Trends and Advances in Inductively Coupled Plasma Tandem Quadruple Mass Spectrometry (ICP-QMS/QMS) With Reaction Cell

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ABSTRACT: Trends and advances in the development and application of inductively coupled plasma tandem quadrupole mass spectrometry (ICP-QMS/QMS) with a reaction cell is reviewed mainly based on publications from January 2018 to July 2021. ICP-QMS/QMS has been applied in various research fields covering the sciences of biology, energy, environmental, food/medical, geology, materials, and radionuclide. The objectives of analysis cover the determination of elemental concentration, ion-gas reaction, isotope analysis, single particle analysis, and chemical speciation analysis. Measurement of most elements in the periodic table are reported except for H, N, O, F, rare gas, and some of the radionuclides. In addition to the default reaction/collision gases (*i.e.*, He, H_2, O_2, and NH_3), N_2O, CO_2, CH_4, CH_3F, C_2H_4, and C_2H_6 have been used as reaction gases to improve the capability of separating spectral interferences or to study the ion-molecule reactions. Typical applications of ICP-QMS/QMS analysis in the major research fields are also discussed.

INTRODUCTION

Inductively coupled plasma mass spectrometry (ICP-MS) is predominantly used for elemental analysis due to its powerful ionization source, *i.e.*, argon plasma up to 10000 K, including the capability of multielement/isotope analysis, much simpler spectra in comparison to optical emission spectrometry, excellent limits of detection at ng/L or even lower, and wide linear dynamic range up to 9 orders of magnitude. In the past three years, the number of publications based on ICP-MS at least doubled the sum of those based on optical emission spectrometry and atomic absorption spectrometry.

However, one of the obstacles for the application of ICP-MS is spectral interference due to isobaric ions (*e.g.*, $^{40}Ar^+$ interference with $^{40}Ca^+$), polyatomic ions (*e.g.*, $^{40}Ar^{16}O^+$ interference with $^{56}Fe^+$), or multiply charged ions (*e.g.*, $^{138}Ba^{2+}$ interference with $^{69}Ga^+$). A straightforward approach for separating spectral interference from an element of interest is double focusing high resolution (HR) ICP-MS, which is also known as sector field (SF) ICP-MS (or ICP-SF-MS) or HR-ICP-MS. This instrumental arrangement is usually composed of a magnetic field mass spectrometer and an electric field mass spectrometer. In this kind of ICP-MS instrument, a higher resolution ($R = m/\Delta m$) is obtained by adjusting the physical width of the inlet slit and that of the outlet slit to manipulate the ion beam. In principle, a narrower slit width provides a higher resolution in return for a lower signal intensity (*i.e.*, trading off sensitivity) due to a decrease of ion transmittance through the instrument. In this case, the separation of a spectral interference from an element of interest is based on a tiny difference (*e.g.*, 0.3 to 0.01, or even lower) in the mass-to-charge ratio ($\Delta m/z$). The resolution required for separating the spectral interference from an element of interest in the measurement by HR-ICP-MS is illustrated in Fig. 1, where ^{118}Sn is given as an example and is approximately located at the middle of the range of the atomic number from ^1H to ^{235}U. This is supposing that an HR-ICP-MS instrument,

Fig. 1 Resolution required for separating a spectral interference from an element of interest in the measurement by HR-ICP-MS. (A), low resolution; (B), medium resolution; (C), high resolution.

operated at low resolution, provides a signal intensity of 1,000,000 counts per second (CPS) for 1 ng/mL of Sn standard solution. The signal intensity obtained at middle resolution and high resolution will be approximately 95,000 CPS and 34,000 CPS, which can be calculated from a simulation based on a normally distributed profile of the ion beam.

An alternative approach for separating ICP-MS spectral interference is the collision/reaction cell technique. A spectral interference can be separated from an element of interest based on the different chemical properties in reaction with the cell gas molecules or based on the kinetic energy discrimination (KED) effect during the collision with the cell gas molecules. After separation in the collision/reaction cell, the initial spectral interference can be excluded from entering the mass spectrometer due to the KED effect or significant difference in $\Delta m/z$ (minimum value = 1, loss or gain a hydrogen atom) from an element of interest. As a result, better separation can be obtained without compromising the sensitivity.

