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The impact of gas purity on observed reactivity with NO using inductively coupled plasma tandem mass spectrometry†

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Interference removal in inductively coupled plasma tandem mass spectrometry (ICP-MS/MS) is strongly dependent on the gas selected for use within the collision/reaction cell. There has been little investigation on the effects that reaction gas impurities may have on the resulting spectra. The reactivity of 60 elements was evaluated using nitric oxide (NO 99.5%) with and without a gas purifier to reduce H_2O impurities to <100 pptV. Experiments were performed using V, Ce, Tl and Th to investigate the effects of purified NO at various flowrates (0.22–1.49 mL min^{-1}). Purified NO was shown to significantly mitigate oxy-hydride interferences, improve total ion sensitivity (notable at high gas flows), and shift product distributions advantageously. The reduction in oxy-hydride species results in a product distribution favoring the major expected products, where signals were shown to increase by an order of magnitude. Reduced background and increased signal for the major expected products provides avenues for improving various analytical applications of ICP-MS/MS.

Introduction

Commercial collision/reaction cells (CRCs) were first implemented into single quadrupole inductively coupled plasma mass spectrometry (ICP-MS) instruments in the early 2000's allowing for improvements in analyses not previously possible.[1–3] A CRC removes interferences through the introduction of a collision or reaction gas. Interferences are mitigated by decreasing polyatomic ion (interferent) transmission through kinetic energy discrimination and/or chemical removal of interferences through reaction of reactant ion (M^+) or interferent ion with a reaction gas.[1–3]

The purity of gases utilized within the CRC is not often discussed beyond a mention in the methods section of ICP-MS related publications. Typically, instrument manufacturers recommend using a minimum gas purity of 99.999% (5N) to achieve the best results when using the CRC.[4] However, overall purity may not capture the effects of individual contaminants present at trace levels. For example, a 5N pure gas may behave differently if the 0.001% impurity is O_2 as compared to H_2O. In high purity gases (*e.g.*, O_2, CO_2, He, *etc.*) H_2O content can range from 0.2–2.0 ppm depending on the gas and the source. Further, the 5N recommendation, if followed, limits the gases that could be used within the CRC as some gases that may provide advantageous separations cannot be readily sourced at 5N purity (*e.g.*, NO, OCS, SO_2, *etc.*).

There have been limited studies focusing on the effects (both positive and negative) of gas impurities in collision/reaction gases despite early mentions of its significance.[5,6] Single quadrupole ICP-MS instruments do not mass filter ions created in the plasma prior to the CRC, which may result in undesirable reactions that produce interferences in the mass spectrum. On CRC single quadrupole instruments, Yamada *et al.*, reported that gas impurities in lower purity H_2 (99.99% compared to 99.999%) had a negligible effect on the reduction of argide (*e.g.* ArH^+, ArN^+, ArO^+) species and suggested that the most prevalent impurity was H_2O at concentrations < 100 μg g^{-1}.[5] Dexter *et al.*, reported that H_2O impurities present in collision gases (He) may be advantageous for the removal of some interferences; thus, controlling the H_2O impurities is necessary for reproducible results. The authors also report that H_2O impurities in a reactive gas mixture of H_2 and He (1.7 mL min^{-1} H_2 + 1.0 mL min^{-1} He) does not significantly alter the M^+ signal intensities at the flow rate used for the 22 elements assessed.[6] Consequently, the type of gas used (collision *versus* reaction) may dictate how gas impurities impact a given analysis.

A comprehensive review on reaction and collision cells by Tanner *et al.*, mentions that gas impurities potentially aid or hinder analyses using reaction gases. The authors state that the amount of impurity present within a gas has an increas-

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ingly significant effect as the gas flow increases that ultimately results in an increased number of reactant ion (M^+) collisions with the gas and impurities.[2] The added collisions slow the ions down within the CRC and ultimately increases the probability that M^+ will collide with the gas and the impurity(ies). Added collisions from gas impurities could allow for improved interference removal with collision gases as the ion kinetic energy of the polyatomic ions will be reduced further than the primary M^+ ion. Conversely, the reaction gas impurities could also cause a competitive or additional reaction to occur with the impurities resulting in a reduced sensitivity for a given reaction product.

In 2012, commercial inductively coupled plasma tandem mass spectrometers (ICP-MS/MS), with the CRC between two quadrupoles, were released. This provided the ability to mass filter ions prior to entering the CRC using the first quadrupole (Q1) and mass filter ions exiting the CRC with a second quadrupole mass filter (Q2) to better deconvolute ion/gas interactions in the CRC. The added mass filtering limits additional, unwanted reactions of other ions from occurring in the CRC. This capability has provided a significant advancement in the field of ICP-MS analyses, allowing additional interferences to be resolved.

