower levels the measured ratios were higher than expected due to the background.

The unique feature of a *TEAMS system* of simultaneous injection, transmission and detection over a relatively broad mass range has been used to investigate the feasibility of REE measurement[97]. The LOD for Pr, acid extracted from the surface of metallic palladium samples, was 1–2 ng cm^{-2} when Sm (100 ppm) was added to the solution as internal standard. Adjusting the ratio of neutral Cs to primary ion current in a high–current caesium sputter source (by reducing the heater current in the helical tungsten wire ionizer while holding the caesium boiler temperature constant) produced stable anion beams from natural non–conducting samples[98]. The technique was applied to the determination of Au and PGE in silicate matrices but the complexity of such matrices resulted in variable ion beam formation and SRM could not be used reliably to quantify the PGE. Many potential interferences were formed. Implantation of the ions of interest into the actual sample was considered necessary for reliable concentration measurements.

2. Electrospray mass spectrometry (ESMS)

A new procedure for determining the *structure of Se–containing compounds*, based on LC–ES–TOFMS, was applied to the identification of two previously unreported Se species in the low–molecular–weight fraction of selenized yeast separated from water extracts by size exclusion chromatography (SEC). [99]The use of TOFMS provided greater sensitivity for full–scan analysis than quadrupole– or ion trap–based–techniques. The characterization of the Se species involved accurate mass measurements of both the protonated molecules and fragments produced by collision–induced dissociation (CID) in the ion source. The high–resolution isotopic signatures not only confirmed unequivocally the presence of Se atoms but also identified the individual isotopes from their unique mass defects. This approach was limited, however, by the size of the species. Those with relatively high weights (>500 or >700 amu containing 1 or 2 Se atoms, respectively) gave too many possible combinations of elements and additional fragmentation information was needed. The in–source CID was only partially successful because not all compounds fragmented satisfactorily even at high fragmentor voltages.

Although most studies on Se speciation have been on selenized yeast, attention is now being paid to the determination of *Se–containing compounds in natural foods* such as Brazil nuts in which Se concentrations are 10–25 fold lower than in yeast[100]. A sample purification procedure, optimized to remove the 100–fold excess of S analogues and matrix interferences, was based on consecutive SEC of proteins and tryptic peptides and enrichment of the Se–containing fractions. The characteristic isotope patterns were detected in the spectra, produced by nanoHPLC–ES–MS–MS (quadrupole–TOF), at retention times which had been indicated precisely by ICP–MS using a collision cell. The hybrid ESMS instrument could be operated either in full–scan (300–2000 *m/z*) TOF mode or in product ion MS/MS mode. The potential of the method was demonstrated by the identification of 15 Se–containing peptides in Brazil nuts. This was the first successful attempt at selenoproteomics in natural foods containing Se at concentrations of <100 ppm. A similar study used orthogonal separation techniques (SEC, cation exchange and ion–pairing reversed phase HPLC) to isolate three low–molecular–weight species from water extracts of monkeypot nuts[101]. The same nanoHPLC hybrid ESMS system used in the previous study provided the first MS identification of selenocystathionine and two isoforms of γ–glutamyl–selenocystathionine in a biological sample.

A previously reported method for the qualitative determination of seven *As compounds in seafood products* has been further developed for quantitative analysis. The LOQ (S/N = 10) were 800, 600, 50, 10, 5, 5, and 5 ng ml^{-1} for As^{V}, monomethylarsonic acid (MMA), dimethylarsinic acid, arsenobetaine, trimethylarsine oxide, arsenocholine and trimethylarsonium ion, respectively[102]. The compounds were quantified on a single–quadrupole LC–ESMS instrument by constructing linear calibration curves of the peak area counts for adduct ions against As concentrations. An anion exchange column was used to isolate MMA and As^V whereas the other compounds were separated on a cation exchange column. The eluate from the columns was split 3:7 to introduce 30% into the ESMS instrument. Selected–ion monitoring was carried out in the negative–ion mode for MMA and As^V and in the positive–ion mode for the other compounds. In order to obtain the highest signal responses for the adduct ions, the cone and capillary voltages were set at 45 and 100 V, respectively, in the positive–ion mode, 30 and 3500 V, respectively, for As^V and 40 and 3500 V, respectively, for MMA. Although this was the first reported use of ESMS to quantify As^V, the poor LOD was a limitation and further improvements were required.

3. Gas chromatography–electron ionization mass spectrometry (GC–EIMS)

The extraction of *organotin compounds* (OTC) from solid samples is the most difficult step in the determination of OTC due to their limited stability and strong interaction with the matrix. The efficiency of different extraction procedures for the simultaneous determination by GC–EIMS of OTC in mussels has been evaluated critically[103]. After testing the use of three different solvents (0.1, 0.5 and 1 M HCl in methanol; 0.5, 5 and 13 M acetic acid in methanol; 25% aqueous solution of tetramethylammonium hydroxide) and three extraction procedures (mechanical shaking; ultrasonic; closed-vessel microwave–assisted), the chosen optimum procedure was ultrasonic extraction (50°C, 1 h) in 0.1 M HCl in methanol. In a companion study on the extraction of butyltin compounds from marine sediments, the optimum conditions were ultrasonic extraction (30 min) in 100% acetic acid[104].

Mono– and di–organotin compounds, especially butyl– and octyl–tin species, are used in the PVC industry as heat and light stabilizers. Under certain conditions, migration of these stabilizers from packaging material to food can occur. A simple chromatographic procedure for the *simultaneous determination of butyl– and octyltin compounds* in two food simulants (water and 3% (w/v) acetic acid) was based on one–step derivatization and extraction with sodium tetraethylborate directly in the aqueous phase in the presence of 0.05% (w/v) tropolone in hexane[105]. The ethylated compounds were determined by GC–EIMS using tripropyltin and diheptyltin as internal standards for butyl– and octyl–tin compounds, respectively. Careful optimization of the ethylation conditions found that 200 μl of a 2% (w/v) sodium tetraethylborate solution (pH 4.8) gave best derivatization efficiency. Calibration was linear over the range 0.1–5.0 mg l^{-1} with LOD in the range 1.9 (monobutyltin) to 8.8 (tributyltin) μg l^{-1} (as organometallic cation). The precisions were 13% (within batch) and 16% (between batch). Organotin compounds were found at low but detectable concentrations in several food packaging materials.

A method for the quantification and certification of *methylmercury* concentrations in fresh–frozen marine biota (fish and mussel) SRM involved closed–vessel microwave extraction in HCl or acetic acid, derivatization with sodium tetraphenylborate, headspace solid–phase microextraction (SPME) with a polydimethylsiloxane-coated silica fibre and quantification using an isotopically labelled methylmercury compound as internal standard[106]. The methylmercury concentrations of 241±16 and 6.71±0.20 μg kg^{-1} (as Hg on wet–mass basis) measured in NIST SRM 1947 (Lake Michigan fish) and 1974b (mussel), respectively, compared well with independent measurements using GC–ICP–MS and with the certified values of 233±10 and 6.89±0.25 µg kg^{-1}, respectively.

Tetraalkyllead species are rapidly degraded in the environment by sunlight and atmospheric constituents (e.g. ozone or hydroxyl radicals) into soluble forms such as trialkyllead and dialkyllead and, finally, ionic lead species. Use of a liquid–membrane extraction probe, developed as an extraction and preconcentration tool in the *speciation analysis of organolead compounds*, allowed low concentrations to be determined in complex matrices[107]. Optimization of pH, stirring rate and extraction time gave an LOD for all organolead species of 4.7 µg l^{-1} and an LOQ of 15 µg l^{-1}. The degradation of tetramethyllead in the environment took 24–37 days.

4. Glow discharge mass spectrometry (GDMS)

4.1. Review

A comprehensive treatise of *fundamental studies, improved sources and methods* stressed the progress in fast–flow dc GDMS which can now provide LOD in the ng g^{-1} range[108]. Major research advances exploited the pulsed regime and even conventional rf GDMS profited from pulsing to reduce the thermal stress for labile samples and to address problems associated with surface analysis and depth profiling of non-conducting thin films. Use of signals in different time domains of the pulsed discharge made it possible to determine both the molecular and the atomic composition of a sample. These so-called tuneable sources, which allow both elemental and speciation analysis to be achieved, were seen to be an emerging field. The lack of commercial instrumentation was, however, considered to be a major bottleneck.

A 54–reference review covered the not yet fully understood effects due to the *addition of* H_2 to the Ar or Ne discharge gas[109]. The influence of H_2 addition on the discharge parameters, crater shapes, sputtering rates and analytical signals was thoroughly discussed. The corrections needed for calibration in quantitative analysis were reviewed. Theoretical modelling showed the importance of some collisional and radiative processes, which required experimental verification. The previously uninvestigated effects of H_2 present in the sample matrix were considered to be an important niche of basic research.

4.2. Instrumentation

A *simple GDMS instrument with quadrupole analyser* was developed specifically for the quick analysis of multilayered samples[110]. The dc GD cell used the sample as a cathode and was operated with an Ar pressure of ~1 hPa and a sputtered area of ~ 12 mm^2 The quadrupole was fitted with an energy filter. Analysis of various steel and alloy samples showed detection of components with concentrations greater than 100 ppm but it was claimed that a LOD of 1 ppm should be feasible. The fact that the relative sensitivity factors (RSF) fell within a narrow range around 1 was a major advantage in comparison to, for instance, SIMS analysis. This feature together with the simple instrumentation and short analysis time represented major assets for applications in material sciences.

4.3. Fundamental study

An attempt at modelling the ionization and transport phenomena in a dc GD source for the *calculation of RSF* for various elements in metal matrices met with limited success[111]. The agreement between calculated and experimental RSF was initially very poor with deviations of up to a factor of six. Adjusting the asymmetric charge transfer coefficient for the reference elements Cr or Fe by a factor of four improved agreement by about 50% but the authors admitted that there was no real justification for doing this. It was anticipated that the agreement between calculations and experiments would be improved by taking into account the discharge geometry and asymmetric charge transfer between analyte ions.

4.4. Analytical methodology

Referencing RSF to a matrix element of known concentration is unworkable in many samples. A study on the *use of the Ar ions from the discharge gas as an internal standard* showed that the $^{38}Ar^{40}Ar^+$ ion intensity was linearly correlated with the ratio of the matrix ion intensity to the matrix content in steel samples[112]. This new method provided the same corrections for experimental conditions as the traditionally used matrix–element–based RSF. Experiments on steel CRM showed that, unlike in the conventional matrix element method, the use of the Ar_2^+ as internal standard improved the accuracy slightly but the precision not at all.

A detailed study of the µs–pulsed GD process in a fast–flow Grimm–type cell revealed the *existence of a secondary discharge* behind the sampler orifice on the side facing the quadrupole analyser[113]. Such discharges were known to occur under dc conditions but had never been seen in a fast–flow source before. During the analysis of copper RM, the Cu^+ ion intensities reached a maximum at about 1 ms after the pulse, whereas theoretical models predicted maxima at 70 and 740 µs for the ion signal and the flow of neutral Cu, respectively. The hypothesis of ion generation in a secondary discharge process at the sampler orifice was confirmed by measuring the current on the sampling orifice and by observing the light emission from the secondary discharge. The secondary discharge explained the ion yield increase typically observed in pulsed GD because the voltages were 2-3 times higher than under dc conditions.

A systematic *comparison of continuous and µs-pulsed GDMS* using a Grimm–type source and a TOF mass analyser showed clear analytical advantages for the µs-pulsed system[114]. The effects of the pulse parameters on the signal intensities, crater shapes and sputtering rates were determined for model samples with a stainless steel, zinc, brass or aluminium matrix. The average power in the pulsed mode was low and reduced the sputtering rate by a factor of 3 – 6 in comparison to the dc mode. The high voltage reached in the pulsed mode improved the LOD 20 – 80 fold. The repeller delay was revealed to be the most critical parameter for optimizing the flux of the sputtered atoms into the ionization region whereas the pulse width was important for the crater shape. Optimized conditions kept crater bottom flatness to within 2 µm for craters of 10 µm depth.

A *sub-µm depth resolution* was achieved in the analysis of multilayers of Cu-Cr pseudo-alloys with different Cu:Cr ratios by using dc GDMS with Ar as discharge gas[115]. By using an etch rate of 0.5 µm min^{-1} and measuring the ions over a 10-15 s period, a depth resolution as good as 0.1 µm was achieved. The depth distributions of both Cr and Cu and impurity elements such as Ag, Fe, Mn, Ni and Ti were determined with LOD of 1 – 100 ng g^{-1}. The wide dynamic range made it possible to quantify the minor and major components in the same analysis, something that is not possible using, for instance, SIMS.

5. Inductively coupled plasma mass spectrometry (ICP–MS)

5.1. Fundamental studies and instrumentation

A theoretical study of *coincidence laser spectroscopy* (CLS), which is laser–excited fluorescence correlated with ion counting, as a technique for improved specificity in ion detection found that the ICP–MS interface was the main limitation to the technique[116]. The kinetic energy distribution (KED) produced by the ICP was calculated to be too large for optimum optical excitation because the ensuing Doppler shift meant that the narrow–line laser source did not excite all ions efficiently. Inspection of isotopes considered appropriate candidates for analysis (^{241}Am, ^{10}Be, ^{55}Fe, ^{63}Ni, ^{147}Pm, ^{238}Pu, ^{90}Sr, ^{99}Tc, ^{238}U) showed that ICP–MS–CLS could reduce high backgrounds for ions like ^{90}Sr and ^{10}Be. These ions had simple spectra with only a few high probability excitation states which could be used to generate a characteristic photon burst. Compared to conventional ICP–MS, LOD for such ions were improved by 2 – 3 orders of magnitude by using ICP–MS–CLS. The technique was reasoned to be less efficient for ions such as ^{55}Fe and ^{238}U which had a large number of excitation states. In these cases the required photon burst was compromised by optical trapping into other excitation states or a hyperfine transition structure. The paper also considered possible instrumental configurations, the saturating laser power, the effects of ion energy and energy spread on pumping efficiency and the optical abundance sensitivity for adjacent isotopes of the same element. The performance of the optical detector and of the correlation step for reducing background was also simulated.

The *effect of the mass spectrometer sampling interface* on fundamental ICP properties was investigated in two related papers, the first varying rf power and interface vacuum[117] and the second varying central gas flow and sampling depth[118]. An imaging instrument used a nickel sampling cone with 0.9 mm diameter orifice to mimic the sampling interface of an ICP–MS. Thomson and Rayleigh scattering were used to obtain radially resolved values for electron number density (n_e), electron temperature (T_e), and gas–kinetic temperature (T_g) of the ICP upstream from the sampling cone. Radial profiles of n_e from a "Ca–only" solution, $Ca(NO_3)_2$, were characterized by a maximum in the outer regions of the plasma, downstream from the toroidal region inside the load coil, and a minimum at the axial position. Similarly, T_e and T_g were also maximum in the outer regions of the plasma and minimum in the central channel. The finding that the sampling interface reduced both T_e and T_g, particularly at low rf power, agreed with previous studies showing that the sampling interface intercepted rf power that would otherwise sustain the plasma. Changes in T_g suggested that the sampling interface caused an increasing departure from local thermodynamic equilibrium (LTE) as rf power increased. Addition of Cu, Li or Zn to the "Ca–only" solution reduced the Ca^+ concentration measured at the axial position, either by shifting ionization equilibrium or through accelerated lateral diffusion. Applying an interface vacuum did not effect T_e or T_g but increased n_e in the central region and decreased n_e in the outer region very close to the sampling cone orifice, possibly as a result of increased flow of extracted gasses into the evacuated interface. In the second paper, it was found that increasing central gas flow generally decreased n_e and the presence of the sampling interface produced lower n_e at flow rates <1 l min^{-1} than without the interface[118]. Similarly, T_e and T_g generally decreased with increasing central gas flow rate,. Increasing central gas flow exacerbated the deviation from LTE, as T_g decreased at a greater rate than T_e. As the sampling interface was brought closer to the ICP load coil, T_e and T_g both decreased upstream. The changes caused by the presence of the interface were exacerbated as the sampler was brought closer to the load coil. The findings suggested that ICP diagnostics performed through MS methods should not be directly compared to those obtained on an unperturbed plasma.

Direct evidence of *collision–induced changes in plasma composition* during ion extraction and transport was obtained by laser–induced fluorescence spectroscopy analysis of ion and atom number densities in the first vacuum stage of an ICP–MS interface[119]. Number densities of Ca atoms, ions and metastable ions all decreased within the first few mm of the supersonic expansion. However, differing rates of decrease suggested that ions were lost to ion–electron recombination in the supersonic expansion. The effects of recombination were most evident at low rf power. Addition of Na^+ caused further decreases in the number densities of both the ground–state and metastable–state Ca^+ ions. While the ion data were consistent with cooling of the plasma by a matrix species, this was not the case for the atom data. Additional experimental work was required to develop an understanding of the effect of matrix on supersonic expansion.

5.2. Interferences

A *signal enhancement* caused by dissolved inorganic carbon (DIC) was responsible for a twofold overestimation of As concentrations in carbonated waters[120]. Laboratory experiments showed that the effect occurred with concentrations as low as 5–10 mM DIC. However, the interference was removed by degassing the solution with N_2 before analysis. An interference measured on $^{52}Cr^+$ was attributed to the production of $^{40}Ar^{12}C^+$ rather than signal enhancement. In a study of the response of 12 Se compounds, signal enhancement was found for two volatile species, dimethyl selenide and dimethyl diselenide[121]. Using a conventional Babington nebulizer and spray chamber, these two volatile Se species gave ICP–MS responses up to 58–fold stronger than those for selenite because volatilization in the spray chamber resulted in enhanced transport to the plasma. The quantitative consequence of this effect was demonstrated by direct flow injection (FI) analysis of NIES CRM 18 (human urine), for which the total Se concentration was measured as more than twice the certified value. Reversed phase (RP) HPLC–ICP–MS analysis of NIES CRM 18 confirmed the presence of dimethyl selenide in addition to selenosugars and trimethylselenonium ion in the CRM. The use of FI was therefore unsuitable for total Se measurements and quantification of urinary Se metabolites by ICP–MS required mineralization before analysis. The validity of the "dilute and shoot" approach for the determination of other metals in clinical analysis of biological fluids was questioned.

Numerous applications using *collision or reaction cells* were reported during the year. A review of such cells in isotope dilution (ID) MS summarized the mechanisms by which different commercial collision or reaction cell ICP–MS instruments removed interferences[122]. The majority of applications involved the determination of Se but other metals such as Ca, Cd, Cr, Fe, Sr, and U had also been determined. The authors anticipated that the introduction of cell technology to sector field (SF) ICP–MS would give greater flexibility for either reducing or resolving interferences and thereby improve LOD.

Although the use of O_2 in a dynamic reaction cell (DRC) ICP–MS efficiently removed ^{90}Zr interferences in the *determination of* ^{90}*Sr*, suppression of additional interferences caused by in–cell reaction of Fe and Ni with O_2 required DRC bandpass tuning[123]. An ion exchange separation lowered the Zr concentration to <5 $\mu g\ l^{-1}$, as needed for effective interference removal by DRC–ICP–MS. Analysis of 100 μg l^{-1} Fe and Ni solutions showed that Fe and Ni interferences at *m/z* 90 were reduced by up to four orders of magnitude when ions at *m/z* <70 were rejected from the DRC. At the same time the Sr sensitivity was also reduced but only by a factor of two. While bandpass tuning removed Fe interferences in the analysis of plant and lake water samples, the high concentration of Fe in sediments and the low affinity of Fe for the ion exchange resin meant an additional ion exchange procedure was necessary to lower the Fe concentration. Although the LOD for radiometric counting was an order of magnitude better than that (0.1 ng l^{-1}) for ICP–MS, the analysis time for ICP–MS was only minutes rather than the weeks required for radiometric counting. Analysis of aquatic plant, sediment, and lake samples by both DRC–ICP–MS and radiometric counting produced results that agreed well. In another study, the reactions of ^{90}Sr and ^{90}Zr with O_2 were modeled using density functional theory as an example of using quantum chemistry calculations to forecast in–cell reactions[124]. Systematic calculation of the electron configuration and ground state of Sr and Zr oxides demonstrated that a strong covalent bond formed in ZrO^+ but only a weakly covalent bond formed in SrO^+. The exothermic and endothermic nature of Sr and Zr reactions were qualitatively predicted by enthalpy calculations and the first determination of the SrO_2^+ formation enthalpy, ΔH_f (SrO_2^+), at 846 kJ mol^{-1} was produced.