A drawback of the collision/reaction cell technique in traditional ICP-MS is that unwanted reactions may occur in the collision/reaction cell and result in new spectral interferences not formed in the argon plasma. Fortunately, ICP-MS with tandem quadrupole mass spectrometers (ICP-QMS/QMS) significantly improved the reaction management in comparison to previous generation of collision/reaction cell ICP-MS instruments that lacked a filtering quadrupole in front of the reaction cell. In ICP-QMS/QMS, the quadrupole mass filter placed upstream of the reaction cell controls the ionic species entering the reaction cell and effectively decreases the occurrence of unwanted reactions. There are multiple names used for tandem quadrupole ICP-MS, *e.g.*, ICP-QQQ, triple quadrupole (TQ) ICP-MS, and multiple quadrupole ICP-MS. ICP-QMS/QMS is used in the present work to emphasize the merits of the filtering quadrupole in front of the reaction cell and the analyzing quadrupole at back of the reaction cell.

MECHANISM FOR SEPARATING SPECTRAL INTERFERENCE IN ICP-QMS/QMS

There are two modes, namely on-mass mode and mass-shift mode, for separating spectral interference from an element of interest in the measurement by ICP-QMS/QMS. Figs. 2 (A) and (B) illustrate the mechanism for on-mass mode and mass-shift mode, respectively.

In both modes, only the ions with an m/z value equal to m_1 can pass through the first quadrupole mass spectrometer (QMS1) and enter the reaction cell. All other ions with an m/z value different from m_1, *e.g.*, $^{40}Ar^+$, cannot pass through QMS1 and cannot arrive at the reaction cell. As a result, the ion species entering the reaction cell are greatly simplified and the unwanted reactions in the reaction cell are effectively suppressed.

On-mass mode. On-mass mode is applied for the measurement of an element not reacting with the cell gas, *i.e.*, an ion is detected with its initial m/z value. As is shown in Fig. 2 (A), both QMS1 and the second quadrupole mass spectrometer (QMS2) are set to permit the passing of ions with an m/z value of m_1 ($m_2 = m_1$). An ion of interest ($^{56}Fe^+$) and an interfering ion ($^{40}Ar^{16}O^+$) whose m/z values are both equal to m_1 can pass through QMS1 and enter the reaction cell. Without reacting with the cell gas content, $^{56}Fe^+$ passes through the reaction cell and QMS2 sequentially and arrives at the detector to be observed as a measurement signal.

On the other hand, $^{40}Ar^{16}O^+$ changes to ^{40}Ar and $^1H_2{}^{16}O^+$ ($m/z \neq m_2$) after reacting with the cell gas and cannot pass through QMS2 to arrive at the detector. It is to be noted that there may be other product ions/atoms in addition to ^{40}Ar and $^1H_2{}^{16}O^+$ ($m/z \neq m_2$), *e.g.*, $^{40}Ar^+$ and $^1H_2{}^{16}O$, which have m/z values different from m_2 and, therefore, also cannot pass through QMS2.

Mass-shift mode. Mass-shift mode is applied to the measurement of an element reacting with the cell gas, *i.e.*, an ion is detected with an m/z value different from its initial one. As is shown in Fig. 2 (B), QMS1 and QMS2 are set to permit the

Fig. 2 Mechanisms for separating spectral interference from an element of interest in the measurement by ICP-QMS/QMS.

passing of ions with *m/z* values of m_1 and m_2 ($\neq m_1$), respectively. Both $^{32}S^+$ and $^{16}O_2^+$ can pass through QMS1 and enter the reaction cell. In the reaction cell, $^{32}S^+$ reacts with the cell gas and converts to $^{32}S^{16}O^+$ having an *m/z* value of m_2 ($= m_1 + 16$). Then, $^{32}S^{16}O^+$ passes through the reaction cell and QMS2 sequentially and arrives at the detector to be observed as a measurement signal.

Meanwhile, $^{16}O_2^+$ keeps its initial *m/z* value, *i.e.*, m_1 ($\neq m_2$), and cannot pass through QMS2 to arrive at the detector. There may be reactions between $^{16}O_2^+$ and O_2 resulting in some product ions with *m/z* values different from m_2. These ions can also not pass through QMS2.

In both modes, only selected ions with an *m/z* value of m_1 are permitted to pass through QMS1, which simplifies the reactions in the reaction cell. Further separation of an ion of interest from an interfering ion can be effectively obtained by shifting either the *m/z* of the interfering ion (on-mass mode) or that of the ion of interest (mass-shift mode). These mechanisms permit the effective separation of spectral interference without trading off sensitivity, *i.e.*, independent of the resolution required for HR-ICP-MS. Partly attributable to this advantage, more and more applications using ICP-QMS/QMS have been published since the commercial availability in 2012. The relatively low price (roughly half of) in comparison to that of HR-ICP-MS may be another reason for the increasing application of advantage of ICP-QMS/QMS.