To the authors best knowledge, investigations into collision/reaction gas purity have not been reported using ICP-MS/MS. The additional mass filtering available with ICP-MS/MS allows for conditions within the CRC to be limited to a single *m*/*z* interaction with the collision/reaction gas being used and any associated impurities. To address this knowledge gap, we have analyzed a lower purity gas (nitric oxide; NO 99.5%) for use in the CRC and the effects of using a gas purifier to reduce H_2O impurities to <100 pptV. A total of 60 elements were assessed for their reactivity with NO with and without the gas purifier in use. The full Q2 mass spectra were collected to determine common interferences. Additional experiments were performed using V, Ce, Tl and Th to investigate the effect of flow rate for the purified gas compared to the non-purified gas. The use of the purifier was found to eliminate several interferences, improve total ion sensitivity, and shift product distributions to favor the primary expected products (M^+, MN^+, MO^+ and MO_2^+). The use of a gas purifier provides an avenue to utilize gases that are limited to lower purities within the CRC to realize applications that were not previously feasible without the purifier.

Experimental methods

Stock standards (1000 μg g^{-1}; Inorganic Ventures) were used to prepare a 10 ng g^{-1} multi-element (ME) standard containing 60 elements (Li, Be, B, Na, Mg, Al, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, Rb, Sr, Y, Zr, Nb, Mo, Ru, Pd, Ag, Cd, In, Sn, Ba, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Re, Ir, Pt, Au, Tl, Pb, Bi, Th and U). Single element standards of V, Ce, Tl, and Th were prepared at 5 ng g^{-1} and 10 ng g^{-1} for the varying gas flow rate experiment. All standards were diluted with 2% HNO_3 (Optima Grade; Fisher Scientific; Pittsburgh, PA) and 18.2 MΩ cm deionized water.

All work was carried out using an Agilent 8900 ICP-MS/MS system equipped with an octopole-based CRC. Nitric oxide (NO; 99.5% purity; Advanced Specialty Gases; Reno, NV; Table S1†) was used as the reaction gas. Instrument parameters relating to the CRC are reported in Table S2† for each experiment. A general tuning scheme was used to ensure products would be detected across the entire mass range (6–238 amu). Experiments were performed initially without a gas purifier for the "un-purified" experiments. The specifications sheet for NO from the manufacturer list the H_2O content < 20 ppmV. "Purified" NO experiments were performed using an Entegris GateKeeper GPU WX Media gas purifier (GPU 70; Billerica, MA) in-line with the fourth cell gas line. The primary function of this purifier is to remove contaminant H_2O (<100 pptV; Table S1†) from the source gas. Similar to previous studies,[7–10] Q1 was fixed on a single ion *m*/*z* (the reactant ion, M^+) and Q2 was scanned from 2 to 275 *m*/*z* to observe all possible product species formed within the CRC and acquisition times were set to 0.1 s for each *m*/*z*. Multiple isotopes of each element were analyzed, where feasible, to ensure there are no additional spectra interferences for the products analyzed. The percent product formation was calculated by dividing the product produced by the sum of all Q2 species greater than 1000 cps.

To investigate the effect of flow rate, a subset of elements was selected ranging in mass and reactivity (V, Ce, Tl, and Th).[10] Based on previous work, these four elements show different levels of reactivity; Tl being unreactive, V being slightly reactive and Ce/Th being more reactive with NO.[10] Additionally, these 4 elements span a large mass range to ensure there were no mass bias effects. Each M^+ was analyzed in a 5 and 10 ng g^{-1} single-element standard with a 0.1 s acquisition time. The full Q2 mass spectra (amu 2–275) were collected to determine the change in hydride and oxy-hydride species along with any product distribution shifts. A total of five gas flows (0.00, 0.22, 0.45, 0.89, and 1.49 mL min^{-1}), including no gas, were assessed. These gas flows equate to approximated pressures of 0.00, 0.35, 0.71, 1.4, and 2.3 Pa. The octopole bias voltage (V_{oct}), used to control ion kinetic energy, and deflect voltage (focusing voltage applied after the octopole and prior to Q2) tuning parameters were adjusted with each gas flow (Table S2†) during tuning where Q1 → Q2 were monitored at *m*/*z* 205 → 205, 140 → 140 and 140 → 156 for optimal sensitivity. The V_{oct} and deflect settings were kept the same when analyzing a given gas flow with and without the purifier; these parameters were only changed between gas flows for maximum sensitivity.