5.3. Sample Introduction

5.3.1 Laser ablation (LA). A *review of LA–ICP–MS* stressed the need to study matrix effects as a prerequisite for highly precise and accurate LA–(MC)–ICP–MS analysis[125]. The issue was most acute for isotope ratio measurements that require standard–sample–standard bracketing for bias correction. Matrix–dependent elemental and isotopic fractionation was also discussed in terms of laser–sample interactions and the behaviour of laser–generated particles in the ablation cell, transfer tubing and ICP torch. Recent innovations included signal smoothing, in–torch laser ablation and on–line ID.

Numerous studies investigated new or modified *ablation cells* for improved LA–ICP–MS. An on–line low–pressure ablation cell was evacuated by a constant–flow diaphragm pump, with the pressure in the cell and transport efficiency controlled by changing the flow rate of the He carrier gas[126]. The evacuated gas was then mixed with an Ar make–up gas and introduced into a baffled–type stabilizer, which acted as a particle filter and suppressor of a pneumatic pulse from the pump. Analyte signal intensity was maximized at He carrier and Ar make–up gas flow rates of 0.4 and 1.2 l min^{-1}, respectively. The resulting gas pressure in the cell was 30 – 35 kPa. The transient signal intensity profile of $^{63}Cu^+$ from NIST SRM 976 (isotopic standard for copper) did not contain the spikes that are typically a large source of analytical error when conventional atmospheric chambers are used. The resulting 2 – 3% (n = 10, 2SD) precision for ^{63}Cu:^{65}Cu ratios was about half that (6 – 10%) obtained by LA under atmospheric pressure. Sample redeposition around the ablation pit was also significantly reduced at a cell pressure of <50 kPa. A new variable-volume and low–memory LA chamber included an active inner cell and a closed external cell[127]. This gave the advantages associated with both cells such as the lower risk of gas leaks of closed cells and the lower dead volume of open cells. The external cell with gas inlet was large enough to accommodate numerous targets. The inner cell was a transparent cylinder placed on the sample with the fixed gas outlet connected to the outer transfer tube. Effective cell volume was two orders of magnitude smaller than that in the standard cell but use of too small an inner cell led to aerosol deposition on the walls rather than to transport to the ICP–MS instrument. Compared to those obtained with a standard cell, the sensitivities of La, Th, and U were improved 3.5–13 and 1.1–2 fold using the new chamber with single–pulse and continuous ablation (λ = 193 nm), respectively. Precision was also improved. Cell–related memory effects were lower, with only 0.4 s required for a signal to reduce to 10% of the maximum peak height, compared to 5 s required in the standard cell. Another novel ablation cell, based on fundamental fluid dynamic theory, decreased cell washout time to tens of ms, and could therefore distinguish between single laser pulses up to a 20 Hz repetition rate[128]. Instead of the typical circular design, the cell was linear and tapered at both the carrier gas inlet and outlet. Experiments varying the length of the chamber and the position of the ablation point within the chamber demonstrated that turbulence arose from the gas inlet. Ablation closer to the gas outlet resulted in higher and narrower peaks as the effect of turbulence was minimized. Even when turbulence was minimized, minor peak broadening was still observed for ns–LA compared to fs–LA and was attributed to the larger and heavier particles produced by ns–LA. Resolution of individual shots was ultimately limited by the sampling rate of the ICP–MS detector rather than the washout time. In–depth profiling was demonstrated on examples of an Al–Zn multilayer structure and an industrial Mg–Zn coating. Analysis of brass aerosols generated by near–IR (λ = 795 nm) fs–LA using three different ablation cells with both short and long washout times showed that transport efficiency was independent of cell geometry within experimental uncertainty and that particle loss within the cells was minimal[129]. Transport efficiencies were determined by weighing the samples before and after ablation with a micro–balance and by collecting the particles by low–pressure impaction and evaluating the impacted masses quantitatively by total reflection XRF. The estimated value (~77%) was considered a lower limit since the mass lost by deposition in the impactor and by gas transport into the pump could not be quantified.

In a *LA system for the analysis of highly radioactive samples*, the ablation was carried out in a α–box isolated from the laser generator and MS instrument in order to avoid radiation–induced damage[130]. The ablation cell was designed so that samples could be changed using a stick manipulator within the airtight α–box and laser beam pulses (up to 60 mJ per pulse) were delivered through a window within the α–box. The high output energy was used to compensate for energy losses between the laser and the sample that were larger than for standard LA systems. The long tubing (8 m) between the LA cell and the ICP–MS instrument resulted in a higher than normal signal dispersion and a washout time of approximately 30 s. The system was coupled to a MC–ICP–MS instrument and evaluated by LA of unirradiated uranium dioxide. Isotope ratios were measured with a precision of 0.3% at a spatial resolution of 50 μm. Although higher resolution sampling (to 25 μm crater diameter) was possible, the measurement precision for the minor U isotopes was compromised by the low count rates.

In a short review, *fs–LA–ICP–MS* was described as less susceptible to laser–induced elemental fractionation than ns–LA thereby providing better precision and accuracy for a wide range of matrices[131]. However, minor variations in the small material flux (~ng s^{-1}) to the ICP could result in inaccurate quantification due to mass–load–induced matrix effects, even if the composition of the aerosol corresponded to that of the sample material. Increased mass loading particularly affected those elements whose volatility and first ionization potential (IP) departed significantly from those of the internal standard. The authors considered that comparison of ns– and fs–LA would remain incomplete as long as fs-LA radiation was non–homogenized. An investigation of UV fs–LA (λ = 196 nm) used a tunable Ti–sapphire fs seed source pumped by a 5 W continuous wave Nd:YLF (yttrium lithium fluoride) laser, which resulted in an output wavelength range tunable from 775 to 785 nm[132]. The fourth harmonic of the output wavelength (λ = 196 nm) was close to the more commonly used λ = 193 nm and delivered a maximum pulse energy of 0.01 mJ. In contrast to ns–LA, this fs–LA system produced unfractionated U:Th and Pb:U elemental ratios and Fe–isotope measurements free of mass bias other than that produced by the MC–ICP–MS instrument itself. The precisions for ^{207}Pb:^{206}Pb and ^{206}Pb:^{238}U were 0.03 and 0.2% (2 RSD), respectively. The precision obtained for the δ^{56}Fe was 0.1‰ (2 SD), which was close to that obtainable by solution MC–ICP–MS. Elemental fractionation was absent even when using different LA protocols such as comparing spots versus raster lines.

Use of a *new solid–state Nd:YAG LA system* with λ = 193 nm instead of the more commonly used λ = 213 nm and with short pulses (<3 ns) gave improved precision, accuracy, sample consumption and elemental fractionation in the SF–ICP–MS trace element analysis of geological glasses[133]. The analyses of various CRM gave element ratio precisions of 0.8% for conventional three–spot analysis (spot sizes: 50 – 100 μm diameter) for 26 trace elements using Ca as internal standard. This could be improved to 0.2% by using a high precision protocol for simultaneous determination of up to three elements. These precision values were better than those obtained using a λ = 213 nm Nd:YAG laser (1.1 and 0.6% for the conventional multi-element analysis and the high precision protocol, respectively). The mean reproducibility of trace element data obtained over a period of three months was about 2% (100 μm spot size) and 3% (50 μm spot size). The ratio of detected ions to ablated atoms over the *m/z* range 85–238 was $0.2 \times 10^{-3} - 2 \times 10^{-3}$, about 40% higher than that for the λ = 213 nm laser. While element fractionation factors (relative to Ca) were closer to unity for the λ = 193 nm laser than for the λ = 213 nm laser, significantly varying factors were observed for some elements (e.g., Pb, Rb, Y) in glasses in which the major element composition varied significantly. Therefore, calibration using RM with a matrix similar to that of the sample was still required to achieve highly accurate LA–ICP–MS analyses.

Further investigation of an *in–torch LA system*, described in previous reviews, used fast data acquisition to describe fine structure of in–torch LA signals[134]. Fast readout of the ICP–MS analog signal from a Nd:YAG λ = 266 nm laser was possible using a digital oscilloscope with 20 μs time resolution and triggered by the Q–switch of the laser. Measurements of Cs and La in NIST SRM 610 showed a double peak in the first 1–2 ms of the signal, resolved as two overlapping Gaussian peaks equivalent to about 77% of the total signal and a tail lasting for more than 30 ms. The signal decay from single–hole drilling experiments was explained by removal of increasingly less mass from consecutive shots. Fast data acquisition also allowed aerosol travel time through the plasma to be measured. This was useful for future modeling of aerosol gas flow. Velocities of 7.3–11.4 m s^{-1} were determined from the Cs signals.

Studies of *elemental and isotopic fractionation* resulting from LA have continued. Laser–generated (λ = 266 nm) metal particles from Al and Zn alloys using 150 fs– and 4 ns–laser pulses with identical fluence (50 J cm^{-2}) differed in size and morphology[135]. Whereas ns–LA of metal alloys produced mainly irregular primary particles and hard agglomerates, fs–LA produced spherical primary particles and soft agglomerates. Examination of LA craters by white light interferometric microscopy revealed that a rim of material was formed after ns–LA but not after fs–LA. It was calculated that 5 – 9 times more ablated mass was released with fs–LA than with ns–LA. The Al^+ and Zn^+ signal intensities were greater by factors of 12 and 50, respectively, for fs–LA, which also reduced temporal fluctuations in the Zn transient signal 10 fold compared to ns–LA. A follow–on study of particles from glass samples showed that, unlike for metal samples, particles produced from ns– and fs–LA had similar primary sizes and morphology but that soft agglomerates from ns–LA were more numerous and larger than those from fs–LA[136]., There was no correlation between major elemental concentration and the median particle size. Compared to the metal alloy study, particles from glass were larger and craters shallower. The signal intensity generated by fs–LA was more intense than that generated by ns–LA but this effect was less pronounced for glass samples than for metal alloys. In a study of isotopic fractionation, LA–MC–ICP–MS measurements of Cu showed that aerosol particles of <200 μm diameter were isotopically lighter by up to 0.7‰ compared to larger particles[137]. During repeated ablation of a 40 μm spot at a pulse rate of 5 Hz, the signal decreased by about an order of magnitude. The $^{65}Cu:^{63}Cu$ ratio decreased by about 1‰ during the first 30 seconds and increased by 2‰ during the next 60 seconds. Removal of the >200 nm particle fraction from the aerosol generated mitigated the change in $^{65}Cu:^{63}Cu$ ratio somewhat but the trend remained. The authors hypothesized that the variations were related to crater depth. Whereas ablation droplets were dispersed radially at the onset of ablation, a deepening crater forced them into vertical trajectories thereby increasing their residence time in the laser plume and resulting in preferential vaporization of the lighter isotope. However, as the crater deepened further, the proportion of heavier isotope vaporized also increased.

Separation of the large particles from the aerosol significantly reduced within–run fractionation and produced results closer to those from solution analysis and was therefore recommended for the analysis of copper metal.

Significant *mass–load–dependent matrix effects in LA–ICP–MS* exceeded the contribution of laser–induced fractionation for most elements and could not be explained by particle size distribution effects or changes in crater diameter[138]. A variety of ICP mass loads was achieved using ArF excimer LA (λ = 193 nm) of NIST SRM 610. As the crater diameter increased from 30 to 120 µm, the ICP mass load increased by a factor of 16 and some elemental intensity ratios (e.g., Cd:Ca, Cu:Ca, Pb:Ca, Zn:Ca) decreased by up to 25%. 'Excessive' mass loads from two λ = 193 nm LA systems operated simultaneously further decreased the ion signal intensities of volatile elements relative to that of Ca. In contrast, diluting aerosols by up to 30 times stabilized intensity ratios (e.g. Cd:Ca) to constant values. Matrix effects independent of the ablation process were also induced by adding a desolvated Rb aerosol to the laser aerosol. This observation indicated that elements considered previously to be primarily influenced by laser–induced elemental fractionation (Cd, Cu, Pb, U, Zn) were also affected by significant ICP–induced matrix effects. Mass–load–enhanced matrix effects were most severe for elements with low melting points (e.g., Ag, Cd, Cu, Pb, Zn) but were apparently unrelated to IP.

The *movement of the laser–induced sample particles* generated from a Si wafer was visualized at a time resolution of 1 µs using a high–speed camera (10^6 frames s^{-1} and 200x magnification) coupled with a shadowgraphy technique[139]. Although shadowgraphy is a 2–D projection of a 3–D structure, it was found to be suitable to monitor the speed and trajectory of sample aerosols released from the ablation point and to study the mechanism of redeposition in the sample pit. A dome–shaped dark area was observed when the laser was shot onto the Si wafer. This reflected changes in the refractive index of ambient He as it expanded hemispherically from the ablation pit with a velocity close to the speed of sound (~1000 m s^{-1} for He at 300 K). Production of the sample aerosol was delayed ~ 4 µs from the onset of the laser shot and the typical speed of particles released from the ablation pit was 100–200 m s^{-1}, significantly slower than the velocity of the plasma plume expansion. Sample particles were not released isometrically from the ablation pit and most large particles were released at a very shallow angle (<10°), possibly induced by thermal expansion of the ambient gas just above the ablation pit. This shallow emission angle caused sample redeposition and large elemental and isotopic fractionation.. Almost no visible laser–induced sample particles were observed from NIST SRM 610, mainly because of the smaller size distribution of the glass aerosols. The authors believed the technique of high–speed camera imagery had important potential in furthering understanding of ablation processes.

Improved sensitivity of 2 – 4 times for most of 47 elements investigated was achieved by adding 5 ml min^{-1} of H_2 to the He carrier gas flow (1.15 l min^{-1}) in a λ =193 nm ArF excimer LA system[140]. The signal improvement was even higher (5 – 7 times) for some elements, including As, Au, Be, P and Pt. The enhancement factor was correlated to the first IP of each element, although significant scatter indicated IP was not the only factor. Oxide formation increased minimally with H_2 addition (0.45% instead of 0.3% normally), indicating that the plasma gas temperature was reduced. This finding was in contrast to those of previous studies. Increasing doubly to singly charged ratios for Ba, Ce and U were attributed to higher electron temperatures, in line with previous studies. Hydride formation was <0.01% and LOD were improved for all elements except those with H–based polyatomic interferences (e.g. Ca, K, Se, Si). A similar but weaker effect was found when CH_4 was added but almost no sensitivity enhancement was found for N_2 addition.

The use of optically absorbing organic binders in the preparation of *pressed–powder LA calibration standards* provided a robust calibration method for the analysis of powdered samples[141]. Three binders (vanillic acid, pyrazinoic acid and nicotinic acid) with high optical absorbance at the wavelength of the laser (λ = 213 nm) were compared to polyvinyl alcohol (PVA), a 'non–absorbing' binder and pressed powder discs prepared with no binder at all. Discs prepared with vanillic acid had the highest optical absorbance at λ = 213 nm which resulted in the lowest and most consistent ablation depths and improved signal sensitivity. Despite the greatest volume of sample ablation, discs prepared with PVA produced the lowest signal, suggesting that the increased optical absorbance of the other binders had improved coupling between laser beam energy and the sample and that smaller particles were formed during the ablation process. Analysis of three CRM, specifically IRMM CRM IMEP–14 (trace elements in soil) and GBW CRM 07401 (podzolitic soil), and 07311 (stream sediment), were accurate to within 8% for discs prepared with 40% vanillic acid but only to within a factor of two for other discs. Calibration of NIST SRM 8435 (whole milk powder) using a geological CRM was also most accurate for 40% vanillic acid discs, although use of an internal standard (^{65}Cu) resulted in comparable data being obtained for all three disc compositions. These data provided further evidence that standardization of ablation conditions and mass flux to the plasma are prerequisites for robust calibration in the absence of a suitable internal standard.

5.3.2 Nebulization. Direct *ICP–MS measurement of laboratory–on–a–chip separations* was achieved by incorporating a micro–crossflow nebulizer directly into the microchip assembly[142]. Losses associated with traditional spray chambers were overcome by using an evaporation chamber with no waste outlet and optimized internal volume. Inertial impact losses on the front wall of the chamber were minimized and allowed almost the entire sample aerosol to enter the plasma. Although a make–up solution was still required for nebulizer operation, the flow rate (5 µl min^{-1}) was much less than that previously used (typically 0.5–2 ml min^{-1}). The optimized system achieved a sensitivity of 13 500 cps for 10 µg In l^{-1}, while stability over 10 min was 2.6% RSD (n = 453). The reproducibility of the hydrodynamic sample injection, performed via a manual switching valve, was 5% (n = 6). Although volumes as low as 440 nl could in theory be analysed, no data from real samples were reported.

Several new *multi–mode sample introduction systems* were described. A triple–mode, HF–resistant sample introduction system could be used for nebulization only, vapour generation (hydride or cold vapour) only or both together (dual–mode). [143]A commercially available HF–resistant (polypropylene) cyclonic spray chamber was modified so that the original aerosol–to–ICP outlet and waste drainage ports were used to add sample and reductant, respectively, for vapour generation. Two additional ports were added for waste drainage and aerosol transport to the ICP. The port for nebulization was fitted with a commercial parallel path nebulizer. The spray chamber could be dismantled for ease of cleaning. Compared to a conventional crossflow nebulizer with double pass spray chamber, the new system improved the analytical performance of Hg 17 and 57 fold in vapour generation and dual modes, respectively, while figures of merit of other elements (Cd, Cu, Pb) were improved twofold in dual mode. Analysis of various CRM using the vapour generation mode for the determination of Hg, and dual mode for simultaneous determination of Hg and other elements gave concentrations in agreement with the certified values. The simultaneous introduction of organic and aqueous solutions into the plasma using a dual inlet torch permitted mass bias correction of lead isotope ratios in crude oils using NIST SRM 981 (natural lead). [144]The conventional inlet, in line with the torch injector point, was used to introduce crude oils diluted with xylene through a microflow nebulizer and chilled double pass spray chamber. A second port introduced at an angle a dry aqueous aerosol from an ultrasonic nebulizer. This overcame the lack of isotopic CRM in organic matrices as it enabled a standard bracketing procedure to be developed. A dry aerosol of NIST SRM 981 was introduced at the same time as a xylene blank and then a blank dry aerosol was introduced with the crude oil sample. Replicate measurements (n = 10) of organic samples containing 10 ng g^{-1} Pb gave precisions better than 0.2% for ^{208}Pb:^{207}Pb, ^{208}Pb:^{206}Pb, ^{206}Pb:^{207}Pb, and 0.5% for ^{206}Pb:^{204}Pb, ^{207}Pb:^{204}Pb, ^{208}Pb:^{204}Pb. Isotope ratios measured by this method for two different crude oils were in good agreement with results from samples that had been digested prior to aqueous analysis. While the precision of the new method was generally poorer than that obtained with digested samples, the analysis was faster and less vulnerable to contamination.