RECENT APPLICATIONS OF ICP-QMS/QMS

There are multiple brands of ICP-QMS/QMS instruments commercially available. Agilent Technologies launched the Agilent 8800 series in 2012, followed by the Agilent 8900 series in 2016. Thermo Fisher Scientific launched the iCAP™ TQ ICP-MS and PerkinElmer, Inc., the NexION® 5000 Quadrupole ICP-MS series in 2017 and 2020, respectively. Most works published so far have been using the Agilent 8800 and 8900 ICP-QMS/QMS. In this paper, the references on ICP-QMS/QMS published from January 2018 to July 2021 are comprehensively reviewed, as shown in Table 1.

References investigated. In the present review, the references cited are generally obtained from the Web of Science database operated by Clarivate Analytics. The time of publication is between January 2018 and July 2021. The reference search was carried out following two criteria:

(1) At least one of the following words was included as the topics: ICP-MS/MS, ICP-QQQ, ICP-QMS/QMS, TQ ICP-MS, NexION 5000.

(2) At least one of the following words was included as the topics: reaction gas, reaction cell, collision gas, collision cell.

As a result, 77 references were collected and are discussed in the following text.

Research fields and objectives. The research fields of the above references covered biology,[1-15] energy,[16] environment,[9,17-32] food/medical,[10-12,25-27,33-40] geology,[28,41-47] material,[48-60] and radionulide,[4,22-23,61-71] respectively. In addition to these conventional elemental analysis topics, a study on the gas phase catalytic reaction has also been reported by using the reaction cell of ICP-QMS/QMS as the in-situ reaction field.[73] Furthermore, ICP-QMS/QMS has been covered by principle studies and reviews on the ICP-MS reaction/collision cell technology,[72,74,75] gas chromatography (GC-) ICP-MS,[76] and high performance liquid chromatography (HPLC-) ICP-MS for quantitative profiling analysis of metalloids in biological samples,[77] respectively.

Table 1. Summary of References Based on ICP-QMS/QMS and Published from January 2018 to July 2021

No.	Research Field	Topic	Sample	Element	Reaction Cell Gas
1	Biology	Concentration	Human Serum	Mn, Fe, Ni, Cu, Zn, Se	N_2O
2	Biology	Concentration	Whole Blood	As	O_2
3	Biology	Isotope	Insects	Sr	N_2O
4	Biology, Radionuclide	Isotope	Urine	Sr	O_2
5	Biology	Single Particle	Radish	Ti	H_2, O_2
6	Biology	Single Particle	Breast Cancer Cells	Nd, Eu, P	No-Gas, O_2
7	Biology	Speciation	Organotin-Protein Samples	Sn, S, Se	O_2
8	Biology	Speciation	Fish Tissue	Br	H_2, O_2, N_2O
9	Biology, Environment	Concentration	Environment, Biology	Mg, Al, Fe, Cu, Zn, Se, Cd	No-Gas, O_2
10	Biology, Medical	Speciation	Plasma	Se, S	O_2
11	Biology, Medical	Speciation	Human Blood	Se, S	O_2
12	Biology, Medical	Speciation	Human Plasma	Br, Cl	H_2, O_2
13	Biology	Concentration	Human Serum	Ti	O_2, H_2
14	Biology	Concentration	Clinical Samples	Non-Specified	Non-Specified
15	Biology	Single Particle	Human Cell	P, S, Fe, Cu, Zn, Pt	O_2, NH_3, He
16	Energy	Speciation	Light Petroleum	Si	H_2
17	Environment	Concentration	Environment Water	Pd	He, CH_3
18	Environment	Concentration	Seawater	La, Ce, Pr, Nd, Sm, Eu,Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	H_2, He, O_2
19	Environment	Concentration	Particulate Matter	Li, Be, B, Na, Mg, Al, Si, P, S, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga,Ge, As, Se, Br, Rb, Sr,Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, Cs, Ba,La, Ce, Nd, Sm, Eu, Gd, Tb, Ho, Tm, Lu, Hf, Ta, W, Be, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Th, U	He, O_2, No-Gas
20	Environment	Concentration	Seawater	Mn, Fe, Ni, Cu, Zn, Pb	H_2, O_2
21	Environment	Concentration	Model Solution	As, Se	O_2
22	Environment, Radionuclide	Isotope	Environment Samples	Pu	NH_3, He
23	Environment, Radionuclide	Isotope	Environment Samples	Cs	N_2O
24	Environment, Radionuclide	Isotope	Environment Samples	U	O_2, CO_2
25	Environment, Food	Concentration	Food and Environment Samples	Rb	CH_3F
26	Environment, Food	Isotope	Environment and Food Samples	Ga	He, H_2, O_2, NH_3, He
27	Environment, Medical	Isotope	Environment and Forensic Samples	Pu	CO_2, He
28	Environment, Geology	Isotope	Water and Geology Sample	Ra	N_2O
29	Environment	Concentration	Sediment	Sc, Ga, Ge, Nb, In, Te, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Yb, Lu, Ta	N_2O, O_2, No-Gas
30	Environment	Concentration	River Water	La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	O_2
31	Environment	Single-Particle	Seawater	C	No-Gas, H_2, O_2, NH_3, He
32	Environment	Concentration	Road Dust, Soil, Rock	Ru, Rh, Pd, Os, Ir, Pt, Re	NH_3, He
33	Food	Concentration	Food Sample	Ca, Cl	H_2
34	Food, Medical	Concentration	Hearbal Tea	Si, P, S, Cl, Br, I	O_2, H_2
35	Food, Medical	Concentration	Fruit Wines	Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Hg, Pb	O_2, H_2, NH_3, He, H_2
36	Food, Medical	Concentration	Wild Artemisia Selengensis	As, Se, Cr, Mn, Fe, Co, Ni, Cu, Zn	O_2, NH_3, He, No-Gas
37	Food, Medical	Concentration	Jatropha Curcas L. Oil	Na, Si, P, S, Cl, K, Ti, V, As, Na	O_2, H_2
38	Food, Medical	Concentration	Z. Bungeanum Oil	Cr, Ni, As, Cd, Hg, Pb	He, O_2, No-Gas
39	Food, Medical	Concentration	Food Samples	As, Co, Mn	O_2, NH_3, He
40	Medical	Single Particle	Model Solution	Fe	O_2