For all experiments, product percentage was calculated by dividing the product signal by the sum of all major product signals observed (*e.g.*, $MO^+/\sum(M^+ + MO^+ + MO_2^+)$, *etc.*). Similarly, total ion sensitivity was calculated as the sum of all Q2 species observed, excluding the NO^+ signal (a product of a charge transfer reaction).

Results and discussion

The effects of NO purity on elemental analyses were investigated across the periodic table with and without the use of a gas purifier. For clarity, gas utilized directly from the manufacturer with no additional treatment will be referred to as "non-purified gas/NO" and gas purified with an Entegris GPU WX Media purifier prior to entering the CRC will be referred to as "purified gas/NO". Initial experiments were performed with a single gas flow rate (0.89 mL min^{-1}) analyzing 60 elements followed by a variable gas flow rate experiment focusing on four elements (V, Ce, Tl and Th). The following sections take an in-depth look at each step of the process where we first investigate total ion sensitivity (ion transmission), then changes in product distribution, and the effects of increasing NO flow rate (pressure).

Ion transmission

Total ion transmission was assessed by summing all significant Q2 signal intensities (>1000 counts per second) for each Q1 analyzed to compare ion transmission through the CRC with and without the purifier. Fig. 1 displays the normalized total ion transmission (purified signal/non-purified signal) for each Q1 analyzed at 0.89 mL min^{-1} NO (instrumental parameters are reported in Table S2†). Most elements show an increase in total ion transmission when using purified NO at 0.89 mL min^{-1} (Table S2;† $V_{\text{oct}} = -20.0$ V), except for Mg^+, Yb^+, Ta^+, and Au^+ (Fig. 1; Table S3†). The total decrease in ion sensitivity was 8%, 13%, 26% and 66% for Mg^+, Yb^+, Au^+, and Ta^+, respectively. Thus, the decreased sensitivity for Mg^+ and Yb^+ could be due to slight variability between the two analyses. Gold was the only element that became more reactive with the purified NO and the larger loss in total ion sensitivity may be due to the increased reactivity. The significant decrease in sensitivity for Ta^+ may be explained by the production of higher order products that have a $m/z > 275$. Other group 5 elements (V^+ and Nb^+) both formed products as high as M + 136 which would not be obtainable for ^{181}Ta due to the m/z limitations on the instrument. For elements that are primarily non-reactive (*e.g.*, ^{205}Tl, >99% remains at M^+) total ion transmission increased by ~25% when using purified NO (elements with a normalized sensitivity close to 1.0 in Fig. 1). This suggests that the lower total ion transmission observed for highly reactive M^+ in the non-purified gas may be caused by the reduced kinetic energy of the resulting products (formed upon collision/reaction) which allows for additional collisions and subsequent energy loss due to the larger cross-section of the polyatomic ions. The use of purified NO allows for higher gas flows to be used more practically because total ion sensitivity is