Of five *sample introduction systems* compared for the determination of Se isotope ratios using MC–ICP–MS, hydride generation (HG) produced best signal intensity and precision[145]. The systems studied were a conventional crossflow nebulizer and spray chamber, two different desolvation systems, a multi–mode sample introduction system operating in HG mode and a dedicated HG system. Each was operated using parameters for highest S/N for Se. The dedicated HG system provided

5 times higher S/N for all Se isotopes compared to the multi–mode system, 20 times higher than either desolvation unit and 100 times higher than the conventional nebulizer and spray chamber. The mass bias was small in comparison to instrumental bias for all sample introduction systems. The external precision (n=7) for ^{78}Se:^{82}Se in NIST SRM 3149 (Se standard solution) was 63 and 47 ppm using the multi–mode system and dedicated HG system, respectively. This was about two orders of magnitude better than for the other systems. While the absolute intensities of the Se peaks measured using the two desolvation systems were two and fivefold stronger than those for the nebulizer, this did not translate into significant improvements in precision. In a study of low–flow sample introduction for the determination of REE, comparison of a desolvating system and micronebulizer, a nano–volume FI system fitted to a total consumption nebulizer and a concentric micronebulizer fitted to a mini cyclonic spray chamber demonstrated that the desolvation system reduced refractory oxides (e.g. ^{139}La^{16}O) to the greatest extent[146]. The solution uptake rate for the nano–volume FI system (8 μl min^{-1}) was lower than that for the desolvation system (330 μl min^{-1}) and that for the concentric micronebulizer and spray chamber (700 μl min^{-1}). Relative LOD for the REE ranged from 0.57 to 6 ng l^{-1} for the desolvation system and 30 to 170 ng l^{-1} for the nano–volume FI system and the desolvation system also had better precision. However, the difference in flow rate meant that absolute LOD were better for the nano–volume FI system (3.1–7.6 fg) than for the desolvation system (6.7–54 pg). Determination of REE in BCR CRM 668 (mussel tissue) and in slug organs by quadrupole ICP–MS gave better precision and accuracy with the desolvating system than with the nano–volume FI system. Use of the nano–volume FI system did however allow REE concentrations to be determined in as little as 76 nl of digested sample solution.

5.3.3 Thermal vaporization. A *review* of recent progress in electrothermal vaporization (ETV) ICP–MS and ICP–AES focused on devices, the vaporization mechanism, chemical modifiers, direct solid sample analysis, preconcentration/separation techniques, as well as recent applications for biological, environmental, refractory, and high–purity materials[147]. While the main field of ETV–ICP–AES/MS remained direct solid sample analysis, the method could be extended to the determination of ultra–trace elements in microvolume biological and environmental samples. In addition, ETV could be combined with miniaturized separation/preconcentration techniques such as liquid–phase micro–extraction, stir bar sorptive extraction, SPME, and capillary electrophoresis.

A *multi–element dry plasma optimization system* used three parallel conduits containing solid NbF_5 (containing Si impurities), $SnBr_4$ and a low wattage tungsten filament loaded with Pb to deliver dry multi–element (Br, F, Si, Sn, Pb, and W) vapours to an ICP–MS system[148]. The multi–element vapours were used to tune ICP–MS sample introduction systems that do not produce a wet plasma, such as ETV–ICP–MS. By overcoming the disparity between optimized conditions for wet and dry plasmas, the dry plasma optimization system enhanced signal for 26 elements by ETV–ICP–MS by an average 4.5–times compared to optimization with a conventional nebulizer. While the device was designed for optimization over the entire mass range, the authors suggested that a simpler device using $SnBr_4$ only would offer similar advantages.

5.3.4. Chemical vapour generation. On–line photo–oxidation after microbore anion–exchange chromatography enabled sensitive analysis of urinary arsenic species by HG–ICP–MS to be performed[149]. The optimized nano–TiO_2 photocatalytic oxidation process quantitatively converted As^{III}, monomethylarsenoic acid and dimethylarseinic acid to As^{V}. The As^{V} was reduced almost instantaneously to As^{III} upon on–line mixing with a 0.5% $Na_2S_2O_4$ solution. This provided maximum HG efficiency. Chromatographic resolution was considerably improved when Ar gas was used to segment flow directly after chromatographic separation as it suppressed post–column analyte dispersion. The LOD of 0.17 – 0.37μg l^{-1} for all four species were all better than those for HPLC–ICP–MS except in the case of As^{III}, for which the LOD was the same for both methods. Long–term precision for all species was better than 10%. The method was applied successfully to the analysis of urine.

In a new methodology for the determination of low levels (μg l^{-1}) of *total reduced S species in natural waters and acid volatile sulfides in sediments,* S species were isolated as H_2S after reaction with HCl in a commercial vapour generator[150]. Polyatomic isobaric interferences at *m/z* 32 caused by $^{16}O_2$ and $^{14}N^{18}O$ were minimized both because vapour generation eliminated the sample matrix, and by use of a mixture of He and H_2 gases in an octopole reaction cell. The system was optimized using a full factorial experimental design for best S/N at *m/z* 32. The LOD of 2 μg l^{-1} was an order of magnitude better than that for the standard potentiometric method.

5.3.5 Flow injection. An *on–line standard addition method for transient signals* provided the advantages of conventional standard addition but required only a single sample run[151]. A small volume of standard, injected as a spike into the sample/carrier stream, overlaid the analyte peak. The sample was loaded into a large injection loop (1.4 ml), while the standards were loaded into a smaller injection loop (0.33 ml), which led to a series of short calibration peaks at regular intervals overlaying a wider sample peak. Reproducibility of injections was 1.0 and 0.5% for the standard and sample loop, respectively. A peak–fitting program was used to determine the area of the underlying sample peak. The placement of the standard addition spikes over the sample peak did not have a significant effect on the accuracy of the method but spikes positioned over either the apex or leading edge of the underlying peak led to slightly poorer precision. The results for eight analytes (Cd, Co, Mn, Mo, Pb, Sb, Se and Tl) in the concentration range 0.82 – 233.2 μg l^{-1} in a urine CRM agreed with the certified values. Accuracy and precision were better than 2 and 5%, respectively.

5.4. Speciation

A *review* of HR–ICP–MS as a detector for capillary (CE) and gel electrophoretic separations suggested that progress had been made in interface development and analyte quantification[152]. Sources of band broadening and separation artifacts were discussed and numerous applications summarized in fields as diverse as biochemistry and experimental geochemistry. Since its introduction ten years ago, publications in CE–ICP–MS had diverged from interface development to a variety of applications. Research remained dominated by the bioanalytical community and studies of metalloproteomics particularly, and there was a continuing trend towards further miniaturization and better LOD. A review summarizing the evolution of analytical methods for quantitative protein phosphorylation analysis based on ^{31}P detection by ICP–MS described current approaches[153]. The advantages of ICP–MS over other techniques, such as ES and MALDI molecular MS, included good precision and accuracy and the ability to measure absolute phosphopeptide abundance. Methods for removing polyatomic interferences on ^{31}P were described. Further development of adequate P–containing standards for analysis by hyphenated ICP–MS techniques was required.

A low cost, easily demountable *capillary GC–ICP–MS interface* maintained the capillary column at a high temperature right through to the tip of the torch injector by using a transfer line heated by a combination of hot Ar gas and electrical resistance[154]. Full details were given for the design and construction of the interface which was suitable for analytes with boiling points <230 ºC. Good accuracy was achieved for butyltin species in NRCC CRM PACS–2 (harbour sediment) using conventional calibration with tripropyltin dichloride and an internal standard, and methylmercury in BCR CRM 464 (tuna fish) via species–specific ID. Signal stability varied <5% over a 12–hour analytical run.

5.5. Isotope dilution (ID)

Four different numerical approaches for *multiple–spiked species–specific ID analysis* (Calculation of Stable Isotope Concentrations, Speciated ID Analysis, Species–Specific ID Analysis, and Isotope Pattern Deconvolution) were explained and compared in terms of complexity, analytical figures of merit and specific advantages[155]. All four methodologies provided the same accuracy and precision of degradation–corrected concentrations for dibutyltin and tributyltin in NRCC CRM SOPH–1 (marine sediment). Slight differences in calculated degradation factors were attributed to the fact that calculation of degradation factors was independent of calculation of the concentration in the Calculation of Stable Isotope Concentrations and Species–Specific ID Analysis methods, but not in the Speciated ID Analysis and Isotope Pattern Deconvolution methods. No method was consistently better than the others but each had merit for different situations.

5.6. Isotope ratio measurement

A review documenting *developments and applications* in the field of isotope ratio measurements suggested that development of both instrumentation and analytical protocols was primarily driven by researchers in the Earth and environmental sciences[156]. While TIMS has traditionally underpinned the field, the uptake of MC–ICP–MS instrumentation had prompted an unprecedented rate of technique and application development. The review discussed application for numerous isotopic systems including Hf, Nd, Os, Pb, Sr, Th and U, as well as newer 'non–traditional' stable isotopic tracers. The rapid proliferation of analytical instrumentation and techniques was considered to have created a vacuum in the development of CRM and material characterization was an increasingly important endeavour.

A ^{207}Pb–^{204}Pb double–spike MC–ICP–MS technique for *Pb isotope analysis without Tl addition* overcame inherent problems of differing mass bias correction factors for Pb and Tl and variable oxidation of Tl during desolvation[157]. The precisions for measurement of the ^{206}Pb:^{204}Pb, ^{207}Pb:^{204}Pb and ^{208}Pb:^{204}Pb ratios in a 50 ng ml^{-1} solution of NIST SRM 981 (equivalent to consumption of 11 ng Pb) were in the range 0.002 – 0.003% (RSD, n=35) and consistent with previous TIMS and MC–ICP–MS studies. Use of lower Pb consumptions (4 and 20 pg) resulted in poorer precisions of 0.007 – 0.009 and 0.3 – 0.7%, respectively.

Protocols for the *precise and accurate measurement of Th and U isotope ratios* by MC–ICP–MS were developed for a wide range of applications including the dating of young and ancient carbons, measurement of Th and U isotope ratios in natural waters and U–Th disequilibrium in volcanic rocks[158]. By paying particular attention to mass fractionation, intercalibration of detectors, the response of the ion counting system and background levels, each could be corrected for individually rather than together as in other protocols. The mass fractionation of Th and U (0.48 and 0.45% per amu, respectively) was indistinguishable at per mil precision levels. However, multiplier–Faraday cup gain differed for Th and U by 1% and therefore determination of mass fractionation coefficients required separate Th and U bracketing standards. An in–house Th RM with a composition produced for the analysis of samples with low ^{232}Th concentrations was also suitable for the analysis of silicate rocks with ^{230}Th :^{232}Th ratios of $<10^{-5}$. The protocols were designed for MC–ICP–MS instruments with an ion counting detector and were applicable for samples as small as 20 mg.

A method for the *measurement of Ti isotopes* in geological materials using HR MC–ICP–MS overcame the limitations of TIMS (e.g. TiO_2 formation) and low resolution MC–ICP–MS (argide interferences) analyses[159]. Titanium was separated from the matrix using two–stage anion exchange chromatography to ensure that the Ca:Ti, V:Ti, Cr:Ti, and Zr:Ti ratios were <5, <0.3, <0.2 and < 1, respectively, and that isobaric interferences from singly charged ^{46}Ca, ^{48}Ca, ^{50}Cr and ^{50}V and from doubly charged Zr were corrected reliably. A resolution (M/ΔM) of 2000 ensured that polyatomic ions such as $^{14}N^{36}Ar^{+}$ were resolved from $^{59}Ti^{+}$. An aliquot of each sample was analysed by quadrupole ICP–MS to measure the Zr:Ti and Mo:Ti ratios and so correct for doubly charged Mo and Zr interferences. Because of the large number of isobaric interferences requiring correction, data were collected in two cycles (*m/z* 44–49 and 47–53). Instrumental mass fractionation was internally corrected using the ^{49}Ti:^{47}Ti ratio and an exponential fractionation law although there was very little dependence on the fractionation law if normalization to the synthetic standard was used. Replicate measurements of synthetic standard solutions, terrestrial rocks, and the carbonaceous chondrite Allende yielded a long–term reproducibility (2σ) of 28, 34 and 28 ppm for ^{50}Ti:^{47}Ti, ^{48}Ti:^{47}Ti, and ^{46}Ti:^{47}Ti, respectively. The results for terrestrial samples agreed within analytical uncertainties but were consistently different from previously published values. The calculated atomic weight for Ti differed significantly from the value currently recommended by IUPAC.

6. Laser ionization mass spectrometry (LIMS)

This section covers the one-step laser desorption-ionization (DI) of analytes from solids. The increasing use of lasers for the post-ionization of neutrals generated by laser-beam irradiation or primary ion bombardment of solids is treated in the section on SNMS. Because the aim of RIMS is typically different from that of solid state analysis with focused laser or ion beams, publications dealing with the ionization of atomic beams or gas-phase neutrals under resonant conditions are dealt with separately from SNMS in the section on RIMS. Laser microprobe mass spectrometry (LMMS) refers to the use of a focused laser with a spot diameter on the sample of <5 μm. The application of LMMS to suspended particles in combination with TOF analysis is called aerosol-TOF LMMS (aTOF LMMS). In this section, symbol τ denotes the nominal laser pulse duration.

A comprehensive *review of aTOFMS* addressed the development of instruments to determine the chemical composition of single aerosol particles with aerodynamic diameters in the (sub) μm range[160]. The different design options for the inlet, particle sizing, laser ionization and MS analysers were discussed in terms of their operational characteristics and potential for future development. Excimer lasers had a shorter response time between particle detection and firing and were preferred over traditional Nd:YAG lasers because ionization took place closer to the particle detection system. This reduced the problem of focusing the particle in the beam waist and the high fluence improved the ionization yield. Power densities close to 10^{10} W cm^{-2} were considered to be a prerequisite for element quantification, whereas speciation studies typically required power densities of 10^8 W cm^{-2}. Processing the huge datasets was seen as the main bottleneck for taking full advantage of the powerful aTOFMS methodology.

A *post-focusing electrical field in aTOFMS* improved the mass resolution from about 225 to 600 (50% valley) and increased the S/N of initially split peaks sixfold[161]. Basically, the ions were allowed to drift into a post-focusing zone in front of the mass analyser. Application of a pulsed voltage with duration adapted to the kinetic energy of the ions meant that slow ions, still at the beginning of the focusing zone, were accelerated fully whereas high energy ions, already at the end of the zone, were accelerated less. For ablated ions with an average energy of 8 eV, a voltage of 3.7 kV had to be applied after a time delay of 1500 ns.

Development of a new ion source and dedicated ion transfer optics allowed *detection of a single monolayer with Fourier transform LMMS* to be achieved with a 5 μm spot diameter[162]. Calculations predicted trapping of ions emitted initially at angles of up to 40^o and 60^o from the surface and from a distance of 1 mm above the sample, respectively. The improved analytical performance was demonstrated by the speciation of a copper complex present as a single monolayer. The signals were detected with mass resolution and S/N exceeding 100 000 (10% valley) and 10, respectively. Analysis of the sample by S-SIMS, the current reference method for monolayer analysis, showed that both techniques had similar LOD but that FT LMMS provided superior analytical specificity because of its high mass resolution.

7. Resonance ionization mass spectrometry (RIMS)

The number of papers dealing with the new analytical developments in RIMS has been gradually decreasing over the years in spite of the intrinsic potential of the method. There is no alternative to RIMS in terms of selectivity and ionization efficiency, but it requires expensive dedicated equipment and highly trained personnel for measurement of a limited number of analytes. On the other hand, there is an increasing trend to use resonance–enhanced multiphoton ionization or even resonant ionization in SNMS, where the neutrals are sputtered from the solid with a focused ion beam. These developments of great analytical interest in material and biological sciences owe a lot to the fundamental research and investigations in the field of RIMS.

The use of *coherently driven quantum systems* was investigated to overcome the loss of selectivity and spectral resolution due to power broadening of the radiative transition[163]. Use of laser fields with intrinsically narrow bandwidths for excitation and ionization allowed the property of collective population return to be exploited to eliminate power broadening. The theoretical description of the method was verified experimentally by the detection of trace NO by means of selectively ionized $^{15}N^{16}O$. The new method dramatically improved the distinction between $^{15}N^{16}O$ and $^{14}N^{16}O$ signals in the high power regime of 1.3 M cm^{-2} and improved the LOD by about an order of magnitude.

8. Secondary ion mass spectrometry (SIMS)

The bombardment of a sample with primary ions in the 1–25 keV range causes the development of a collision cascade over a distance of several tens of nm below the surface. Along its trajectory the projectile imparts sufficient energy to the lattice to break all intermolecular forces and to move individual atoms from their initial positions in the lattice. The generation of the secondary ions is believed to occur through the recoil of momentum towards the surface. Extensive atom relocation destroys the molecular structures in the subsurface. However, a major fraction of the molecules in the upper (few) monolayer(s) remain intact. Static SIMS (S–SIMS) limits sputtering to a fraction of the upper monolayer allowing the contribution of ions specific to the molecular form of the element to be maximized. Speciation and organic surface analysis form the major applications while depth profiling is incompatible with the principle of S–SIMS. This review restricts the acronym SIMS to the dynamic mode using continuous sputtering for the erosion of subsequent layers and depth profiling of elements. As TOFMS is beneficial in dynamic and static experiments, explicit distinction is made between TOF SIMS and TOF S–SIMS. The incidence angles, mentioned throughout this section, are expressed as the angle between the beam and the normal to the sample surface.

8.1. Reviews

A comprehensive review with over 150 references discussed the *use of nanoscale SIMS in soil ecology applications*[164]. The combination of high-resolution microscopy and isotopic analysis at high mass resolution with excellent LOD and a lateral resolution of 50 nm made nanoscale-SIMS the method of choice for a wide variety of studies for determining the distribution of organisms and chemical constituents at the biophysical interfaces in soils. A thorough treatise of instrumental features and modes of operation was complemented with practical considerations on sample size and preparation, simultaneous collection and quantification of isotopes, mass resolution and isobaric interferences. Research areas benefiting from the high spatial and high mass resolution offered by nanoscale–SIMS were reviewed.

A 51-reference review covered the *application of SIMS in nuclear fuel and cladding research*[165]. Principles, operating modes and in particular the modifications required to use a SIMS instrument for the analysis of highly radioactive materials, as well as the pitfalls in quantification and isotope analysis were described. Applications discussed included the study of the fission gas Xe and volatile fission products (e.g. Cs, I and Te) in UO_2 nuclear fuel, the measurement of the radial distribution of Pu isotopes in mixed oxide fuel and the determination of the distribution of B and Li in the external oxide layer on Zircaloy cladding. The authors considered SIMS to be a powerful technique complementary to electron probe microanalysis for these types of study.

8.2. Fundamental studies

An investigation into the formation mechanisms of MCs^+ and MCs_2^+ ions from silver, selected because of its high polarisability, under different conditions of oxygen flooding revealed a remarkable *dependence of the KED on the oxygen pressure*[166]. The sample was bombarded with 5 keV Cs^+ ions at an incidence angle of 22.5° and an oxygen pressure between 2×10^{-8} and 9×10^{-7} mbar. The KED were measured with a resolution of 0.003–0.679 eV for an energy range of 0.05-20eV. The intensity of the $AgCs^+$ signal decreased exponentially with the oxygen pressure in a similar way to the work function, thereby confirming the applicability of the tunnelling model. Whereas the KED for the Cs^+, Cs_2^+ and $AgCs_2^+$ ions were of similar width, that for the $AgCs^+$ ions was much broader. Hence, different formation mechanisms had to be involved. The data supported the formation of MCs^+ via the recombination of neutral M and Cs^+

with an efficiency dependent on the oxygen pressure. In contrast, MCs_2^+ ions originated from recombination of MCs and Cs^+, and not from recombination of M with Cs_2^+.

The *KED shifts due to changes of the work function* during bombardment of a H-terminated silicon wafer with Cs^+ primary ions at an incidence angle of 45° were measured using the reflector in a TOF instrument for a 250 – 2 keV projectile energy range[167]. Bombardment with Se^+ provided reference data. Combination of 300 eV Cs^+ projectiles with increasing fluxes of the neutral beam caused a continuous decrease of the work function over a range of about 2.5 eV. The observed dependence of the work function changes on the ion beam energy was explained by the formation of a dipolar layer at the surface of the silicon.