41	Geology	Concentration	Uranium Ore	P, S, Br, I	O_2
42	Geology	Concentration	Minerals	Rh, Pd	NH_3, He
43	Geology	Isotope	Molybdenite	Re, Os	CH_4
44	Geology	Isotope	Apatite, Titanite	Pb	NH_3
45	Geology	Isotope	Water and Geology Sample	U	N_2O
46	Geology	Isotope	Rock	Sr	O_2
47	Geology	Concentration, Isotope	Geological samples	Non-Specified	Non-Specified
48	Material	Concentration	Soft Magnetic Ferrite Powders	Na, Mg, Al, K, Ti, Co	NH_3, He, H_2
49	Material	Concentration	Ru Compounds	P, S, Ti, V, Cr, Mn, Fe, As	O_2, NH_3, He
50	Material	Concentration	High Purity Molybdenum Powder	Si, Ca, Cd, P, S, As, Se, Ta, Sn, Sb, Ba, W, Na, Mg, Al, K, V, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb, Bi, Th, U	H_2, O_2, NH_3, He, No-Gas
51	Material	Concentration	High Purity Cobalt	P, S, V, As, Se, Si, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Na, Mg, Al, K	O_2, H_2, NH_3/He
52	Material	Concentration	High Purity TMAH	Si, P, S, Cl, As, Se	He, H_2, O_2
53	Material	Concentration	High Purity TMAH	Mg, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Cd, Pb	O_2, NH_3, He
54	Material	Single Particle	Nanoparticle	Fe	H_2, NH_3
55	Material	Single Particle	Nanoparticle, Protein	Fe, S, V	O_2
56	Material	Single Particle	Nanoparticle	Au, Ag, Pt, Fe	H_2, He, CH_3
57	Material	Single Particle	Nanoparticle	Fe, Ti, Si, Cr, Al, Ni, Cu, Au, Pt	NH_3, O_2-H_2
58	Material	Concentration	Lithium Hexafluorophosphate	Na, Mg, Al, K, Ti, V, Mn, Fe, Co, Ni, Cu, Zn, Ag, Cd, Sb, Ba, Pb	O_2, H_2, NH_3, He
59	Material	Concentration	Lithium Tantalate	Au, Na, K, Ca	O_2, NH_3, He
60	Material	Concentration	Propylene Glycol Methyl Ether	Na, Mg, Al, Ti, V, Cr, Fe, Ni, Cu, Zn	H_2, NH_3, He
61	Radionuclide	Concentration	Model Solution	U, Pu	No-Gas, O_2, H_2, He
62	Radionuclide	Isotope	Nuclear Decommissioning Samples	Sm	O_2
63	Radionuclide	Isotope	Nuclear Waste, Disposal	Zr	NH_3/He
64	Radionuclide	Isotope	Calcium Fluoride Sludge	U	He
65	Radionuclide	Isotope	Certified Reference Material	Pu	CO_2, H_2, He
66	Radionuclide	Isotope	Model Solution	Cl, Ca, Ni, Se, Sr, Zr, Nb, Tc, Pd, Sn, I, Cs, Sm, U, Np, Pu	H_2, He, O_2, NH_3
67	Radionuclide	Concentration	Soil	U	CO_2, He
68	Radionuclide	Concentration, Isotope	Seawater	Cs	N_2O
69	Radionuclide	Concentration	Lake Water, Groundwater, Seawater	Sr	O_2, H_2
70	Radionuclide	Concentration	Lake Water, Seawater, Urine	Sr, U, Am, Pu	O_2, H_2, He
71	Radionuclide	Concentration	Concrete	Zr, Mo	H_2, NH_3, He
72	Principle	Concentration	Model Solution	U, Th	O_2
73	Principle	Gas-Phase Reaction	Gaseous Catalysts	Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, In, Hf, Ta, W, Re, Ir, Pt, Au, S, As, Se, Sn, Sb, Te, Pb, Bi, Hg	CH_4, C_2H_6, C_2H_4
74	Principle	Concentration	Model Solution	Ag, Cd, Ce, Co, Cs, Cu, Fe, Ga, Ge, In, Mg, Rh, Sc, Ti, Tl, Y, Zn	NH_3, He
75	Review	Non-Specified	Non-Specified	Non-Specified	Non-Specified
76	Review	Speciation	Non-Specified	Non-Specified	Non-Specified
77	Review	Speciation	Non-Metal Medicals	Non-Specified	Non-Specified