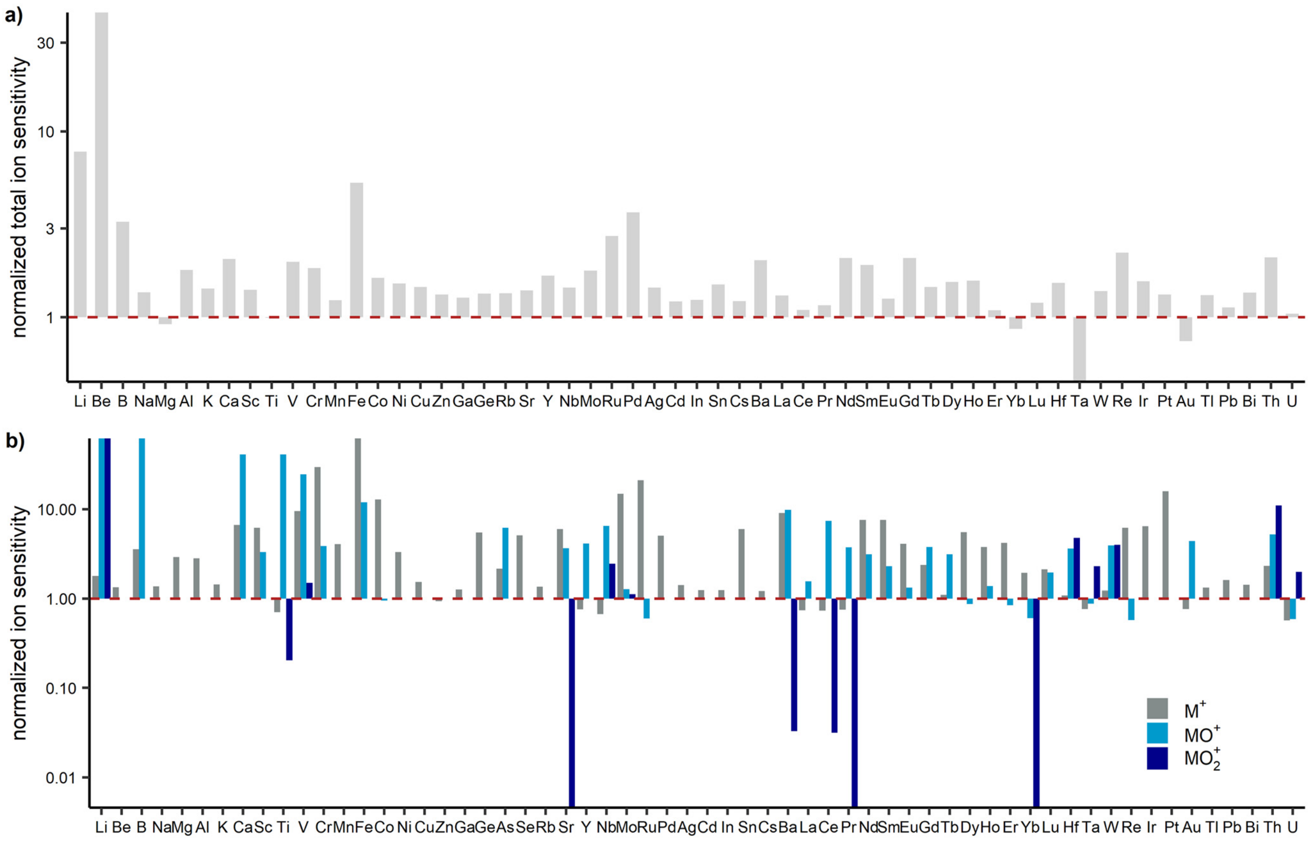

Fig. 1 (a) Normalized total ion transmission (sum of Q2 products > 1000 cps; purified signal/non-purified signal) for each Q1 analyzed at 0.89 mL min^{-1} NO. (b) Normalized ion sensitivity of the major products expected (M^+, MO^+, MO_2^+). The red dashed line represents a ratio of 1.0; thus, elements > 1.0 show enhanced ion transmission, elements < 1.0 shows decreased ion transmission when the purifier is used.

retained or enhanced. Without the purifier, the maximum gas flow has limited utility in most application spaces due to the significant loss in ion transmission leading to poorer detection limits. Purifying NO provides significant improvements in sensitivity allowing for analyses not previously feasible.

Lighter elements, Li, Be, and B, show a greater level of sensitivity enhancement when the purifier is used compared to other elements analyzed (Fig. 1). This mass dependent enhancement may be caused by to increased scattering occurring from gas escaping the CRC. Typically, lighter elements are scattered more than heavy elements and a larger amount of gas impurities appears to increase the amount of scattering observed. Assuming the primary impurity is H_2O, this effect could be primarily due to collisions outside of the octopole ion guide. Notably, H_2O is a notoriously difficult gas to remove from vacuum background, so removal from the reaction gas would lower the overall vacuum background decreasing the probability of a collision outside of the ion guide, ultimately resulting in higher sensitivity.

For ^{232}Th and ^{238}U, it is likely that there are missing products in the spectra because m/z = 275 is the maximum m/z on Q2 for the Agilent 8900. Previous guided ion beam mass spectrometry (GIBMS) studies show the hydrolysis of Th^+ to form $Th(OD)_3^+$ (m/z = 286) that likely supports the hypothesis that Th^+ is forming higher mass products that we cannot detect with current instrument limitations.[11] Furthermore, $^{140}Ce^+$, the lanthanide analog for $^{232}Th^+$, formed 12.5% $^{140}Ce^{16}O_3{}^1H_3^+$ at 0.89 mL min^{-1} (Fig. 2) without the purifier. It is suspected that this shift to higher order products (*e.g.*, ThO_3^+)[12] is greater with the purified gas, as more Th^+ collisions can occur with NO rather than the impurities. Further, the actinides have often showed greater reactivity and increased higher order products than other M^+.[10] While an increase in total ion transmission was observed for both Th and U, the total ion sensitivity (cps ppb^{-1}) for both elements is lower than expected when compared other high mass M^+ (*e.g.*, Tl, Pb or Bi).