The *simultaneous use of a Cs neutral beam and another projectile beam* gives additional degrees of freedom to accommodate, for instance, the trade off between signal intensity and depth resolution. In order to get an insight into previous experimental results, computer simulations were used to estimate Cs surface concentrations in a silicon sample bombarded with Ga^+ primary ions and Cs neutrals[168]. Although the calculations yielded the implantation profiles for Cs and described the sputtering yields as a function of the primary ion fluence, the surface binding energy and the sticking of the neutral Cs to the surface were not described adequately. The dependence of the negative secondary ion intensities on the calculated Cs surface concentration was consistent with the electron tunnelling model. However, the shortcomings of the simulations motivated subsequent measurements of how the useful yield varied depending on the conditions used for the deposition of Cs neutrals in combination with Cs^+ or Ga^+ bombardment[169]. The work function range for aluminium, silicon, nickel, GaAs and InP samples was 4.3 – 5.3 eV. The work function shifts were derived from the contact potential between the sample and the electrostatic analyser. The spectrometer's energy bandwidth was reduced from 130 to 2–3 eV to obtain a resolution of 0.15 eV. The neutral Cs deposition rate was measured with a quartz balance. The increase of the useful yields from the nickel sample as a function of the Cs deposition was explained by the electron tunnelling model. However, the development of topography at the crater bottom in the other samples compromised the agreement between experiment and theory.

The *formation of* MCs^+ *and* MCs_2^+ *by a mixture of* Cs^+ *and* Xe^+ *projectiles* was investigated to improve the analytical optimization of the trade off between increasing the Cs surface concentration and decreasing the positive ionization probability[170]. The Cs and Xe sources were mounted on the same ion optics column, which was also fitted with deflection units to obtain a mixed projectile beam by adjusting the duration of the pulse on each deflector. The experiments were performed on a silicon wafer with its native oxide layer removed by sputtering with Cs^+ or Xe^+ projectiles and by using Ga^+ primary ions for analysis. The Cs surface concentration built up in the surface layers was measured from the Cs^+ secondary ion signal produced during the Ga^+ primary ion bombardment. The Si^+ ion intensity decreased exponentially with Cs surface concentration while that of the $SiCs^+$, Cs^+ $Cs_2^+$and $SiCs_2^+$ ions went through a maximum. While the yield variation of elemental ions was consistent with the electron tunnelling model, other mechanisms had to be active in the formation of adduct ions. The data from this study were used to explain the yield variations seen experimentally in the interface zone when a gold layer on bare silicon and Pd/Rh films were depth profiled with a mixed Xe^+ and Cs^+ sputter beam[171, 172].

Extensive simulations gave insight into the mechanisms behind the so-called *adjacent electron flooding method*, in which a 6.5 keV electron beam is directed onto a metal coated sample area in the vicinity of the crater and not on the crater itself[173]. The modelling showed that the backscattered electrons from the metal coated area could not be responsible for the charge compensation because these electrons returned to the sample far outside the crater. In contrast, the secondary electrons generated by the electron gun from the metal coating effectively landed inside the crater to achieve the charge compensation. The findings were confirmed experimentally by the improved charge compensation at lower electron beam currents when the metal coating was removed from an area of ~500 × 500 μm^2 for the analysis of a central 120 × 120 μm^2 area.

The development of a relatively simple gas cluster ion beam (GCIB) source producing 7.5-27.5 keV Ar_n^+ projectiles (n up to 10 000) through electron ionization of a adiabatically expanded gas at high pressure triggered the investigation of the *effect of cluster size and energy on ion emission*[174]. The decreasing sputter yield for silicon with increasing 20 keV cluster sizes fitted well an empirical formula with a non-linearity factor of 1.1, which compared well with the value of 1.24 predicted by molecular dynamics simulations. Hence, multiple collision cascades and the development of a high energy density zone in the subsurface of the sample were considered to be responsible for "non–linear phenomena". A subsequent study focused on the dependence of Si atomic and cluster ion yields on the size and energy of the incident Ar_n^+ (n = 750 – 10,000) projectiles[175]. Specifically, the yield of the Si_n^+ (n $\leq$7) ions increased with the projectile energy according to an asymptotic function while the signal intensity ratio Si_6^+:Si^+ was maximised for Ar_{700}^+ projectiles. This could be explained either by the lower IP of Si_6^+ ions relative to that of Si^+ ions or by the increased probability of emission through thermal evaporation, as known from laser irradiation.

The re-examination of secondary ion yield data in the literature revealed the *applicability of the thermal spike model to polyatomic projectile bombardment* in both dynamic and S–SIMS[176]. According to this theory, ion formation would occur through thermal evaporation from a hot cylindrical region around the projectile track. The model provided an excellent description of ion sputtering yields for elemental targets over a wide range of energy, primary ion cluster type (Au_n^+, Bi_n^+) and size (e.g. Au^+ to Au_{13}^+). Fitting the experimental data to the model required realistic values for the fitting parameters such as the diameter of the thermal spike.

8.3. Analytical methodology

A new method for the *vertical scale calibration in step height measurements* by stylus profilometry was based on the use of a multiple δ–layer film[177]. The expanded uncertainties on commonly used step height standards were typically in the range of several nm. Therefore, a Si/Ge multiple δ–layer film with 6 δ–layers at a distance of ~40 nm was developed and HR TEM was applied to a cross section for the determination of the layer positions. Using the Ge signal, SIMS depth profiling was stopped at each δ–layer, allowing the profilometry data to be calibrated against the results of the HR TEM over a depth of about 250 nm. The new calibration reduced the uncertainty on the depth of the δ–layers from 1.4–1.6 nm to 0.2–1 nm for a typical step height standard with certified height of 89.4 nm.

A *set of CRM for calibrating the concentrations of* ^{75}As, ^{10}B *and* ^{31}P *in silicon* was obtained by application of nuclear analytical methods for the accurate determination of the dopants in existing doped silicon SRM (NIST SRM 2137, 2134 and 2133). [178]Specifically, neutron depth profiling, instrumental neutron activation analysis (NAA) and radiochemical NAA were used for the determination of As, B and

P, respectively. An interlaboratory comparison of dopant doses, determined with the aid of these CRM for calibration, showed agreement typically to within 2% except when the concentrations were close to the LOD. For example, the agreement of the B concentrations in doped epitaxial films was 2.3 and 9.2% for samples containing 8×10^{17} and 8.2×10^{15} atoms cm^{-3}, respectively.

Charge compensation in shave-off depth profiling was found to be critical for obtaining a symmetrical and flat topped profile from the analysis of an embedded spherical particle with a constant element concentration[179]. The shave-off method eroded the sample by moving the primary beam sideways i.e. in a plane perpendicular to the depth axis. The collected secondary ions reflected the composition of the sample along the line scan. The depth scale depended on the position of the beam and not on the sputter time as in conventional SIMS. A dedicated electron flood gun with full control of the emitter, suppressor and extractor potentials was developed. Measurement of a spherical silica particle without electron flooding gave a highly asymmetric depth profile with a dip in the middle. Careful tuning of the electron flooding conditions allowed the expected Gaussian profile to be obtained. Calculations showed that the dip seen without electron flooding could be explained by subsequent charging and discharging events when the beam passed the spot, causing a periodic fluctuation of the signal with a frequency of between 0.1 and 100 Hz depending on the properties of the material and the primary beam.

A new *data processing procedure for the shave–off depth profiling of thin films* was based on a deconvolution method that accounted for the Gaussian profile of the primary ion beam intensity[180]. A 1 μm thin cross section was prepared from an Al–doped zinc oxide film (thickness 100 nm) on silicon by using a focused ion beam

(FIB) and the lift–off technique. The deconvolution method revealed the fine details of the Al accumulation in a zones about 150 nm under the surface and about 10 nm under the interface.

Detailed characterization of the KED of the secondary ions as a function of the target and the extraction voltage was necessary to optimize the *energy filter setting in quadrupole SIMS*[181]. Monocrystalline Si and Ti as well as polycrystalline Si were bombarded with 20 and 30 keV monoisotopic Ar^+ ions. The measured KED showed that increasing the extraction voltage broadened the distributions with little increase in the maximum intensity above 80 V for Si^+ secondary ions whereas the maximum intensity of Ti^+ secondary ions continued to increase. The KED width decreased similarly for both secondary ions with increasing projectile energy. Experimental and simulated data agreed well with respect to the energy of maximum ion intensity. However, the predicted distributions for Si^+ and Ti^+ secondary ions were wider and narrower, respectively, than the experimentally measured ones. Use of an extraction voltage of 80 V optimized both signal intensity and mass resolution.

Use of *oxygen flooding in combination with the 20 keV* Ar_{1000}^+ *projectiles* from a GCIB source was an extremely efficient way for producing a fully oxidized surface during analysis of silicon[182]. Furthermore, the cluster ion beam gave the additional advantage of atomic-scale surface smoothing. The SiO^+ ion emission yield steeply increased with oxygen pressure up to ~$4x10^{-2}$ Pa, at which it exceeded the Si^+ ion emission yield. At higher pressures, the SiO^+ ion yield decreased slightly because the surface was already fully oxidized and the collisions of the projectiles with the oxygen atmosphere reduced their energy. Use of 20 keV Ar cluster projectiles at an oxygen pressure of $6.5\ 10^{-3}$ Pa gave a SiO^+:Si^+ signal intensity ratio that was about twice that achieved with 15 keV O_2^+ projectiles.

A new *method for the correction of the in situ H contamination* was based on measurements with different primary beam currents and the inverse relationship between the H:^{30}Si ion intensity ratio and $^{30}Si^+$ counts[183]. Because the Si^+ signal intensity was inversely proportional to the primary ion beam current, all the data fell on a straight line, the slope of which depended on the rate of *in situ* contamination. The intercept with the ordinate gave the true H concentration in the sample. Any variation of the H:Si intensity ratio unrelated to *in situ* contamination caused bending of the line rather than changing its slope. The method was checked on NIST SRM 610 (trace elements in glass), synthetic enstatite crystals and Cr-doped enstatites, analysed under different conditions that varied the extent of the *in situ* H contamination. Consistent levels in the range of 5 – 10 ppm H were found.

Measurement of the yields of B^+, Ge^+ and Si^+ for B-implanted $Si_{1-x}Ge_x$ (x=0-1) samples analysed with 5.5 keV $^{16}O_2^+$ and $^{18}O_2^+$ allowed the unusually strong matrix effects observed during depth profiling to be explained in terms of the *beam-induced modification of the sample composition*[184]. Specifically, the useful yield of B^+ and Ge^+ dropped suddenly by a factor of 10 for values of x between 0.9 and 1. Both medium–energy ion scattering and nuclear reaction analysis (NRA) were used to determine the depth profile of ^{18}O independently of SIMS analysis, thereby allowing the contributions from beam–implanted and adsorbed oxygen to be quantified. The data pointed to a significant change in sample composition caused by the oxygen implantation. Specifically, the top layer with 1 nm thickness was converted into a silicon suboxide with some Ge while the subsequent layer, about 5 nm thick, consisted of silicon– and germanium–suboxides. In both layers, the oxygen came from the sputtering beam.

8.4. Quantitative analysis

A new method accounted for the *matrix effects in silicon–rich–oxide (SRO) layers and silicon nano–crystals*, which hamper the quantitative depth profiling of such opto–electronic materials[185]. Variable angle spectroscopy–ellipsometry (VASE) and XPS were used to determine the thickness and composition of different SRO films on Si wafers, deposited by plasma–enhanced chemical–vapour–deposition using SiH_4, N_2O and NH_3 in different ratios. The correction procedure used scaling factors to normalize the SIMS data to the nominal Si concentration in a silicon dioxide sample and in the bulk wafer. The Si concentrations in the different layers were derived from a simple fitting curve. Comparison with VASE and XPS results showed that the SIMS method was typically accurate to within 5%.

The *SIMS analysis of B–doped single crystal diamond*, which used RSF for B relative to ^{12}C, was calibrated using high–resolution X–ray diffraction analysis[186]. The dependence of the $^{12}C^+$ signal on B concentration in ultra–low–energy SIMS analysis (0.3-1 keV O_2^+ projectiles at normal incidence) was caused by a change in the ionization probability of C rather than by a change in erosion rate or the occurrence of post-ionization in the gas phase. Hence, the use of concentration–dependent RSF was mandatory for accurate analysis of heavily doped materials. These RSF were derived from implanted samples in which the B concentration was quantified with NRA.

The first reported *use of C_{60}^+ projectiles* for the quantitative surface analysis of homogeneous Fe–Ni alloy thin films used ID ICP–MS calibration[187]. One sample was used as a RM to derive the RSF and the others were treated as unknowns. The analysis involved bombardment with 15 keV C_{60}^+ ions and signal accumulation over a depth interval of 15 to 150 nm. The sputter depth scale was calibrated by stylus profilometry. Application of Auger electron spectrometry and XPS confirmed the in–

depth homogeneity of the films seen with SIMS. Measured concentrations of Fe were accurate to within 4% and the in–sample precision was <0.05 %.

Differences in sputtering and ionization mechanisms when Cs^+ or O_2^+ primary ions were used for the generation of negative or positive secondary ions, respectively, from organic materials made the *mass fractionation of C and H isotopes dependent on the projectile*[188]. Specifically, the ^{13}C:^{12}C and ^{2}H:^{1}H isotope ratios were considered. In the case of O_2^+ bombardment and positive–ion detection, the relative ion yield of the light to heavy isotope equalled the ratio of the masses. In the case of Cs^+ projectiles and negative ion detection, the ion yield ratio corresponded to the square root of the mass ratio. The results were consistent with previous measurements on inorganic samples. Hence, the authors warned of pitfalls if mass fractionation was not accounted for in the analysis of isotope–labelled materials.

Instrumental mass fractionation (IMF) in the *H isotope analysis of silicate glasses* caused an average –220‰ depletion in the heavy isotope of measured ^{2}H:^{1}H ratios[189]. Differences in IMF within subsets of glasses correlated with variables such as water content, density and other chemical parameters. The energy– and composition–dependence of the IMF was well described by the KE transfer analysis in a simple elastic two-collision cascade model. This gave an important insight into the origins of the matrix effects and allowed a quantitative correction model based on sound physical effects to be developed. The resulting method predicted the experimental IMF to within 8‰.

A single–particle isolation procedure was developed for the determination of *^{234}U:^{238}U and ^{236}U:^{238}U isotope ratios in 1 μm particles of swipe samples* that also contained lead particles causing isobaric interferences on the U signals[190]. The U-containing particles were identified using SEM–EDS and transferred to a glassy carbon platelet using a manipulator with gold coated tip (diameter ~ 1 μm). The method was tested on a simulated swipe sample containing Pb metal particles and a uranium CRM (NBL CRM U010). An 11.5 keV O_2^+ primary ion beam focused to a beam spot of <10 μm was used for analysis at a mass resolution of 300. In the presence of the Pb–containing particles, the ^{234}U:^{238}U and ^{236}U:^{238}U ratios increased linearly with the peak intensity ratio. Spots in which the ^{208}Pb:^{238}U signal intensity ratio was 1.5 gave ^{234}U:^{238}U and ^{236}U:^{238}U ratios of 4 and 6 times the expected values, respectively. The particle isolation procedure improved the agreement between experimental and reference ratios to typically 1%. The maximum deviations measured for 20 particles were 9 and 13% for ^{234}U:^{238}U and ^{236}U:^{238}U, respectively.

The feasibility of *N isotope ratio measurements for isotopically enriched soil bacteria with a lateral resolution of 100 nm* was investigated using model samples consisting of ^{15}N–enriched bacteria grown on white sand and soil[191]. The precision of the ^{15}N:^{14}N isotope ratio was ~7%. The feasibility of imaging areas as large as 270 × 270 μm or as small as 10 × 10 μm was seen as a major asset for correlating soil structure to the microscale and nanoscale chemical compositions, respectively.

Optimization of the *in situ* measurement of the *^{44}Ca:^{40}Ca isotope ratio in carbonates* with a spatial resolution of 15–20 μm improved the external and internal precisions to better than 0.13 and 0.1‰, respectively[192]. The SIMS analysis was achieved with O^- projectiles, a magnetic mass analyser tuned for a mass resolution (M/ΔM) of 5000 and simultaneous detection of the two Ca isotopes on Faraday cups. The $^{41}K^+$ and $^{88}Sr^+$ signals were used to correct interferences of $^{40}K^+$ on $^{40}Ca^+$ and $^{88}Sr^{2+}$ on $^{44}Ca^+$, respectively. By using the natural calcite sample MEX, in which the

δ^{44}Ca values had been determined by TIMS, as calibration standard in SIMS analysis, the δ^{44}Ca value measured in the BRET sample agreed to within experimental error with the value determined by TIMS. The analytical precision was sufficient for measurement of the intra–shell variability of δ^{44}Ca in planktonic foraminifera.

8.5. Single and multi-dimensional analysis

8.5.1. Depth profiling. The optimum conditions for the *low–energy ultra–shallow depth profiling of B doped δ-layers in silicon* were the use of 0.5 keV O_2^+ projectiles at 44° incidence angle together with oxygen flooding[193]. Under these conditions, the decay length was 0.8 nm. Oxygen flooding decreased the surface roughening significantly from 3.85 to 0.17 nm for 1 keV O_2^+ at 48° incidence angle and from 0.21 to 0.14 nm for 0.5 keV projectiles at 44° incidence angle. Surface roughness affected the erosion rate, causing shifts in the δ-layer positions as well as in the ion yield. The Gaussian broadening parameter of the depth resolution function was closely related to the surface roughness of the crater bottom.

Comparison between HR RBS and SIMS for the *ultrashallow–depth profiling of N* in Si_3N_4 and SiO_2 stacked layers with thickness of 2.5 nm and 1 nm, respectively, showed that use of 0.25 keV O_2^+ projectiles at 78° incidence angle gave accurately positioned profiles[194]. Close agreement with RBS results for the ultrashallow–depth profiling of As–implanted silicon demonstrated that effects caused by the native oxide layer from a depth of 2 nm onwards were adequately accounted for.

The serious discrepancies between SIMS and nuclear reference techniques that existed when the commonly used conditions of normal incidence and oxygen flooding were applied to the *near-surface analysis of the B in silicon* were removed through the use of 500 eV O_2 projectiles at 60° incidence angle in the absence of oxygen flooding[195]. The distribution and concentration in the top few nm closely agreed with the results from elastic recoil detection, NRA and high-resolution RBS analysis. The simultaneous detection of the B and O signals provided an accurate oxide marker for positioning the B profile with respect to the SiO_2/Si interface. Results from SIMS and NRA agreed to within 5% for high near-surface dopant concentrations up to 2.5 10^{22} atoms cm^{-3}.

A systematic investigation of *ultralow–energy depth profiling* of multiple Ge-doped δ-layers in silicon showed that a depth resolution of 1.9 nm was feasible with a 320 eV Cs^+ primary ion beam and 50° incidence angle[196]. The mixing–depth roughness information (MRI) model proved useful for distinguishing between the contribution to the depth resolution from atomic mixing and beam–induced surface roughness. For instance, lowering the impact energy to 320-500 eV and increasing the impact angle up to about 50° reduced the contribution from atomic mixing. While in principle the decay length would be minimized at an impact angle of 70°, the onset of surface roughening occurred at depths of 23 and 12 nm with 320 and 500 eV projectiles, respectively, and at an incidence angle of 60°.