The objectives of the above references covered elemental concentration,[1,2,9,13,14,17-21,25,29,30,32-39,41,42,47-53,58-61,67-72,74] ion-gas molecule reaction,[73] isotope,[3,4,22-24,26-28,43-47,62-66,68,] single particle,[5,6,15,31,40,54-57] and chemical speciation,[7,8,10-12,16,76,77] respectively.

Figs. 3 (A) and (B) show the reference distribution of research fields and objectives. In Fig. 3 (A), the distribution of the research fields shows a roughly equal distribution in six research fields, except for energy, indicating the wide application of ICP-QMS/QMS in these major research fields. On the other hand, as shown in Fig. 3 (B), the applications in the elemental concentration and isotope analysis occupied 53.9% and 22.4%, respectively, followed by the applications in single particle analysis and chemical speciation analysis with over 10% each.

Fig. 3 Distributions of research field and objective in works carried out by using ICP-QMS/QMS.

Elements covered by the references. The elements reported in the references are summarized in the periodic table in Fig. 4. The number of references for each element is shown in color scale. As is shown in Fig. 4, a total of 78 elements were reported based on the measurement by ICP-QMS/QMS. In addition to some radioactive elements/isotopes, these reports covered most elements having natural stable isotope(s), except for H, N, O, F and the rare gas elements. It can be said that ICP-QMS/QMS is the unique instrument permitting such a wide and predominant application in atomic spectrometry.

As shown in Fig. 4, the elements S, Ti, Mn, Fe, Ni, Cu, Zn, As, and Se were all reported at least in 10 references. This can be attributed to the following facts: these elements are attracting attention in multiple research fields, such as biology, environment, food/medical, materials, and so on; spectral interferences with the measurement of S, Ti, Se, and As can be achieved at mass-shift mode by using O_2 as the reaction gas; measurement of the first row transition metals by ICP-QMS/QMS can be achieved at much less spectral interferences in comparison to traditional collision cell ICP-MS.

Reaction gases used in the measurement by ICP-QMS/QMS. The most important advantage of ICP-QMS/QMS is the effective separation of a spectral interference from an element of interest based on the reaction with the cell gas. Similar to traditional ICP-MS using the collision/reaction cell techniques, He, H_2, O_2, and NH_3 are usually the default cell gases for ICP-QMS/QMS. In addition, there are some reports using N_2O, CO_2, CH_4, CH_3F, C_2H_4, and C_2H_6 as the cell gas for ICP-QMS/QMS. Fig. 5 shows the number of references for using each kind of cell gas.

As shown in Fig. 5, over 80% of the references used He, H_2, O_2, or NH_3 as the cell gas, regardless of the fact that some references also reported measurement at no-gas condition. It is worth noting that 47 out of 74 references use O_2 as the cell gas. The reason can be partly attributed to the fact that there are many reports on P, S, As, and Se, as shown in Fig. 4, for which the mass-shift mode using O_2 as the cell gas is effective in the separation of the spectral interferences (*e.g.*, $^{14}N^{16}O^1H^+$, $^{16}O_2^+$, $^{40}Ar^{35}Cl^+$, and Ar_2^+, respectively) from the measurement of these elements. Another reason can be attributed to the fact that old generation reaction cell ICP-MS instruments are sufficient for the analysis of some other elements.

Due to the inert chemical property of He, it is mainly used as a collision gas. Application of H_2 as the cell gas is effective for removing argon-related polyatomic spectral interferences. Taking advantage of ICP-QMS/QMS, H_2 can also be applied to the measurement of Si, P, S, Cl, and Br at the mass-shift mode.[78] These elements can react with H_2 to form hydrate ions. There are

Fig. 4 Counts of reference for each element measured by ICP-QMS/QMS.

Fig. 5 Counts of reference for each kind of reaction cell gas used in ICP-QMS/QMS.

many more references using O_2 or NH_3 as the cell gas, which can be attributed to the fact that many elements can react with these cell gases to obtain MO_x^+ or $M(N_xH_y)^+$ type product ions with *m/z* values different from that of the initial ion, *i.e.*, M^+. These reactions permit the application to measurements at mass-shift mode.

Figs. 6 (A) and (B) illustrate the maximum percentage of product ions by using O_2 and NH_3 as the cell gas, respectively. The value of a maximum percentage was calculated based on the data in Reference (78). As shown in Fig. 6 (A), P, S, Cl, Sc, Ti, V, As, Y, Nb, Ta, Th, U and the lanthanoids have high maximum MO_x^+ percentages (90% or more). The maximum MO_x^+ percentages for Br, Zr, Mo, Sb, Hf, W, and Gd are in the range from 50% to 89%. It can be expected that the measurements of these elements at mass-shift mode with O_2 as the cell gas provide relatively higher sensitivity.

As shown in Fig. 6 (B), none of the elements have a maximum $M(N_xH_y)^+$ percentage over 70%. Four elements, *i.e.*, B, Hf, Ta, and Th, have maximum $M(N_xH_y)^+$ percentages in the range from 50% to 69%. Five elements, *i.e.*, As, Zr, La, W, and U, have maximum $M(N_xH_y)^+$ percentages in the range from 30% to 49%. Twelve elements, *i.e.*, Be, Si, P, Sc, Ti, V, Ge, Y, Nb, Ce, Gd, and Tb, have maximum $M(N_xH_y)^+$ percentages in the range from 10% to 29%. These elements can be measured by ICP-QMS/QMS at mass-shift mode with NH_3 as the cell gas.

As shown in Fig. 5, N_2O, CO_2, and CH_4 were also used in multiple reports instead of the default cell gases. By using N_2O as the cell gas, the production rate of the oxide ions of (Mn, Fe, Ni, Cu, Zn, and Se),[1] Sr,[3,68] Br,[8] Ba,[23] (Ge, Eu, Yb)[29] and Ra,[28,45] is greatly improved in comparison to those obtained by using O_2 as the cell gas. This feature provides a higher sensitivity and/or a better separation of spectral interference. Application of CO_2 as the cell gas was specifically useful for separating the spectral interference in the isotopic analysis of U and Pu.[24,27,65,67] The use of CO_2 benefited the complete conversion of U^+ to oxide ions (UO^+ and UO_2^+), which permitted the spectral interference-free measurement of Pu^+ at on-mass mode. The reaction of ($Os^+ \rightarrow OsCH_2^+$), achieved by using CH_4 as the cell gas, was effective for separating a spectral interference in the measurement of Re^+.[43]

Determination of elemental concentration. One of the main applications of ICP-MS, including ICP-QMS/QMS, is the determination of elemental concentrations. Due to spectral interferences, the determination of lower concentrations (ng/mL order or lower) of P, S, Si, Cl, Br, and I is often challenging for traditional ICP-MS. Measurement by ICP-QMS/QMS at mass-shift mode using O_2 as the cell gas permitted a better performance for analysis of these element and has been reported for P,[15,19,34,41,45,49-52] S,[15,19,34,40,41,45,44-52] Si,[19,34,45,50,52] Cl,[34,45,52] Br,[34,41] and I,[34,41] respectively.