The detection of the negative cluster ions Si_2^- and TiO_2^- overcame the strong *matrix effects and ion interferences* which hampered the depth profiling of Ti/Si multilayer films with 5 keV Ar^+ projectiles[197]. The sample consisted of 4 alternating layers of Si and Ti with thickness of 2 and 18 nm respectively, capped with a SiN layer and deposited on a crystalline wafer with SiO_2 layer. Contaminants such as C, Fe and Ni caused numerous isobaric interferences on the positive ions of interest and the Ti^+ ion yield depended strongly on the local O content. The described method using negative ion detection allowed the redistribution of elements in the structure upon annealing to be studied in detail.

Use of 10 keV $Ir_4(CO)_7^+$ projectiles for the depth profiling of B δ–doped layers over 14 nm (45° incidence angle and with oxygen flooding) revealed an *unusual increase in the sputter yield* in comparison to bombardment at 60° incidence angle[198]. This was explained by formation of a thick carbon layer at low incidence angle as a result of the low sputtering rate. This layer also lowered the projectile energy to <5 keV thereby preventing any improvement in depth resolution. The development of an Ir_4^+ primary ion gun was proposed to overcome the problem.

A comprehensive study on the *surface transient widths in ultra–low–energy* Cs^+ *depth profiling* of Ge–δ–doped Si (nominal thickness of 0.4 nm at a distance of 12 nm from the surface) focused on determining the optimum analytical conditions with respect to projectile energy and impact angle[199]. A transient width (1.4 nm) very close to the penetration depth was obtained using a primary ion energy and incidence angle of 320-500 eV and 30-50°, respectively. Use of a 30° incidence angle was preferred to optimize the signal intensity and sputter rate.

The *quantitative depth profiling of alternating Pt–Co multilayers* with individual layer thickness of ~20nm using 14.5 keV C_{60}^+ projectiles and negative ion detection revealed a severe matrix effect at the interface where the presence of Co significantly enhanced the Pt ion yield[200]. The matrix effect was correlated with variations in matrix composition through the Pt/Co and Co/Pt interfaces. Use of different RSF derived from Pt-Co mixed Co alloys films improved accuracy to within 1 – 10%.

A systematic study on wear-protective coatings such as CrN/CrC multilayer, binary TiN–CrN coatings and a Si–implanted TiC layer on stainless steel or carbon, using 0.88 and 5 keV Ar^+ primary ions, showed the importance of the *selection of specific secondary ions for the reduction of matrix effect*[201]. Auger electron spectrometry with ion sputtering served as reference method for quantification. Serious matrix effects in SIMS were due to the variable uptake of oxygen from the environment during sample preparation. However, measurement of secondary ion clusters such as $^{52}Cr^{12}C^+$ and $^{52}Cr^{14}N^+$ rather than atomic ions minimized the matrix effects. The use of 550 eV beam sputtering of the Si-implanted TiC layer and detection of the $^{23}Si^{12}Cs^-$ ions provided an accurate distribution of Si dopant in the TiC material.

8.5.2. 2-D analysis. The confusing existence of different approaches for determining *lateral resolution* motivated an interlaboratory comparison of the imaging of a nanoscale strip pattern CRM (BAM-L002) with the Ga^+ liquid metal ion gun[202]. The sample provided a series of strips of $Al_xGa_{1-x}As$ or $In_xGa_{1-x}As$ with a width between 0.4 and 500 nm at different spacings. Lateral resolution was evaluated using the ion images to determine distance between narrow strips, strip width and the line and edge spread functions. The FWHM of the profiles across a δ-strip that was narrower than the spot size of 150 nm, showed serious scatter within ranges of 69 – 127 and 189 – 380 nm for strips of 5 and 50 nm, respectively. The study concluded that more laboratories should use the CRM during optimization and apply a deconvolution procedure to improve results.

8.5.3. 3-D analysis. Several *multivariate statistical methods for data processing,* including PCA, evolving factor analysis and multivariate curve resolution, were investigated to reduce the output of a 3–D analysis to chemically meaningful factors[203]. Data scaling was important in this process. Keenan scaling worked in the case of simple depth profiling whereas normalization to the total ion yield over all pixels was more useful for 3–D analysis. Examples given included the depth profiling of a Cu layer grown on TaN coated silicon wafer and 3–D analysis of buried inclusions in silver-glass paste residues on SiN–coated Si.

The 3–D micro-scale analysis of *frozen hydrated samples* using a FIB for cross sectioning and SIMS imaging of the section surface exploited the reduced beam–induced damage that a FIB produced at the surface of the cross section[204]. To compensate for the loss of ice by evaporation, the protective ice layer was restored when necessary by using a water vapour jet system incorporated in the instrument. The feasibility of the approach was demonstrated on different test samples.

8.6. Static SIMS (S-SIMS)

A 13–country interlaboratory study involving 32 TOF instruments considered a *mass accuracy of better than 10 ppm* to be mandatory for useful analytical work[205]. Although 84% of the instruments provided data repeatable to within 1.9%, the mass accuracy was much poorer than expected with deviations of up to 60 ppm for peaks at m/z <200. The importance of using ions with the same KED for calibrating the mass scale was shown. The common approach of including organic ions in the calibration was to be avoided and only atomic ions should be used. A generic protocol was developed allowing the mass accuracy to be improved by a factor of 2 – 8 depending on the instrument.

A *memory–efficient format for storing sparse datasets from TOF-S-SIMS imaging experiments* was developed to reduce data processing time and to increase the TOF resolution[206]. Application of three multivariate techniques on both sparse data and the original data sets showed no significant qualitative difference in the processed images. A new technique for visualization combined both spectral loadings and spatial scores into one 3–D view of the complete data cube.

Monoatomic and polyatomic projectiles have been compared for the speciation and quantification of particulate samples collected from a laboratory ventilation manifold[207]. Specifically, 12 keV Ga^+ and 5.35 keV polyatomic ReO_4^- projectiles were used in combination with TOF and quadrupole mass analysers, respectively. The negative ion mass spectra featured atomic ions and high *m/z* adducts or fragments for speciation. Use of monoatomic and polyatomic projectiles was preferred for quantification and speciation, respectively. In contrast to the use of monoatomic primary ions, polyatomic bombardment eliminated the need for charge compensation. Imaging of large areas, typically $240 \times 240\ \mu m^2$, was achieved with a lateral resolution of 1–2 μm, for both atomic and speciation ions. There was a systematic bias between the intensity ratios for the two instruments which was addressed through the use of proper calibration lines.

A *high–throughput screening methodology* was developed using TOF SIMS imaging for the fast and detailed chemical characterization of sputter–deposited gradient films as large as 70×70 mm^2 in area[208]. Using a mask, various elements including Cr, Fe and Ti were sputter deposited under different conditions to obtain the desired gradient film. Subsequently, the sample was exposed to deuterium gas in order to probe the local adsorption characteristics. The entire 90 mm diameter wafer was imaged in less than 90 minutes. The inherent panoramic detection also provided information on various inorganic contaminants such as K and Na, which are of use for troubleshooting and identifying faulty devices. Multivariate statistical analysis tools were necessary for assisting data interpretation.

9. Sputtered neutrals mass spectrometry (SNMS)

A concise *review* surveyed the potential offered by combining focused ion beam sputtering and laser post-ionization compared to that offered by modern SIMS nanoprobes[209]. The useful yield was identified as the key factor determining the limits of the methodology. Use of literature data allowed the ultimately attainable lateral resolution to be estimated for different experimental configurations of laser post–ionization SNMS and SIMS instruments. While the useful yield of SIMS was considered to remain <1%, that of SNMS was already in the range of 25 to 40% further improvements to 80% were anticipated. As a result, SNMS methods could provide a LOD of 0.3 atom% for elements in a 15 nm feature whereas SIMS would need the analysis of a 50 nm feature to detect the same concentration.

A new *instrument using resonance ionization (RI) of ion–beam–sputtered neutrals*, a beam spot diameter on the sample of 30 nm and a TOF mass analyser gave useful ion yields in the order of 1-10% and 20% for elements ionized in a one- and two-step resonant scheme, respectively[210]. The laser system consisted of two YAG and three dye lasers, making up to four colours available for RI. A liquid metal ion source with a specially designed ion optical column gave a primary projectile beam with a current density as high as 8 A cm^{-2}. The use of a two-step RI scheme allowed a LOD of $4x10^{18}$ atoms cm^{-3} to be achieved in the 3–D analysis of an Fe–implanted silicon wafer. Even with a one–colour scheme, imaging of P in a patterned wafer could be performed with a LOD of $5x10^{19}$ atoms cm^{-3}. The useful yields were at least one to two orders of magnitude higher than those in TOF SIMS.

Depth profiling of magnetoresistant Co-Ni-Cu nanolayer devices using a low pressure rf Ar discharge in the direct bombardment mode revealed the existence of concentration gradients within individual layers that could badly effect the quality of the device[211]. A series of Co-Ni-CuCu/Cu and Co/Cu multilayers films deposited on commercial copper sheets and a Cr/Cu layer on silicon provided a suite of test samples with different surface roughness and individual layer thickness between 5 and 100 nm. Quantification was performed using RSF. The depth scale was based on the determination of the total layer thickness and accounted for differences in the sputtering rate of individual layers. The depth resolution was less dependent on the initial roughness of the substrate than expected and instead total sample thickness (120–500 nm) was the determining factor. Layers with a thickness of <30 nm could not be resolved in samples with a total thickness of 500 nm.

10. Stable Isotope Ratio Mass Spectrometry (SIRMS)

10.1. Reviews

A *review of stable isotopes in environmental and forensic geochemistry* stressed the important role they had acquired, especially for identifying sources of contaminants[212]. The argument was made that C and H stable isotope analyses have become as equally important as GC–EIMS methods for isotope analysis. The isotope fingerprint of individual compounds has been an especially powerful tool for source assessment.

Measurement of the ^{13}C:^{12}C ratio crosses a large section of disciplines from a tool revealing the origin of compounds to more recent approaches such as metabolomics and proteomics. A timely review on *LC–SIRMS* for $\delta^{13}C$ determination considered the development of the interfaces required (moving wire, chemical reaction interface, wet chemical oxidation interface). [213]The use of 100% aqueous mobile phase was considered desirable for increasing selectivity and efficiency.

An excellent *overview of the* emerging and technically challenging SIRMS method of *clumped isotopes* analysis included applications in the geological and atmospheric sciences[214]. Clumped isotope geochemistry is concerned with the state of ordering of rare isotopes in natural materials, that is the extent to which rare isotopes associate with each other rather than with the abundant major isotopes. Various mechanisms were proposed for the deviations from stochastic distributions that result in clumping. Examples given included detection of natural abundance anomalies of minor isotopes in CO and CO_2 molecules caused by atmospheric or other natural processes in order to extract information on molecule formation. Measurement of isotopic anomalies of the $^{13}C^{18}O^{16}O$ molecule required additional Faraday cups with variable resistance, highly pure CO_2 gas and long measurement times to achieve precisions of 1–10 ppm on the stable isotope ratio. To date, these measurements have only been accomplished on instruments modified with additional Faraday detectors but other possible measurement protocols were discussed.

Experimental stable isotope data are measured relative to the isotopic composition of a working gas and must be converted to an international reference scale. Routinely used procedures for this conversion, called *normalization*, have been reviewed using a mathematical treatment[215]. The conversion procedures considered were single–point anchoring (versus working gas and CRM), modified single–point normalization, linear shift between measured and true isotopic composition of two CRM and two–point and multi–point linear normalization methods. The computations revealed that single–point anchoring produced normalization errors that exceeded the maximum total uncertainties (typically ±0.1‰ for $\delta^{13}C$) reported in the literature and that it should therefore not be used. Normalization methods using two or more CRM were recommended on the condition that the isotopic compositions of the CRM bracketed that of the unknown sample.

10.2. Instrumentation

In a further development of the *spooling wire microcombustion system*, small numbers of pre-sorted microbial cells were dried on the moving wire and then combusted for $\delta^{13}C$ analysis[216]. A typical analysis required roughly 100 eukaryotic or bacterial cells and gave a precision of better than ±0.2‰ on as little as 25ng C. The precision of similar system was adequate for differentiating between individual pollen grains derived from C3 ($\delta^{13}C$ = –26.9±6.3‰) and C4 ($\delta^{13}C$ = -11.5±9.6‰) plants[217].

A custom–built *gas sampling and injection system* for the compound–specific isotope analysis (CSIA) of environmental gases provided flexible operation and economical use of the small samples containing analytes over a wide concentration range[218]. The system consisted of a customized inlet, two alternative reactors (an oxidation reactor to produce CO_2 and a reduction reactor to produce H_2), a liquid N_2 spray–cooling unit for cryo–GC–focusing at –20˚C and a dryer to remove water vapour. The three injection loops (0.06–500 µl) gave flexibility in choice of injected sample volume in order to match the sample concentration to the dynamic range of the instrument. Reproducible data could be obtained over concentrations ranging from 100% down to 10 ppm.

Incorporation of a special *"ashtray system*" in an EA–SIRMS system to collect the combustion residues improved the LOD to 10 µg C and 1.5 µg N for simultaneous CO_2 and N_2 isotope analysis, respectively[219]. Low system background values and good S/N rendered additional blank correction for these small samples unnecessary. Precisions of ±0.26 and ±0.50‰ (SD) were achieved for 8.2–15 µg C and1.2–2 µg N, respectively.

In order to achieve the good baseline separation of adjacent peaks required for GC–SIRMS analysis, efficient solvent removal is essential. Use of a *cooled injection system* operated in solvent vent mode, in which solvent elimination was supported by an auxiliary pump, eliminated the need for many column fittings (unions, tee pieces, valves) which are associated with the commonly used methods of back–flushing and flow diversion and which lead to significant deterioration of chromatographic resolution[220]. A considerable enhancement of chromatographic resolution was achieved and the analysis of high–boiling and polar compounds was improved. There was no evidence for isotopic fractionation associated with partial loss of low–boiling analytes during solvent elimination.

A major reduction in peak broadening has been achieved in the first reported *coupling of fast GC to SIRMS* which provided 250 ms peak widths (FWHM) at 1 ml min^{-1} flow rates[221]. These widths, one fifth of those previously reported for GC–combustion–SIRMS systems, were achieved by using a programmable temperature vaporization injector in place of a rotary valve or backflush system to optimize the postcolumn interface. The system also included a narrow–capillary combustion reactor and cryogenic trap with narrow–bore transfer lines. Quantitative combustion was demonstrated for injections of CH_4. The precision (0.2–0.3‰) was independent of peak width for injections of >600 pmol C but was considerably better for narrow peaks than for broad peaks when <150 pmol C was injected. For example, the precision of <1‰ obtained for 5–15 pmol C using 250 ms peak widths on the fast–GC system was 10–fold better than that obtained for 2500 ms peak widths on a conventional GC system. The main advantage of the fast GC system over conventional GC was that it provided the same level of precision in much less time.

10.3. Method development

A new method for the *carbon CSIA of volatile fatty acids* combined aqueous mobile phase RP–HPLC separation, chemical oxidation and on–line SIRMS[222]. The low concentrations of these compounds had made large scale analysis difficult but the high sensitivity of the new method improved the LOD to the previously inaccessible 2 µM level for sodium acetate dissolved in artificial seawater and 10 µM in marine prewaters. As little as a few tens of ng C could be analysed. The fully automated on–line operation allowed a larger number of samples to be analysed than had previously been possible.

The *preconcentration of organic compounds* in very dilute liquids is required for the measurement of stable isotopes in a variety of studies where method sensitivity is insufficient. The sensitivity of GC–SIRMS for the analysis of volatile organic groundwater contaminants is poorer than that of GC–EIMS analysis but modifications to a commercial purge–and–trap resulted in the lowest LOD for monoaromatic compounds (0.07–0.35 µg l^{-1}) reported so far using an automated CF–SIRMS system[223] The LOD for halogenated hydrocarbons were in the 0.76–27 µg l^{-1} range. The new method gave good reproducibility, high linearity and small isotopic fractionation. Improvements in the SPME–GC–SIRMS analysis of explosive residues for the determination of isotopic enrichment factors of various nitroaromatic compounds gave LOD for $\delta^{13}C$ and $\delta^{15}N$ of 0.07–0.8 and 1.6–9.6 mg l^{-1}, respectively[224]. The $\delta^{13}C$ and $\delta^{15}N$ signatures determined by SPME–GC–SIRMS and by EA–SIRMS, used as a reference method, agreed to within ±0.7% and ±1.3%, respectively, for most but not all compounds. A new simple and rapid SPME–GC–combustion–SIRMS method for the determination of C, H, and O isotope compositions in aqueous solutions of ethanol at mM concentrations had the advantage of not requiring distillation for ethanol purification[225]. The $\delta^{13}C$, $\delta^{2}H$ and $\delta^{18}O$ values could be determined in 30, 30 and 75 minutes, respectively, with precisions of ±0.3, 0.9 and 0.7‰, respectively.

An ID–SIRMS method for the determination of free glycine in soil extracts was based on addition of ^{15}N–enriched glycine to the extract, removal of humic acids and preconcentration of glycine, derivatization and GC–combustion SIRMS analysis[226]. Derivatization with ethylchloroformate to give the N(O,S)–ethoxycarbonylethyl ester was selected because it was a fast single–step procedure which produced a stable derivative with higher N:C ratio than other derivatives. A 1000–fold preconcentration provided by a solid phase extraction technique combined with reduction of the final solvent volume did not improve sensitivity sufficiently for precise analysis. A further tenfold increase in sensitivity was achieved by adding a spike to bulk the glycine so that sufficient was available for precise analysis. No shift in $\delta^{15}N$ values due to the sample preparation was found. Although the sample requirement for GC–EIMS analysis (0.14–1.4 pg N) was less than that (14–100 ng N) for GC–combustion–SIRMS analysis, the latter technique was chosen because its precision (0.01–0.06 at% N, SD) was much better and smaller spike additions to the soil extracts were possible.

Isotopic analysis of methane trapped in ice samples provides information on the past budgets of atmospheric CH_4 and on changes in source composition or sink processes. A micro–extraction GC–combustion –GC–SIRMS system for the determination of $\delta^{13}C$ in CH_4 from extremely small gas occlusions in ice (~300 pmol CH_4 from 100–250 g ice) featured three innovations[227]. Firstly, flushing of headspace gas instead of expansion into a sample loop provided quantitative transfer with minimal isotopic fractionation. Ice was melted in an evacuated chamber and the released gas collected in the headspace. After equilibration of gas and water, the chamber was filled with He (160 ml min^{-1}) until atmospheric pressure was reached. At this point the gas was flushed into a cryogenic trap, the novel design of which retained the CH_4 quantitatively without any breakthrough. It was essential to operate the trap within a narrow temperature window at –125±0.5 ˚C so that the CH_4 was retained but N_2 and O_2 passed through. The third innovation was the addition of the second GC column after the combustion oven. The first GC column provided good separation of CH_4 from CO and CO_2 but not from N_2O. Following conversion of the CH_4 into CO_2 and H_2O in a micro–combustion oven (Ni–Pd catalyst at 1080 ˚C), the CO_2 was separated from the remaining N_2O on the second GC column. The accuracy and precision of ±0.4 and ±0.32‰, respectively, established through the analysis of in–house ice RM, allowed natural carbon isotope shifts in past atmospheres to be detected.

The *SIRMS analysis of tooth enamel* has not been suitable for small samples because either the technique was destructive or insufficient material was available.

Improvements to LA methods for the *in–situ* determination of δ^{13}C and δ^{18}O reduced the sample requirement by an order of magnitude so that tooth enamel as thin as 100 μm could be analysed[228]. The key improvement was use of CO_2 laser radiation (λ=10.6 μm) with low power (5–15 W) over a short duration (~8.5 ms) in order to reduce the LA pit size. The gas generated from 2–8 ablation events was pooled for each isotopic analysis. Precision for δ^{13}C (±0.1–±0.6‰) was sample dependent but sufficient for application in ecological and paleoenvironmental studies. The accuracy and precision for δ^{18}O determination were, however, poorer than those for conventional methods and so the method was not ideal for applications requiring the best possible accuracy. The method was also unsuitable for analysis of larger teeth such as ungulate molars because of the large CO_2 blanks and significant isotopic fractionation. A unique blank correction for each analysis was based on mass balance calculations. Analysis of intra–tooth variation in irregularly shaped teeth was made possible by using a rotating sample mount.

The use of *sealed–tube combustion* for the high–precision isotopic analysis of nmol quantities of silicate N circumvented fractionation problems which occur in the short–duration heating used in EA systems[229]. Samples were heated (950–1050 °C) with copper metal and CuO reagents in evacuated and sealed quartz tubes (6 mm od). The relatively uniform size and isotopic composition of the small N_2 blank made it possible to achieve precisions for δ^{15}N of ±0.15 and 0.6‰ for >5 and 1–2 ppm N, respectively. The minimum sample size of ~10 nmol took into account blanks and other factors affecting transfer of the N_2 from the tube to the CF–SIRMS system and was two orders of magnitude lower than that previously achievable using a dual–inlet

MS system. Sample through–put was limited, however, to 8–10 samples per day, including standards.

A new *EA–SIRMS* method for the site–specific C isotope analysis of involatile aromatic carboxylic acids was simple and rapid and had a small sample requirement[230]. Samples (~1 μmole) were pyrolysed (750 °C) to produce CO_2 for $\delta^{13}C$ measurement of the carboxyl group. The measured $\delta^{13}C$ values were within 1‰ of those obtained by conventional sealed–tube pyrolysis. A rapid on–line pyrolysis method for the oxygen isotope analysis of silver phosphate (400–500 μg) gave good (±0.2‰) reproducibility[231]. Silver phosphate was recommended as a RM for the determination of ^{18}O:^{16}O ratios of phosphate by high–temperature pyrolysis because it is a very stable material and easy to degas. Addition of a second GC column to a conventional EA system allowed $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ to be determined in a single analysis of environmental samples[232]. Replicate analyses of samples (1–15 mg) agreed within ±1‰ for all three ratios.

A *computational tool* has been derived to calculate elemental isotopic abundance from experimental whole isotope distributions in order to overcome some of the limitations of SIRMS instruments[233]. The limitations of the method were discussed in terms of the required number of ions and S/N. For high–precision estimation of isotope ratios, the method required very precise measurement of the experimental isotopic distributions free from any artifacts introduced by, for example, noise and sample heterogeneity.

10.4. Standards and calibrations

The importance of *interlaboratory comparison exercises* for validating methodologies was demonstrated by a number of such studies. A variety of chemical preparation methods and MS techniques were used in the analysis of three proposed Si isotope RM with the aim of ensuring reproducibility between international laboratories investigating natural Si isotope variations[234]. The SIRMS method utilized fluorination of SiO_2 followed by gas cleanup and conversion to SiF_4 for analysis on a dual inlet instrument. All the methods used gave similar precisions and the differences in the δ^{29}Si and δ^{30}Si values measured in the various laboratories were 0.13 and 0.2‰, respectively. Independent oxygen three-isotope analysis of silicates at two different laboratories gave the same and reproducible slope values[235]. Both laboratories used laser fluorination coupled with high precision dual–inlet SIRMS but the instrumentation and the methodology details differed. This was the first time such a comparison had been made.

Two alternative approaches for the *calibration of the intramolecular nitrogen isotope distribution* in tropospheric N_2O gave different ^{15}N site preference values[236]. The ^{15}N site preference value was defined as the difference in the δ^{15}N values of the central and end nitrogen atoms of the N–N–O molecule. One approach was based on adding a small amount of ^{15}N–labeled N_2O to the N_2O reference gas and tracking the subsequent changes in intensities at *m/z* 30, 31, 44, 45 and 46.This method gave a site preference value of 46.3±1.4‰. The other method, which involved the synthesis of N_2O by thermal decomposition of isotopically characterized ammonium nitrate, gave a site reference value of 18.7±2.2‰. Neither approach fully took into account isotopic fractionation associated with the formation of NO^+ fragment ions from the different isotopic species of N_2O in the ion source of a mass spectrometer. These effects varied with conditions in the ion source and made it impossible to reproduce a calibration based on the addition of isotopically enriched N_2O. These effects had much less impact on the second approach which was successfully replicated. The authors therefore advocated acceptance of a site preference value of 18.7±2.2‰ for tropospheric N_2O as a provisional standard.

In a study directed towards investigating *suitable compounds for use as stable isotope RM* for calibration of GC–combustion–SIRMS, several compounds were selected from the "Grob–test" mixture used for testing chromatography columns[237]. Oxygen– and nitrogen–containing compounds were added to allow the mixture to be used as a multi–isotopic calibration tool for determination of $^{13}C:^{12}C$, $^{2}H:^{1}H$, $^{15}N:^{14}N$ and $^{18}O:^{16}O$ ratios. All the compounds were assessed individually for homogeneity and stability using EA–SIRMS and the results compared with those obtained by GC–combustion–SIRMS using both polar and non-polar columns. Accuracy and precision were assessed under specified GC–combustion–SIRMS conditions.

A model for quantifying the degree of scrambling of C and O isotopes in mixtures of CO_2 gases with different isotopic compositions was developed to allow these gases to be used as *RM with metrological traceability to SI units*[238]. The concept of "isotope ratio space" was introduced to describe the additional isotope scrambling that occurred in the instrument if full isotopic equilibrium was not achieved. The model fitted experimental data and could be used to assess the degree of isotopic equilibrium in the gaseous mixture at any time during the mixing process.

10.5 Sample Preparation

In a new method for determining *$\delta^{15}N$ in ammonia at natural abundance levels*, NH_4^+ was oxidized at pH 12 using hypobromite to produce NO_2^- which was subsequently reduced to N_2O for SIRMS analysis using a CF purge–and–trap system[239]. Reliable $\delta^{15}N$ values (±0.3% RSD) were obtained over a 0.5–10 μM NH_4^+ concentration range using 20 ml of either freshwater or seawater. The method was more robust than previously published methods, readily applicable at low concentrations and small sample volumes and required less preparation and analysis time.

11. Thermal ionization mass spectrometry (TIMS)

11.1. Review

Vogl has prepared a good review of the characterization of RM by IDMS which relies strongly on both TIMS and ICP-MS techniques[240]. Following considerable discussion on error sources and propagation, it was concluded that IDMS was the most important reference method for elemental analysis when reliable high precision measurements were required.

11.2. Instrumentation

A *high–efficiency ionization source cavity* interfaced to a MC–TIMS instrument has been designed to improve the degree of ionization of Nd, Pu and Sr[241]. The source consisted of a small closed tube of rhenium, tantalum or tungsten that was heated by electron bombardment to ≥2000 °C to increase ionization of the evaporated analyte prior to exiting the cavity. Up to 10% ionization was achieved using element-impregnated resin beads loaded into the cavity. A LOQ of <<100 attograms of Pu (~10^4 atoms) was reported.

11.3. Analytical Methodology

Two different approaches have been used for the *analysis of very small (< 5ng) quantities of Nd* for which sample quantity and low concentration place major constraints on isotope composition measurement. Using only 0.5 ng of Nd, total evaporation TIMS gave an external precision of 140 ppm[242]. When using the NdO^+ technique, precision on the ^{143}Nd:^{144}Nd ratio was better than 30 ppm which was comparable to the precision obtained with the conventional method but achieved with a much smaller sample size[243].

The *fractionation of Ca isotopes by biogeochemical processes* is an active area of research. It has been argued that the use of the $^{48}Ca/^{42}Ca$ pair is preferable to the more commonly used $^{44}Ca/^{40}Ca$ pair due to the absence of radioactive in–growth of ^{40}Ca from ^{40}K decay[244]. In addition, the increased mass spread resulted in a statistically better resolution of fractionation if one assumed similar measurement precision. Whereas in this study, a $^{43}Ca/^{46}Ca$ double spike was used, the alternative $^{44}Ca/^{40}Ca$ pair was used in a study of Mesozoic marine carbonates with good results[245].

In an application to the *Sr isotope composition of bird feathers* containing small amounts of Sr (0.5-3 ng), TIMS was used with an ultra-low-blank ion-exchange procedure to give an uncertainty of 26-530 ppm for the ^{87}Sr:^{86}Sr ratio[246]. A meticulous washing and dry nitrogen cleaning procedure for feathers was used to reduce or eliminate natural particulate contamination of feather surfaces. Total procedural blanks of ~12 pg were achieved by using a miniaturized ion exchange procedure with ultra-purified reagents and Sr-Spec resin. The isotope composition of the blank was determined by pooling ~60 blanks to recover sufficient Sr for a reasonable isotope analysis. The poorest precision occurred with sub-ng quantities of Sr but was still sufficient to discriminate different geographic origins of feathers.

The *isotopic composition of Mo* has been measured with significantly improved accuracy using a new TIMS procedure[247]. Gravimetric mixtures of enriched ^{92}Mo and ^{98}Mo were prepared to monitor MS performance, with special attention being paid to tailing effects near Mo peaks and with due attention to the isobaric effects of Ru and Zr. The atomic weight was determined to be 95.9602(23), slightly higher than the standard atomic weight and more precise. The same authors applied this methodology to the study of natural Mo fractionation in oceanographic and biogeochemical processes[248].. A high–efficiency ion–exchange chemical separation procedure was used to remove Ru and Zr prior to analysis. It is foreseen that this study will pave the way for important applications to natural materials.

The *measurement of Ce isotopes by TIMS* has been a major challenge due to small variations in ^{138}Ce:^{136}Ce ratios and the large isobaric interference of ^{138}Ba. From a comparison of various methods, it was concluded that only the oxide species of Ce can be used to yield accurate data[249]. The methodology developed was applied to assess the variation in ^{138}Ce:^{136}Ce in a CRM and delivered a two-fold improvement (to 0.002%) in the ratio. Significant variation in ^{138}Ce:^{136}Ce of the CRM was documented and a new RM with a 'working value' for ^{138}Ce:^{136}Ce of 1.33738 ± 0.000005 (n=35) was prepared from ultra pure cerium metal.

The determination of ^{238}Pu in U–based *nuclear fuels* by TIMS is problematic because of isobaric interference from ^{238}U. A new approach which corrected for the interference was based on the addition of enriched ^{235}U (>90 atom%) to plutonium samples and use of a multiple filament assembly to produce UO^+ ions but no interfering PuO^+ ions[250]. The ^{238}U:^{235}U ratio was determined by measuring the UO^+ ions and the Pu isotope ratios by using the Pu^+ ions in the one filament loading. The ionization and vaporization filaments of a double–rhenium–filament assembly were heated to ~6 and 2–2.4 A, respectively, in order to obtain sufficient UO^+ ion current without forming PuO^+ ions. The same procedure was used to determine trace levels of U in plutonium samples[251]. In this case the UO^+ ion was measured in order to avoid the ^{238}Pu interference on the ^{238}U peak and obviated the need for chemical separation of µg quantities of U from the plutonium matrix. The radioactive decay of ^{238}Pu and ^{240}Pu, added as spikes in the ID determination of Pu concentration, led to systematic uncertainty in the results if not taken into account[252]. Accurate calculation of the correction factor (0.1–4% over a five–year period) was necessary if the aim of an overall uncertainty of 0.1% was to be achieved. Accurate mixing of highly enriched ^{238}Pu and ^{239}Pu isotopes has allowed a RM for ^{238}Pu to be prepared[253]. It was suggested that this RM could be offered as a CRM but it was unclear how the radioactivity would affect the validity of the certified ^{238}Pu values.

The fundamental requirement for *double spiking* is to have a spike that is very different in isotopic composition to the samples being analysed. Whereas highly enriched ^{204}Pb and ^{207}Pb spikes are normally used for the analysis of common lead, the NIST common lead SRM 981 and 982 have been used as spikes for the analysis of highly radiogenic samples such as zircons[254]. Although the method had the advantage of using well–characterized SRM and was considered to be viable, it was not universally applicable and did not provide better performance than established procedures. In a new method for the simultaneous determination of Pb concentration and isotopic composition, a ^{204}Pb–^{205}Pb double spike was added to samples prior to chemical separation and the isotopic composition of the spiked sample determined rigorously by the double spike technique using a ^{204}Pb–^{207}Pb spike[255]. The concentration and isotopic composition of Pb in the starting sample were then calculated using the ID method. Results obtained for CRM were identical, within uncertainty, to the published data. A comprehensive treatment of the derivation of U–Pb isotope ratios and their corresponding uncertainties from ID data used standard parametric statistical methods of error propagation to convolve uncertainties associated with instrumental mass fractionation, tracer subtraction, blank subtraction and initial common Pb correction[256].

12. Other Methods

12.1. Chemical Ionization

The quest for suitable methods *selenium speciation* has seen atmospheric pressure chemical ionization (APCI) investigated as an alternative to ES ionization which lacks sensitivity for direct selenosugar determination in, for example, human urine. A new procedure for the identification and quantification of Se metabolites at the low µg Se l^{-1} level in crude human urine involved RP–HPLC, with and without cation–exchange guard columns, APCI (Ar, 1 mTorr) and selected reaction monitoring (SRM) for selective and sensitive detection[257]. The CID behaviour of three selenosugars was studied in detail using APCI–MS–MS (triple quadrupole instrument) and ESMS (ion trap instrument) in order to obtain dissociation information that was potentially valuable for the characterization of unknown selenosugar metabolites using the neutral loss scanning method. This method was based on the observation that selenosugars in general lose the neutral moiety CH_3SeH upon CID. A scan with a constant difference of 96 amu between parent and daughter ions was carried out to identify the selenosugars. Although the feasibility of the method was demonstrated for known compounds, no new selenosugars were identified in this way.

Although the APCI–MS identification of all species in an unknown mixture is possible in principle, the high levels of chemical noise and low analyte concentrations usually result in more peaks being detectable by ICP–MS than can be identified by molecular MS. In a new *parallel elemental and molecular MS system* designed to overcome this problem, the effluent from a LC column was split into flows through an ICP–MS instrument, to produce elemental profiles, and through an APCI–TOFMS instrument to provide molecular information[258]. The aim was to identify trace molecular species containing specific heteroatoms, using the case of Se in yeast as an example. Although simultaneous elemental and molecular detection had been used before, this was the first attempt at peak profile correlation. The ICP–MS and APCI–TOFMS ion chromatograms were fit by the Haarhoff–VanderLinde function using area, retention time, width and skew as parameters but the APCI–TOFMS fit parameters were less reproducible than the ICP–MS parameters and were the more likely to limit correlation in most cases. Although correction factors were required for differences in flow path length and peak broadening, they were species– and concentration–independent and were stable from run to run. Subtle differences in peak profiles of the test samples were due primarily to column interactions and were well correlated between the two detection systems. Matching of the peak profile data greatly reduced the chemical noise in the APCI–MS data and made species identification easier. The authors suggested that the usefulness of this approach might be limited by the presence of co–eluting compounds that could alter the response of one system in a way different to that of the other system

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12.2. Electron Cyclotron Resonance

The ionization efficiency of an *electron cyclotron resonance ion source* (ECRIS) is generally high and all elements can be ionized by the high–temperature plasma. Details have been given of an ECRIS–MS system used for the isotopic analysis of pure noble gases but not, so far, for more complex samples[259]. Although the system worked well for the pure gases and was considered to have potential for isotope analysis, it is unlikely to be widely adopted because of several potential problems. These included the ease of formation of multiply charged ions which dominated the spectrum and created multiple isobaric interferences; the possibility of as–yet–unexplored isotopic fractionation and the difficulty of introducing anything other than gases into the ion source.

13. Appendix: Glossary of Terms

AES	Atomic Emission Spectrometry
AMS	Accelerator Mass Spectrometry
aTOF	Aerosol Time of Flight
aTOFMS	Aerosol Time of Flight Mass Spectrometry
BAM	Bundesanstalt für Materialforschung und –prüfung
CC	Collision Cell
CE	Capillary Electrophoresis
CF	Continuous Flow
CID	Collision Induced Dissociation
CLS	Coincidence laser Spectroscopy
CRM	Certified Reference Material
CSIA	Compound Specific Isotope Analysis
CSRA	Compound Specific Radiocarbon Analysis
DBT	Dibutyltin
dc	direct current
DI	Desorption Ionization
DIC	Dissolved Inorganic Carbon
DNA	Deoxyribonucleic Acid
DOC	Dissolved Organic Carbon
DRC	Dynamic Reaction Cell

EA	Elemental Analyser
EDS	Energy Dispersive Spectrometer
EI	Electron Ionization
EIMS	Electron Ionization Mass Spectrometry
ES	Electrospray
ESMS	Electrospray Mass Spectrometry
ETV	Electrothermal Vaporization
FI	Flow Injection
FIB	Focused Ion Beam
FT	Fourier Transform
FTIR	Fourier Transform Infrared
FWHM	Full Width at Half Maximum
GBW	National Research Centre for Certified Reference Materials (China).
GC	Gas Chromatography
GCIB	Gas Cluster Ion Beam
GD	Glow Discharge
GDMS	Glow Discharge Mass Spectrometry
HG	Hydride Generation
HPLC	High Performance Liquid Chromatography
HR	High Resolution
ICP	Inductively Coupled Plasma
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IMF	Instrumental Mass Fractionation
IRMM	Institute of Reference Materials and Measurements
IUPAC	International Union of Pure and Applied Chemistry
ID	Isotope Dilution
IDMS	Isotope Dilution Mass Spectrometry
IP	Ionization Potential
IR	Infrared
KED	Kinetic Energy Distribution
LA	Laser Ablation
LC	Liquid Chromatography
LIMS	Laser Ionization Mass Spectrometry
LMMS	Laser Microprobe Mass Spectrometry
LOD	Limit of Detection
LOQ	Limit of Quantitation
LTE	Local Thermodynamic Equilibrium
MALDI	Matrix–Assisted Laser Desorption Ionization
MBT	Monobutyltin
MC	Multicollector
MMA	Monomethylarsonic Acid
MRI	Mixing–depth Roughness Information
MS	Mass Spectrometry
m/z	mass-to charge ratio
n_e	Electron Number Density
NBL	New Brunswick Laboratory
NIES	National Institute for Environmental Studies (Japan)
NIST	National Institute of Standards and Technology

NRA	Nuclear Reaction Analysis
NRCC	National Research Council Canada
od	Outer Diameter
OTC	Organotin Compounds
PCA	Principal Component Analysis
PGE	Platinum Group Elements
pMC	Percent Modern Carbon
ppm	Parts Per Million
PVA	Polyvinyl Alcohol
PXAMS	Projectile X–ray Accelerator Mass Spectrometry
RBS	Rutherford Backscattering Spectrometry
REE	Rare Earth Element
rf	radio frequency
RFQ	Radio Frequency Quadrupole
RI	Resonance Ionization
RIMS	Resonance Ionization Mass Spectrometry
RM	Reference Material
RME	Random Machine Error
RP	Reversed Phase
RSD	Relative Standard Deviation
RSF	Relative Sensitivity Factor
SD	Standard Deviation
SEC	Size Exclusion Chromatography
SEM	Scanning Electron Microscopy
SF	Sector Field
SIMS	Secondary Ion Mass Spectrometry
SIRMS	Stable Isotope Ratio Mass Spectrometry
S/N	Signal-to-Noise Ratio
SNMS	Sputtered Neutral Mass Spectrometry
SPME	Solid Phase Microextraction
SRM	Standard Reference Material
SRO	Silicon Rich Oxide
S-SIMS	Static Secondary Ion Mass Spectrometry
T_e	Electron Temperature
T_g	Gas Kinetic Temperature
TBT	Tributyltin
TEAMS	Trace Element Accelerator Mass Spectrometry
TEM	Transmission Electron Microscopy
TIMS	Thermal Ionization Mass Spectrometry
TOF	Time of Flight
TOFMS	Time of Flight Mass Spectrometry
UV	Ultraviolet
VASE	Variable Angle Spectroscopy–Ellipsometry
XPS	X–ray Photoelectron Spectroscopy
YAG	Yttrium Aluminium Garnet
YLF	Yttrium Lithium Fluoride
2–D	Two Dimensional
3–D	Three Dimensional
λ	Wavelength

τ	Pulse Duration

14. References

1 J. R. Bacon, K. L. Linge, R. R. Parrish and L. Van Vaeck, *J. Anal. At. Spectrom.,* 2007, **22**(8), 973.

2 B. Charlton, A. S. Fisher, P. S. Goodall, M. W. Hinds, S. Lancaster and M. Salisbury, *J. Anal. At. Spectrom.,* 2007, **22**(12), 1517.