Besides, the determination of 29 elements (Si, Ca, Cd, P, S, As, Se, Ta, Sn, Sb, Ba, W, Na, Mg, Al, K, V, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb, Bi, Th and U) was reported by combining multiple cell gas operating conditions, including no-gas, H_2, O_2, and NH_3/He.[49] Most of the references discussed in this review were published in the period from January 2018 to July 2021. The author would like to point out that a reference published in 2017 and authored by Konan and Suzuki reported the determination of 67 elements by ICP-QMS/QMS based on multiple operating conditions.[79]

Isotope analysis. In addition to the determination of elemental concentrations, isotope and isotopic ratio analysis is another major research filed for application of ICP-QMS/QMS. Many references used He, H_2, O_2, or NH_3, which are usually included as the default cell gas for ICP-QMS/QMS.[4,22,26,44,46,62-66] There are also multiple references using N_2O,[3,23,28,45,68] CO_2,[24,27,65] or CH_4[43] as the cell gas to improve the separation of spectral interferences. For single element solution, the typical relative uncertainty of isotopic ratio obtained by ICP-QMS/QMS is roughly in the range from 0.1% to 0.2%, which is inferior to that can be achieved by multiple collector (MC-) ICP-MS by 3 to 4 orders of magnitude. Due to the effective separation of spectral interferences (improvement of abundance sensitivity), the precision of isotopic ratio analysis by ICP-QMS/QMS for real samples of complicate matrix is comparable to that obtained for single element solution. This is a noteworthy advantage in comparison to MC-ICP-MS, which usually requires mathematical correction of spectral interferences for the analyzing real sample of complicate matrix and results in deterioration of analytical precision and accuracy.

The production rates of $^{87}Sr^{16}O^+$, $^{226}Ra^{16}O^+$, and $^{236}U^{16}O^+$ were greatly improved by using N_2O as the cell gas, resulting in an effective separation from the interfering ions $^{87}Rb^+$, $^{218}Pb^{16}O^+$, and $^{235}U^1H^+$, respectively.[3,28,45] On the other hand, highly precise analysis of the Cs isotopes ($^{135}Cs^+$ and $^{137}Cs^+$) was achieved by complete conversion of the interfering ions, *i.e.*, $^{135}Ba^+$ and $^{137}Ba^+$, to oxide ions using N_2O as the cell gas and resulted in the complete elimination of the spectral inteferences.[23,68]

Fig. 6 Maximum percentages of product ions by using O_2 and NH_3 as the reaction cell gas in ICP-QMS/QMS measurement. (Calculated based on the data reported in Ref. 78.) (MO_x^+ includes MO^+, MO_2^+, and MO_3^+; $M(N_xH_y)^+$ includes $M(NH)^+$, $M(NH_2)^+$, $M(NH_3)^+$, $M(N_2H_4)^+$, $M(N_2H_5)^+$, $M(N_2H_6)^+$, $M(N_3H_7)^+$, $M(N_3H_8)^+$, and $M(N_3H_9)^+$; A value for the maximum percentage was calculated as the relative value of the signal intensity of a dominating product ion in comparison to the sum of signal intensities of all product ions considered, including M^+.).

Regardless of the fact that CO_2 as the cell gas did not improve the sensitivity for isotope analysis of U at the mass-shift mode by ICP-QMS/QMS, effective separation of the spectral interferences was achieved for the measurement of Pu^+ at the on-mass mode by improving the conversion of UH^+ to UO^+.[24]

Single particle analysis. Single particle (or single cell) analysis based on ICP-QMS/QMS was reported for Ti,[5] (Nd, Eu, P),[6] (P, S, Fe, Cu, Zn, Pt),[15] C,[31] Fe,[40,54-57] (Au, Ag, Pt),[56] and (Cr, Al, Ni, Cu, Au, Pt)[57], respectively. Complementary software package for single particle analysis can facilitate the data processing, which can also be achieved by using spreadsheet software such as Microsoft Excel.

Suppression of ($^{48}Ca^+ \rightarrow {}^{48}Ca^{16}O^+$) reaction and improvement of ($^{48}Ti^+ \rightarrow {}^{48}Ti^{16}O^+$) reaction were simultaneous achieved by using both H_2 and O_2 as the cell gas, achieving high sensitivity analysis of the TiO_2 nanoparticles. As a result, the detection limits for particle size in pure water and 50 mg/L of Ca matrix were 15 nm and 21 nm, respectively.[5]

Size detection limit of 0.6 μm was achieved for polystyrene-based microplastics by measuring $^{12}C^+$ at on-mass mode with H_2 as the reaction cell gas.[15]

Measurement at on-mass mode by using H_2 as the cell gas was effective for separating the spectral interferences in Fe_3O_4 nanoparticle analysis.[54] A slight broadening of peak width was observed with double the signal intensity in comparison to the measurement by HR-ICP-MS at pseudo-medium resolution mode (only the width of the entrance slit but not that of the exit slit being decreased).

A significant broadening of the peak width was observed for Fe_3O_4 nanoparticle analysis at both the mass-shift mode and the on-mass mode by using NH_3 as the cell gas in comparison to those obtained with He or H_2 as the cell gas or operated at no-gas condition.[56] The broadening of the peak width can be attribute to the apparent larger collisional cross-section when NH_3 is used as the reaction cell gas.

Chemical speciation analysis. Chemical speciation analyses based on ICP-QMS/QMS were mostly reported for S,[7,10,11] Se,[7,10,11] Br,[8,12] Cl,[12] and Si[16], all of which are "challenging elements" for traditional ICP-MS. Measurement at mass-shift mode using O_2 as the cell gas was effective for separating spectral interferences in the analysis of S compounds and Se compounds in proteins, peptides and human blood cells.[7,10,11] Measurement at mass-shift mode using N_2O as the cell gas and at on-mass mode using H_2 was effective for separating the spectral interferences in the analysis of Br compounds in fish tissue and human plasma.[8,12] Measurement at mass-shift mode using H_2 as the cell gas was effective for the analysis of Cl compounds (*e.g.* $^{35}Cl^+ \rightarrow {}^{35}Cl^1H_2^+$) in human plasma.[12] Measurement at on-mass mode using H_2 as the cell gas was effective for the analysis of Si compounds in petroleum products.[16]

In addition, a review article on GC-ICP-QMS/QMS summarized chemical speciation analyses of P, S, Si, Cl, Sn, Pb, Hg, As, Br, and Ge compounds.[76] Chemical speciation analyses of S, Cl, P, Br and Se compounds by HPLC-ICP-MS were reviewed in another reference.[77]

CONCLUSIONS AND PROSPECTIVE

Trends in research based on ICP-QMS/QMS are investigated with a focus on references published from January 2018 to July 2021. Also, a brief introduction is provided about spectral interferences in ICP-MS and the mechanism for spectral interference separation in ICP-QMS/QMS.

Due to the outstanding capability for separating spectral interferences, ICP-QMS/QMS has been utilized in multiple research fields covering biology, energy, environment, food/medical, geology, materials, and radionuclide. The objectives for measuring the advantages of this methodology include the determination of the elemental concentrations, ion-gas reaction, isotope analysis, single particle analysis, and chemical speciation analysis.

In these reports, about 78 elements were measured by ICP-QMS/QMS, also multiple radioactive elements, including most stable isotope elements of the periodic table, with the exception of H, N, O, F and the rare gas elements.

In addition to the default cell gases, *i.e.*, He, H_2, O_2, and NH_3, the literature review showed that multiple alternative gases were investigated as the cell gas for ICP-QMS/QMS analysis, including N_2O, CO_2, CH_4, CH_3F, C_2H_4, C_2H_6. This suggests that reaction gases can be customized and adopted for very specific applications. However, it is notable that due to the limitation of channel for corrosive gas, not every gas can be simultaneously put into the reaction cell of the ICP-QMS/QMS.

Due to the low conversion rate of product ions with mass-shift mode analysis by using O_2 and NH_3, a more reactive cell gas (*e.g.*, N_2O) may find more application in the analysis of transition metals of groups 7 to 14 of the periodic table. Optimization of the operating conditions to elevate the collision energy may improve the conversion rate of product ions which require higher formation enthalpy.[80]

The application of ICP-QMS/QMS permitted the analysis of most elements of the periodic table, including “the challenging elements” (when using traditional ICP-MS), *e.g.*, P, S, Si, Cl, As, Se, and Br, due to severe spectral interferences.

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Notes

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