3 O. T. Butler, J. M. Cook, C. F. Harrington, S. J. Hill, J. Rieuwerts and D. L. Miles, *J. Anal. At. Spectrom.,* 2008, **23**(2), 249.

4 A. Taylor, S. Branch, M. P. Day, M. Patriarca and M. White, *J. Anal. At. Spectrom.,* 2008, **23**(4), 595.

5 M. West, A. T. Ellis, P. Kregsamer, P. J. Potts, C. Streli, C. Vanhoof and P. Wobrauschek, *J. Anal. At. Spectrom.,* 2007, **22**(10), 1304.

6 E. H. Evans, J. A. Day, C. Palmer, W. J. Price, C. M. M. Smithe and J. F. Tyson, *J. Anal. At. Spectrom.,* 2007, **22**(6), 663.

7 A. P. McNichol and L. I. Aluwihare, *Chem. Rev.,* 2007, **107**(2), 443.

8 G. Getachew, S. H. Kim, B. J. Burri, P. B. Kelly, K. W. Haack, T. J. Ognibene, B. A. Buchholz, J. S. Vogel, J. Modrow and A. J. Clifford, *Radiocarbon,* 2006, **48**(3), 325.

9 U. Zoppi, J. Crye, Q. Song and A. Arjomand, *Radiocarbon,* 2007, **49**(1), 173.

10 M. E. Fedi, A. Cartocci, M. Manetti, F. Taccetti and P. A. Mando, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 18.

11 K. Kobayashi, E. Niu, S. Itoh, H. Yamagata, Z. Lomtatidze, I. Jorjoliani, K. Nakamura and H. Fujine, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 31.

12 K. X. Liu, X. F. Ding, D. P. Fu, Y. Pan, X. H. Wu, Z. Y. Guo and L. P. Zhou, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 23.

13 F. Terrasi, D. Rogalla, N. De Cesare, A. D'Onofrio, C. Lubritto, F. Marzaioli, I. Passariello, M. Rubino, C. Sabbarese, G. Casa, A. Palmieri, L. Gialanella, G. Imbriani, V. Roca, M. Romano, M. Sundquist and R. Loger, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 14.

14 W. J. Zhou, X. F. Lu, Z. K. Wu, W. N. Zhao, C. H. Huang, L. L. Li, P. Chen and Z. H. Xin, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **262**(1), 135.

15 E. Cottereau, M. Arnold, C. Moreau, D. Baque, D. Bavay, I. Caffy, C. Comby, J. P. Dumoulin, S. Hain, M. Perron, J. Salomon and V. Setti, *Radiocarbon,* 2007, **49**(2), 291.

16 H. A. Synal, M. Stocker and M. Suter, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 7.

17 G. Skog, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 1.

18 M. G. Klein, H. J. Van Staveren, D. J. W. Mous and A. Gottdang, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 184.

19 S. Freeman, P. Bishop, C. Bryant, G. Cook, D. Dougans, T. Ertunc, A. Fallick, R. Ganeshram, C. Maden, P. Naysmith, C. Schnabel, M. Scott, M. Summerfield and S. Xu, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 66.

20 J. Southon and G. M. Santos, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 88.

21 A. Scharf, T. Uhl, W. Luppold, A. Rottenbach, K. Kritzler, A. Ohneiser and W. Kretschmer, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 50.

22 K. S. Grabowski, D. L. Knies and C. Cetina, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 27.

23 D. L. Knies, K. S. Grabowski, C. Cetina, L. T. Demoranville, M. R. Dougherty, A. C. Mignerey and C. L. Taylor, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **261**(1-2), 582.

24 K. Sasa, Y. Nagashima, T. Takahashi, R. Seki, Y. Tosaki, K. Sueki, K. Bessho, H. Matsumura, T. Miura and M. He, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 41.

25 Y. Nagashima, R. Seki, K. Sasa, T. Matsuhiro, T. Takahashi, Y. Tosaki, K. Bessho, H. Matsumura and T. Miura, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 241.

26 A. Zondervan, M. Poletti, C. R. Purcell and R. J. Sparks, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 47.

27 A. Priller, M. Auer, R. Golser, A. Herschmann, W. Kutschera, J. Lukas, P. Steier and A. Wallner, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 94.

28 Z. Y. Guo, K. X. Liu, X. Q. Yan, Y. Xie, J. X. Fang and J. Chen, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 204.

29 A. E. Litherland, I. Tomski, X. L. Zhao, L. M. Cousins, J. P. Doupe, G. Javahery and W. E. Kieser, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 230.

30 S. Xu, A. Dougans, S. Freeman, C. Maden and R. Loger, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 76.

31 T. Uhl, W. Luppold, A. Rottenbach, A. Scharf, K. Kritzler and W. Kretschmer, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 303.

32 M. Ruff, L. Wacker, H. W. Gaggeler, M. Suter, H. A. Synal and S. Szidat, *Radiocarbon,* 2007, **49**(2), 307.

33 M. L. Roberts, R. J. Schneider, K. F. von Reden, J. S. C. Wills, B. X. Han, J. M. Hayes, B. E. Rosenheim and W. J. Jenkins, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 83.

34 B. X. Han, K. F. von Reden, M. L. Roberts, R. J. Schneider, J. M. Hayes and W. J. Jenkins, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 111.

35 J. P. Doupé and A. E. Litherland, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 217.

36 J. R. Southon and G. M. Santos, *Radiocarbon,* 2004, **46**(1), 33.

37 J. Southon, G. dos Santos and B. X. Han, *Radiocarbon,* 2007, **49**(2), 301.

38 B. X. Han, J. R. Southon, M. L. Roberts and K. F. von Reden, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **261**(1-2), 588.

39 S. J. Fallon, T. P. Guilderson and T. A. Brown, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 106.

40 L. Liu, W. J. Zhou, P. Cheng, H. G. Yu and M. B. Chen, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 208.

41 V. Alfimov, G. Possnert and A. Aldahan, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 199.

42 Y. J. Guan, M. He, X. D. Ruan, H. J. Wang, S. Y. Wu, K. J. Dong, M. Lin, J. Yuan and S. Jiang, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 213.

43 M. Suter, M. Dobeli, M. Grajcar, A. Muller, M. Stocker, G. Y. Sun, H. A. Synal and L. Wacker, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 165.

44 J. Olsen, J. Heinemeier, K. Bahner, B. Graney and A. Phillips, *Radiocarbon,* 2007, **49**(2), 233.

45 V. Palonen and P. Tikkanen, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 154.

46 V. Palonen and P. Tikkanen, *Radiocarbon,* 2007, **49**(2), 369.

47 V. Palonen and P. Tikkanen, *Radiocarbon,* 2007, **49**(3), 1261.

48 G. S. Burr, D. J. Donahue, Y. Tang, J. W. Beck, L. McHargue, D. Biddulph, R. Cruz and A. J. T. Jull, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 149.

49 H. Wang, Y. Guan, S. Jiang, M. He, X. Ruan, S. Du, J. Yuan, W. Wu and L. Luo, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 277.

50 I. Passariello, F. Marzaioli, C. Lubritto, M. Rubino, A. D'Onofrio, N. De Cesare, G. Borriello, G. Casa, A. Palmieri, D. Kogalla, C. Sabbarese and F. Terrasi, *Radiocarbon,* 2007, **49**(2), 225.

51 G. M. Santos, M. Mazon, J. R. Southon, S. Rifai and R. Moore, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 308.

52 X. M. Xu, S. E. Trumbore, S. H. Zheng, J. R. Southon, K. E. McDuffee, M. Luttgen and J. C. Liu, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 320.

53 J. Southon, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 288.

54 G. M. Santos, R. B. Moore, J. R. Southon, S. Griffin, E. Hinger and D. Zhang, *Radiocarbon,* 2007, **49**(2), 255.

55 G. M. Santos, J. R. Southon, S. Griffin, S. R. Beaupre and E. R. M. Druffel, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 293.

56 A. M. Smith, V. V. Petrenko, Q. Hua, J. Southon and G. Brailsford, *Radiocarbon,* 2007, **49**(2), 245.

57 S. R. Shah and A. Pearson, *Radiocarbon,* 2007, **49**(1), 69.

58 R. E. Taylor and J. Southon, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 282.

59 A. G. Hogg, L. K. Fifield, C. S. M. Turney, J. G. Palmer, R. Galbraith and M. G. K. Baillie, *Quat. Geochronol.,* 2006, **1**(4), 241.

60 R. Drosg, W. Kutschera, K. Scholz, P. Steier, D. Wagenbach and E. M. Wild, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 340.

61 F. Brock, C. B. Ramsey and T. Higham, *Radiocarbon,* 2007, **49**(2), 187.

62 M. C. Huls, P. M. Grootes and M. J. Nadeau, *Radiocarbon,* 2007, **49**(2), 193.

63 I. Hajdas, G. Bonani, H. Furrer, A. Mader and W. Schoch, *Quat. Int.,* 2007, **164-65**, 98.

64 M. D'Elia, G. Gianfrate, G. Quarta, L. Giotta, G. Giancane and L. Calcagnile, *Radiocarbon,* 2007, **49**(2), 201.

65 S. X. Yuan, X. H. Wu, K. X. Liu, Z. Y. Guo, X. L. Cheng, Y. Pan and J. X. Wang, *Radiocarbon,* 2007, **49**(2), 211.

66 H. D. Graven, T. P. Guilderson and R. F. Keeling, *Radiocarbon,* 2007, **49**(2), 349.

67 H. A. J. Meijer, M. H. Pertuisot and J. van der Plicht, *Radiocarbon,* 2006, **48**(3), 355.

68 T. M. Jenk, S. Szidat, M. Schwikowski, H. W. Gaggeler, L. Wacker, H. A. Synal and M. Saurer, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 518.

69 Z. Zencak, C. M. Reddy, E. L. Teuten, L. Xu, A. P. McNichol and O. Gustafsson, *Anal. Chem.,* 2007, **79**(5), 2042.

70 S. S. Hah, J. M. Mundt, E. A. Ubick, K. W. Turteltaub, J. P. Gregg and P. T. Henderson, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 763.

71 M. Grajcar, M. Dobeli, P. W. Kubik, H. A. Synal, L. Wacker and M. Suter, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 173.

72 X. L. Zhao, C. Soto, W. E. Kieser, A. E. Litherland, B. L. Tracy, K. Ungar and T. Stocki, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 345.

73 X. L. Zhao and A. E. Litherland, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 224.

74 D. Fink and A. Smith, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 600.

75 A. L. Hunt, G. A. Petrucci, P. R. Bierman and R. C. Finkel, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **260**(2), 633.

76 L. K. Fifield, S. G. Tims, L. G. Gladkis and C. R. Morton, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 178.

77 A. Galindo-Uribarri, J. R. Beene, M. Danchev, J. Doupe, B. Fuentes, J. G. del Campo, P. A. Hausladen, R. C. Juras, J. F. Liang, A. E. Litherland, Y. Liu, M. J. Meigs, G. D. Mills, P. E. Mueller, E. Padilla-Rodal, J. Pavan, J. W. Sinclair

and D. W. Stracener, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 123.

78 T. Aze, H. Matsuzaki, H. Matsumura, H. Nagai, M. Fujimura, M. Noguchi, Y. Hongo and Y. Yokoyama, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 144.

79 C. Maden, P. A. F. Anastasi, A. Dougans, S. Freeman, R. Kitchen, G. Klody, C. Schnabel, M. Sundquist, K. Vanner and S. Xu, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 131.

80 H. Matsuzaki, Y. Muramatsu, K. Kato, M. Yasumoto and C. Nakano, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 721.

81 X. L. Zhao, A. E. Litherland, W. E. Kieser and C. Soto, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 265.

82 Z. Lu, U. Fehn, H. Tomaru, D. Elmore and X. Ma, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 359.

83 E. Englund, A. Aldahan, G. Possnert and V. Alfimov, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 365.

84 T. Suzuki, S. Banba, T. Kitamura, S. Kabuto, K. Isogai and H. Amano, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 370.

85 C. Fitoussi and G. M. Raisbeck, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 351.

86 J. Z. Qiu, S. Jiang, M. He, X. Y. Yin, K. J. Dong, Y. J. Guan, Y. W. Bao, S. Y. Wu, J. Yuan and B. F. Yang, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 246.

87 J. Z. Qiu, S. Jiang, M. He, X. Y. Yin, K. J. Dong, Y. J. Guan and S. Y. Wu, *High Energy Phys. Nucl. Phys.-Chin. Ed.,* 2007, **31**(8), 719.

88 S. Winkler, L. K. Fifield, S. G. Tims and J. Fernandez-Niello, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 260.

89 S. Winkler, L. K. Fifield, S. G. Tims and C. R. Morton, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 256.

90 C. Vockenhuber, A. Bergmaler, T. Faestermann, K. Knie, G. Korschinek, W. Kutschera, G. Rugel, P. Steier, K. Vorderwinkler and A. Wallner, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 250.

91 L. G. Gladkis, L. K. Fifield, C. R. Morton, T. T. Barrows and S. G. Tims, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 236.

92 A. Wallner, M. Bichler, I. Dillmann, R. Golser, F. Kappeler, W. Kutschera, M. Paul, A. Priller, P. Steier and C. Vockenhuber, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 677.

93 G. Raisbeck, T. Tran, D. Lunney, C. Gaillard, S. Goriely, C. Waelbroeck and F. Yiou, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 673.

94 K. M. Wilcken, T. T. Barrows, L. K. Fifield, S. G. Tims and P. Steier, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 727.

95 M. Christl, L. Wacker, J. Lippold, H. A. Synal and M. Suter, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **262**(2), 379.

96 M. He, S. Jiang, B. Peng, X. D. Ruan, K. J. Dong, Y. J. Guan, S. Y. Li, S. Y. Wu, J. Z. Qiu, X. Y. Yin and Y. Q. Ding, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 708.

97 C. Cetina, D. L. Knies, K. S. Grabowski, A. D. Berry and R. L. Mowery, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 188.

98 J. S. A. Krestow, W. E. Kieser, A. E. Litherland, J. C. Rucklidge, G. C. Wilson and X. L. Zhao, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(1), 194.

99 J. F. Garcia-Reyes, M. Dernovics, P. Ortega-Barrales, A. R. Fernandez-Alba and A. Molina-Diaz, *J. Anal. At. Spectrom.,* 2007, **22**(8), 947.

100 M. Dernovics, P. Giusti and R. Lobinski, *J. Anal. At. Spectrom.,* 2007, **22**(1), 41.

101 M. Dernovics, T. Garcia-Barrera, K. Bierla, H. Preud'homme and R. Lobinski, *Analyst,* 2007, **132**(5), 439.

102 T. D. Ninh, Y. Nagashima and K. Shiomi, *Food Addit. Contam.,* 2006, **23**(12), 1299.

103 T. M. Nemanic, L. Zupancic-Kralj, R. Milacic and J. Scancar, *Acta Chim. Slov.,* 2007, **54**(1), 40.

104 T. M. Nemanic, R. Milacic and J. Scancar, *Int. J. Environ. Anal. Chem.,* 2007, **87**(9), 615.

105 S. D. Papaspyrou, N. S. Thomaidis, E. N. Lampi and A. Lioupis, *Appl. Organomet. Chem.,* 2007, **21**(6), 412.

106 W. C. Davis, S. J. Christopher, R. S. Pugh, O. F. X. Donard, E. A. Krupp, D. Point, M. Horvat, D. Gibicar, Z. Kljakovic-Gaspic, B. J. Porter and M. M. Schantz, *Anal. Bioanal. Chem.,* 2007, **387**(7), 2335.

107 E. M. Cukrowska, H. Nsengimana and L. Chimuka, *J. Sep. Sci.,* 2007, **30**(16), 2754.

108 N. Jakubowski, R. Dorka, E. Steers and A. Tempez, *J. Anal. At. Spectrom.,* 2007, **22**(7), 722.

109 A. Martin, A. Menendez, R. Pereiro, N. Bordel and A. Sanz-Medel, *Anal. Bioanal. Chem.,* 2007, **388**(8), 1573.

110 P. Konarski, K. Kaczorek, M. Cwil and J. Marks, *Vacuum,* 2007, **81**(10), 1323.

111 A. Bogaerts, K. A. Temelkov, N. K. Vuchkov and R. Gijbels, *Spectrochim. Acta Pt. B,* 2007, **62**(4), 325.

112 Y. Xing, L. Xiaojia and W. Haizhou, *Europ. J. Mass Spectrom.,* 2007, **13**(2), 125.

113 M. Voronov and V. Hoffmann, *J. Anal. At. Spectrom.,* 2007, **22**(9), 1184.

114 A. Martin, R. Pereiro, N. Bordel and A. Sanz-Medel, *J. Anal. At. Spectrom.,* 2007, **22**(9), 1179.

115 V. D. Kurochkin, *Powder Metall. Met. Ceram.,* 2006, **45**(7-8), 387.

116 B. L. Sharp, P. S. Goodall, L. M. Ignjatovic and H. Teng, *J. Anal. At. Spectrom.,* 2007, **22**(12), 1447.

117 G. Gamez, S. A. Lehn, M. Huang and G. M. Hieftje, *Spectrochim. Acta Pt. B,* 2007, **62**(4), 357.

118 G. Gamez, S. A. Lehn, M. Huang and G. M. Hieftje, *Spectrochim. Acta Pt. B,* 2007, **62**(4), 370.

119 J. H. Macedone and P. B. Farnsworth, *Spectrochim. Acta Pt. B,* 2006, **61**(9), 1031.

120 M. Pettine, B. Casentini, D. Mastroianni and S. Capri, *Anal. Chim. Acta,* 2007, **599**(2), 191.

121 D. Juresa, D. Kuehnelt and K. A. Francesconi, *Anal. Chem.,* 2006, **78**(24), 8569.

122 Y.-C. Yip and W.-C. Sham, *Trac-Trends Anal. Chem.,* 2007, **26**(7), 727.

123 V. F. Taylor, R. D. Evans and R. J. Cornett, *Anal. Bioanal. Chem.,* 2007, **387**(1), 343.

124 G. Favre, R. Brennetot, F. Chartier and P. Vitorge, *Int. J. Mass Spectrom.,* 2007, **265**(1), 15.

125 P. J. Sylvester, *Geostand. Geoanal. Res.,* 2006, **30**(3), 197.

126 T. Hirata, *Anal. Sci.,* 2007, **23**(10), 1195.

127 Y. Liu, Z. Hu, H. Yuan, S. Hu and H. Cheng, *J. Anal. At. Spectrom.,* 2007, **22**(5), 582.

128 E. L. Gurevich and R. Hergenröder, *J. Anal. At. Spectrom.,* 2007, **22**(9), 1043.

129 C. C. Garcia, H. Lindner and K. Niemax, *Spectrochim. Acta Pt. B,* 2007, **62**(1), 13.

130 M. Guillong, P. Heimgartner, Z. Kopajtic, D. Günther and I. Günther-Leopold, *J. Anal. At. Spectrom.,* 2007, **22**(4), 399.

131 J. Koch and D. Günther, *Anal. Bioanal. Chem.,* 2007, **387**(1), 149.

132 I. Horn and F. von Blanckenburg, *Spectrochim. Acta Pt. B,* 2007, **62**(4), 410.

133 K. P. Jochum, B. Stoll, K. Herwig and M. Willbold, *J. Anal. At. Spectrom.,* 2007, **22**(2), 112.

134 M. Tanner and D. Günther, *J. Anal. At. Spectrom.,* 2007, **22**(9), 1189.

135 J. J. Gonzalez, C. Liu, S.-B. Wen, X. Mao and R. E. Russo, *Talanta,* 2007, **73**(3), 567.

136 J. J. Gonzalez, C. Liu, S.-B. Wen, X. Mao and R. E. Russo, *Talanta,* 2007, **73**(3), 577.

137 H. R. Kuhn, N. J. Pearson and S. E. Jackson, *J. Anal. At. Spectrom.,* 2007, **22**(5), 547.

138 I. Kroslakova and D. Günther, *J. Anal. At. Spectrom.,* 2007, **22**(1), 51.

139 T. Hirata and Z. Miyazaki, *Anal. Chem.,* 2007, **79**(1), 147.

140 M. Guillong and C. A. Heinrich, *J. Anal. At. Spectrom.,* 2007, **22**(12), 1488.

141 C. O'Connor, M. R. Landon and B. L. Sharp, *J. Anal. At. Spectrom.,* 2007, **22**(3), 273.

142 G. Pearson and G. Greenway, *J. Anal. At. Spectrom.,* 2007, **22**(6), 657.

143 A. Asfaw and G. Wibetoe, *J. Anal. At. Spectrom.,* 2007, **22**(2), 158.

144 S. Dreyfus, C. Pécheyran, C. P. Lienemann, C. Magnier, A. Prinzhofer and O. F. X. Donard, *J. Anal. At. Spectrom.,* 2007, **22**(4), 351.

145 N. Elwaer and H. Hintelmann, *Anal. Bioanal. Chem.,* 2007, **389**(6), 1889.

146 V. L. Dressler, D. Pozebon, A. Matusch and J. S. Becker, *Int. J. Mass Spectrom.,* 2007, **266**(1-3), 25.

147 B. Hu, S. Li, G. Xiang, M. He and Z. Jiang, *Appl. Spectrosc. Rev.,* 2007, **42**(2), 203.

148 T. Kreschollek and J. A. Holcombe, *J. Anal. At. Spectrom.,* 2007, **22**(2), 171.

149 Y. C. Sun, Y. J. Chen and Y. N. Tsai, *Microchem. J.,* 2007, **86**(1), 140.

150 M. Colon, M. Iglesias and M. Hidalgo, *Spectrochim. Acta Pt. B,* 2007, **62**(5), 470.

151 M. Antler, E. J. Maxwell, D. A. Duford and E. D. Salin, *Anal. Chem.,* 2007, **79**(2), 688.

152 J. E. Sonke and V. J. M. Salters, *J. Chromatogr. A,* 2007, **1159**(1-2), 63.

153 A. P. Navaza, J. R. Encinar and A. Sanz-Medel, *J. Anal. At. Spectrom.,* 2007, **22**(10), 1223.

154 M. J. Watts, A. W. Kim, D. S. Vidler, R. O. Jenkins, J. F. Hall and C. F. Harrington, *Instrum. Sci. Technol.,* 2007, **35**(1), 15.

155 P. Rodríguez-González, M. Monperrus, J. I. G. Alonso, D. Amouroux and O. F. X. Donard, *J. Anal. At. Spectrom.,* 2007, **22**(11), 1373.

156 J. D. Woodhead, *Geostand. Geoanal. Res.,* 2006, **30**(3), 187.

157 A. Makishima, B. N. Nath and E. Nakamura, *J. Anal. At. Spectrom.,* 2007, **22**(4), 407.

158 D. L. Hoffmann, J. Prytulak, D. A. Richards, T. Elliott, C. D. Coath, P. L. Smart and D. Scholz, *Int. J. Mass Spectrom.,* 2007, **264**(2-3), 97.

159 I. Leya, M. Schönbächler, U. Wiechert, U. Krahenbuhl and A. N. Halliday, *Int. J. Mass Spectrom.,* 2007, **262**(3), 247.

160 D. M. Murphy, *Mass Spectrom. Rev.,* 2007, **26**(2), 150.

161 D. Kim, H. Cha and S. Lee, *Microchem. J.,* 2007, **85**(2), 228.

162 H. Moisio, L. Van Vaeck and F. Vangaever, *Anal. Chem.,* 2007, **79**(1), 280.

163 A. P. Conde, L. Brandt and T. Halfmann, *Phys. Rev. Lett.,* 2006, **97**(24), art no. 243004.

164 A. M. Herrmann, K. Ritz, N. Nunan, P. L. Clode, J. Pett-Ridge, M. R. Kilburn, D. V. Murphy, A. G. O'Donnell and E. A. Stockdale, *Soil Biol. Biochem.,* 2007, **39**(8), 1835.

165 S. Portier, S. Bremier and C. T. Walker, *Int. J. Mass Spectrom.,* 2007, **263**(2-3), 113.

166 B. Saha and P. Chakraborty, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **258**(1), 246.

167 J. Brison, N. Mine, S. Poisseroux, B. Douhard, R. G. Vitchev and L. Houssiau, *Surf. Sci.,* 2007, **601**(6), 1467.

168 P. Philipp, T. Wirtz, H. N. Migeon and H. Scherrer, *Int. J. Mass Spectrom.,* 2007, **261**(2-3), 91.

169 P. Philipp, T. Wirtz, H. N. Migeon and H. Scherrer, *Int. J. Mass Spectrom.,* 2007, **264**(1), 70.

170 J. Brison and L. Houssiau, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **259**(2), 984.

171 J. Brison and L. Houssiau, *Surf. Interface Anal.,* 2006, **38**(12-13), 1715.

172 J. Brison, R. Hubert, S. Lucas and L. Houssiau, *Surf. Interface Anal.,* 2006, **38**(12-13), 1654.

173 Z. Zhu, C. Gu, F. A. Stevie and D. P. Griffis, *J. Vac. Sci. Technol., A,* 2007, **25**(4), 769.

174 J. Matsuo, S. Ninomiya, Y. Nakata, K. Ichiki, T. Aoki and T. Seki, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **257**, 627.

175 S. Ninomiya, K. Ichiki, Y. Nakata, T. Seki, T. Aoki and J. Matsuo, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **256**(1), 528.

176 M. P. Seah, *Surf. Interface Anal.,* 2007, **39**(7), 634.

177 K. J. Kim, C. S. Jung and T. E. Hong, *Meas. Sci. Technol.,* 2007, **18**(9), 2750.

178 D. S. Simons, R. G. Downing, G. P. Lamaze, R. M. Lindstrom, R. R. Greenberg, R. L. Paul, S. B. Schiller and W. F. Guthrie, *J. Vac. Sci. Technol., B,* 2007, **25**(4), 1365.

179 M. Nojima, T. Yamamoto, Y. Ishizaki, M. Owari and Y. Nihei, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **258**(1), 250.

180 K. Nakamura, Y. Ishikawa, K. Utsumi, H. Ligusa, R. Tanaka, Y. Ishizaki, T. Yamamoto, A. Maekawa, M. Owari, M. Nojima and Y. Nihei, *Surf. Interface Anal.,* 2006, **38**(12-13), 1734.

181 K. Pyszniak, A. Drozdziel, M. Turek, A. Wojtowicz and J. Sielanko, *Vacuum,* 2007, **81**(10), 1145.

182 K. Ichiki, S. Ninomiya, T. Seki, T. Aoki and J. Matsuo, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **256**(1), 350.

183 T. Ludwig and R. Stalder, *J. Anal. At. Spectrom.,* 2007, **22**(11), 1415.

184 A. Mikami, T. Okazawa, K. Saito and Y. Kido, *Appl. Surf. Sci.,* 2006, **253**(3), 1620.

185 M. Barozzi, E. Lacob, L. Vanzetti, M. Bersani, M. Anderie, G. Pucker and C. Kompocholis, *Rev. Adv. Mat. Sci.,* 2007, **15**(1), 56.

186 B. G. de la Mata, A. Sanz-Hervas, M. G. Dowsett, M. Schwitters and D. Twitchen, *Diam. Relat. Mat.,* 2007, **16**(4-7), 809.

187 K. J. Kim, D. W. Moon, C. J. Park, D. Simons, G. Gillen, H. Jin and H. J. Kang, *Surf. Interface Anal.,* 2007, **39**(8), 665.

188 S. E. Harton, Z. M. Zhu, F. A. Stevie, D. P. Griffis and H. Ade, *J. Vac. Sci. Technol., A,* 2007, **25**(3), 480.

189 E. H. Hauri, A. M. Shaw, J. H. Wang, J. E. Dixon, P. L. King and C. Mandeville, *Chem. Geol.,* 2006, **235**(3-4), 352.

190 F. Esaka, K. T. Esaka, C. G. Lee, M. Magara, S. Sakurai, S. Usuda and K. Watanabe, *Talanta,* 2007, **71**(3), 1011.

191 A. M. Herrmann, P. L. Clode, I. R. Fletcher, N. Nunan, E. A. Stockdale, A. G. O'Donnel and D. V. Murphy, *Rapid Commun. Mass Spectrom.,* 2007, **21**(1), 29.

192 C. Rollion-Bard, N. Vigier and S. Spezzaferri, *Chem. Geol.,* 2007, **244**(3-4), 679.

193 B. Fares, B. Gautier, P. Holliger, N. Baboux, G. Prudon and J. C. Dupuy, *Appl. Surf. Sci.,* 2006, **253**(5), 2662.

194 Y. Kataoka and T. Itani, *Surf. Interface Anal.,* 2007, **39**(10), 826.

195 C. W. Magee, R. S. Hockett, T. H. Buyuklimanli, I. Abdelrehim and J. W. Marino, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **261**(1-2), 594.

196 A. R. Chanbasha and A. T. S. Wee, *J. Vac. Sci. Technol., B,* 2007, **25**(1), 277.

197 M. Cwil, P. Konarski and J. Ciosek, *Int. J. Mass Spectrom.,* 2007, **263**(1), 54.

198 M. Tomita, T. Kinno, M. Koike, H. Tanaka, S. Takeno, Y. Fujiwara, K. Kondou, Y. Teranishi, H. Nonaka, T. Fujimoto, A. Kurokawa and S. Ichimura, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **258**(1), 242.

199 A. R. Chanbasha and A. T. S. Wee, *Surf. Interface Anal.,* 2007, **39**(5), 397.

200 L. H. Keith, L. U. Gron and J. L. Young, *Chem. Rev.,* 2007, **107**(6), 2695.

201 M. Cwil, P. Konarski, W. Gulbinski and V. V. Uglov, *Rev. Adv. Mat. Sci.,* 2007, **15**(3), 253.

202 M. Senoner and W. E. S. Unger, *Surf. Interface Anal.,* 2007, **39**(1), 16.

203 K. G. Lloyd, *J. Vac. Sci. Technol., A,* 2007, **25**(4), 878.

204 T. Iwanami, Y. Liu, M. Okazaki, M. Nojima, T. Sakamoto and M. Owari, *Surf. Interface Anal.,* 2006, **38**(12-13), 1658.

205 I. S. Gilmore, F. M. Green and M. P. Seah, *Surf. Interface Anal.,* 2007, **39**(10), 817.

206 L. A. Klerk, A. Broersen, I. W. Fletcher, R. van Liere and R. M. A. Heeren, *Int. J. Mass Spectrom.,* 2007, **260**(2-3), 222.

207 G. S. Groenewold, M. M. Cortez, A. K. Gianotto, G. L. Gresham, J. E. Olson, R. V. Fox, B. M. White, W. F. Bauer, R. Avci, M. Deliorman and E. Williams, *Surf. Interface Anal.,* 2007, **39**(6), 547.

208 V. S. Smentkowski and S. G. Ostrowski, *Rev. Sci. Instrum.,* 2007, **78**(7).

209 I. V. Veryovkin, W. F. Calaway, C. E. Tripa and M. J. Pellin, *Nucl. Instrum. Methods Phys. Res. Sect. B,* 2007, **261**(1-2), 508.

210 H. Shichi, S. Osabe, M. Sugaya, K. Kanehori, H. Kakibayashi and Y. Mitsui, *J. Vac. Sci. Technol., A,* 2007, **25**(4), 751.

211 G. L. Katona, Z. Berenyi, L. Peter and K. Vad, *Vacuum,* 2007, **82**(2), 270.

212 R. P. Philp, *Environ. Chem. Lett.,* 2007, **5**(2), 57.

213 J. P. Godin, L. B. Fay and G. Hopfgartner, *Mass Spectrom. Rev.,* 2007, **26**(6), 751.

214 J. M. Eiler, *Earth Planet. Sci. Lett.,* 2007, **262**(3-4), 309.

215 D. Paul, G. Skrzypek and I. Forizs, *Rapid Commun. Mass Spectrom.,* 2007, **21**(18), 3006.

216 K. M. Eek, A. L. Sessions and D. P. Lies, *Geobiology,* 2007, **5**(1), 85.

217 D. M. Nelson, F. S. Hu, J. A. Mikucki, J. Tian and A. Pearson, *Geochim. Cosmochim. Acta,* 2007, **71**(16), 4005.

218 M. Henning, D. Strapoc, G. P. Lis, P. Sauer, J. Fong, A. Schimmelmann and L. M. Pratt, *Rapid Commun. Mass Spectrom.,* 2007, **21**(14), 2269.

219 T. Hansen and U. Sommer, *Rapid Commun. Mass Spectrom.,* 2007, **21**(3), 314.

220 U. Flenker, M. Hebestreit, T. Piper, F. Hulsemann and W. Schanzer, *Anal. Chem.,* 2007, **79**(11), 4162.

221 G. L. Sacks, Y. Zhang and J. T. Brenna, *Anal. Chem.,* 2007, **79**(16), 6348.

222 V. Heuer, M. Elvert, S. Tille, M. Krummen, X. P. Mollar, L. R. Hmelo and K. U. Hinrichs, *Limnol. Oceanogr. Meth.,* 2006, **4**, 346.

223 M. A. Jochmann, M. Blessing, S. B. Haderlein and T. C. Schmidt, *Rapid Commun. Mass Spectrom.,* 2006, **20**(24), 3639.

224 M. Berg, J. Bolotin and T. B. Hofstetter, *Anal. Chem.,* 2007, **79**(6), 2386.

225 K. Yamada, N. Yoshida, G. Calderone and C. Guillou, *Rapid Commun. Mass Spectrom.,* 2007, **21**(8), 1431.

226 E. Norlin, K. Irgum and K. E. A. Ohlsson, *Soil Biol. Biochem.,* 2007, **39**(2), 550.

227 H. Schaefer and M. J. Whiticar, *Org. Geochem.,* 2007, **38**(2), 216.

228 B. H. Passey and T. E. Cerling, *Chem. Geol.,* 2006, **235**(3-4), 238.

229 G. E. Bebout, B. D. Idleman, L. Li and A. Hilkert, *Chem. Geol.,* 2007, **240**(1-2), 1.

230 Y. Oba and H. Naraoka, *Rapid Commun. Mass Spectrom.,* 2006, **20**(24), 3649.

231 C. Lecuyer, F. Fourel, F. Martineau, R. Amiot, A. Bernard, V. Daux, G. Escarguel and J. Morrison, *J. Mass Spectrom.,* 2007, **42**(1), 36.

232 B. Fry, *Rapid Commun. Mass Spectrom.,* 2007, **21**(5), 750.

233 P. Kaur and P. B. O'Connor, *Anal. Chem.,* 2007, **79**(3), 1198.

234 B. C. Reynolds, J. Aggarwal, L. Andre, D. Baxter, C. Beucher, M. A. Brzezinski, E. Engstrom, R. B. Georg, M. Land, M. J. Leng, S. Opfergelt, I. Rodushkin, H. J. Sloane, S. van den Boorn, P. Z. Vroon and D. Cardinal, *J. Anal. At. Spectrom.,* 2007, **22**(5), 561.

235 D. Rumble, M. F. Miller, I. A. Franchi and R. C. Greenwood, *Geochim. Cosmochim. Acta,* 2007, **71**(14), 3592.

236 M. B. Westley, B. N. Popp and T. M. Rust, *Rapid Commun. Mass Spectrom.,* 2007, **21**(3), 391.

237 F. Serra, A. Janeiro, G. Calderone, J. M. M. Rojas, C. Rhodes, L. A. Gonthier, F. Martin, M. Lees, A. Mosandl, S. Sewenig, U. Hener, B. Henriques, L. Ramalho, F. Reniero, A. J. Teixeira and C. Guillou, *J. Mass Spectrom.,* 2007, **42**(3), 361.

238 S. Valkiers, M. Varlam, K. Russe, M. Berglund, P. Taylor, J. Wang, M. Milton and P. De Bievre, *Int. J. Mass Spectrom.,* 2007, **263**(2-3), 195.

239 L. Zhang, M. A. Altabet, T. X. Wu and O. Hadas, *Anal. Chem.,* 2007, **79**(14), 5297.

240 J. Vogl, *J. Anal. At. Spectrom.,* 2007, **22**(5), 475.

241 S. Burger, L. R. Riciputi, S. Turgeon, D. Bostick, E. McBay and M. Lavelle, *J. Alloys Compd.,* 2007, **444**, 660.

242 S. Wakaki, S. Shibata and T. Tanaka, *Int. J. Mass Spectrom.,* 2007, **264**(2-3), 157.

243 C. F. Li, F. K. Chen and X. H. Li, *Int. J. Mass Spectrom.,* 2007, **266**(1-3), 34.

244 K. Gopalan, J. D. Macdougall and C. Macisaac, *Geostand. Geoanal. Res.,* 2007, **31**(3), 227.

245 J. Farkas, D. Buhl, J. Blenkinsop and J. Veizer, *Earth Planet. Sci. Lett.,* 2007, **253**(1-2), 96.

246 L. Font, G. M. Nowell, D. G. Pearson, C. J. Ottley and S. G. Willis, *J. Anal. At. Spectrom.,* 2007, **22**(5), 513.

247 M. E. Wieser and J. R. De Laeter, *Phys. Rev. C,* 2007, **75**(5).

248 M. E. Wieser, J. R. De Laeter and M. D. Varner, *Int. J. Mass Spectrom.,* 2007, **265**(1), 40.

249 M. Willbold, *J. Anal. At. Spectrom.,* 2007, **22**(11), 1364.

250 S. K. Aggarwal, D. Alamelu, P. S. Khodade and P. M. Shah, *J. Radioanal. Nucl. Chem.,* 2007, **273**(3), 775.

251 D. Alamelu and S. K. Aggarwal, *J. Alloys Compd.,* 2007, **444**, 640.

252 D. Alamelu and S. K. Aggarwal, *J. Alloys Compd.,* 2007, **444**, 643.

253 S. K. Aggarwal, P. M. Shah, D. Alamelu and N. N. Mirashi, *Radiochim. Acta,* 2007, **95**(4), 233.

254 I. R. Fletcher, *Int. J. Mass Spectrom.,* 2007, **261**(2-3), 234.

255 T. Kuritani, T. Usui, T. Yokoyama and E. Nakamura, *Geostand. Geoanal. Res.,* 2006, **30**(3), 209.

256 M. D. Schmitz and B. Schoene, *Geochem. Geophys. Geosyst.,* 2007, **8**.

257 S. Letsiou, V. Nischwitz, P. Traar, K. A. Francesconi and S. A. Pergantis, *Rapid Commun. Mass Spectrom.,* 2007, **21**(3), 343.

258 G. L. Sacks, L. A. Derry and J. T. Brenna, *Anal. Chem.,* 2006, **78**(24), 8445.

259 M. Kidera, K. Takahashia, S. Enorn, Y. Mitsubori, A. Goto and Y. Yano, *Eur. J. Mass Spectrom.,* 2007, **13**(4), 239.