Product distribution

The use of a gas purifier resulted in significant changes to the product distribution (Fig. 2 and 3), primarily resulting in a reduction of potential interferences and MO_xH_y production

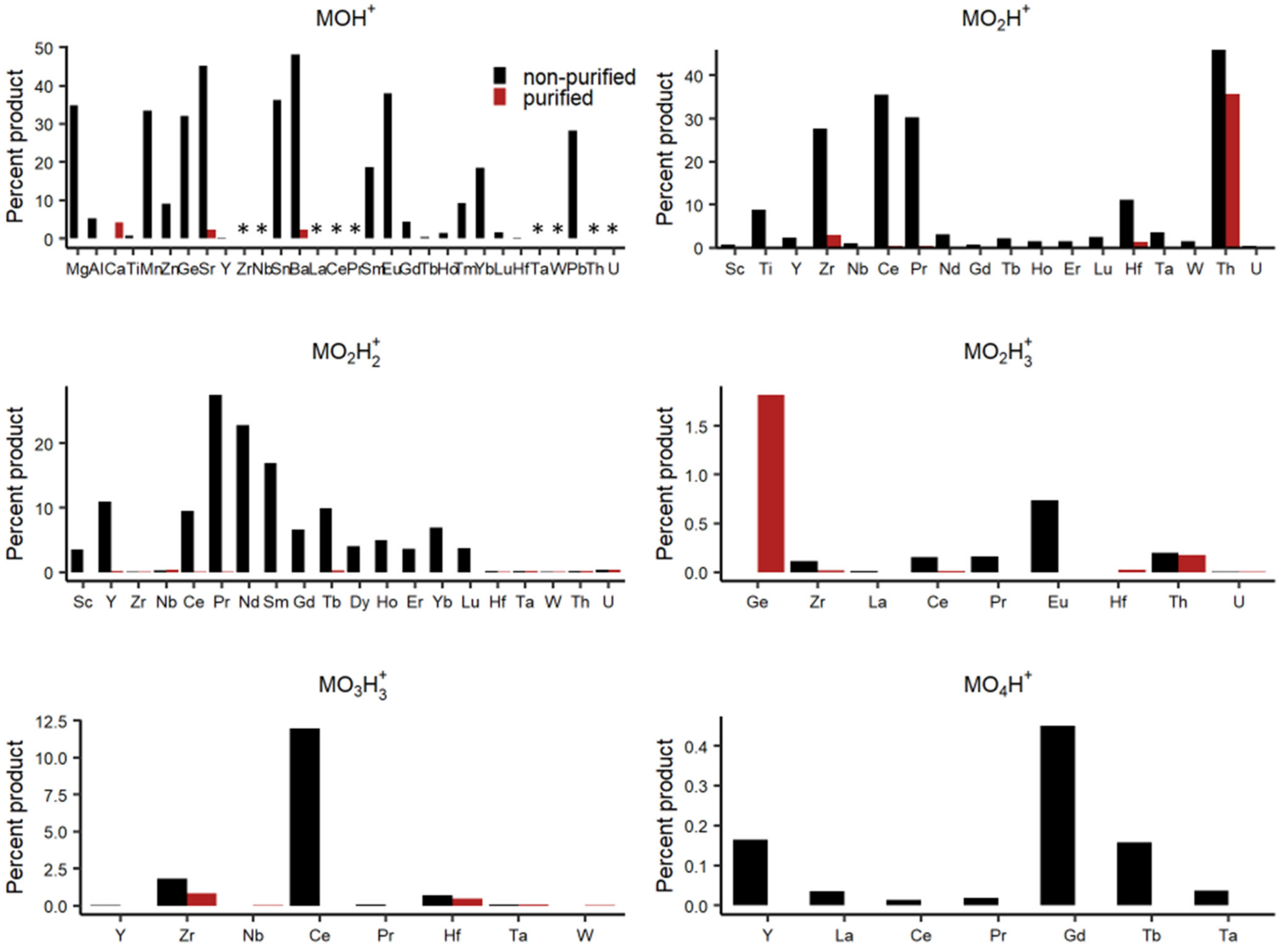

Fig. 2 Signal intensity (cps) of MOH^+, MO_2H^+, $MO_2H_2^+$, $MO_2H_3^+$, $MO_3H_3^+$, and MO_4H^+ for non-purified (red) and purified NO (black) at 0.89 mL min^{-1}. Only M^+ that resulted in a signal without the purifier are displayed. Note the scale change for each product reported. * MOH production was <0.1%.

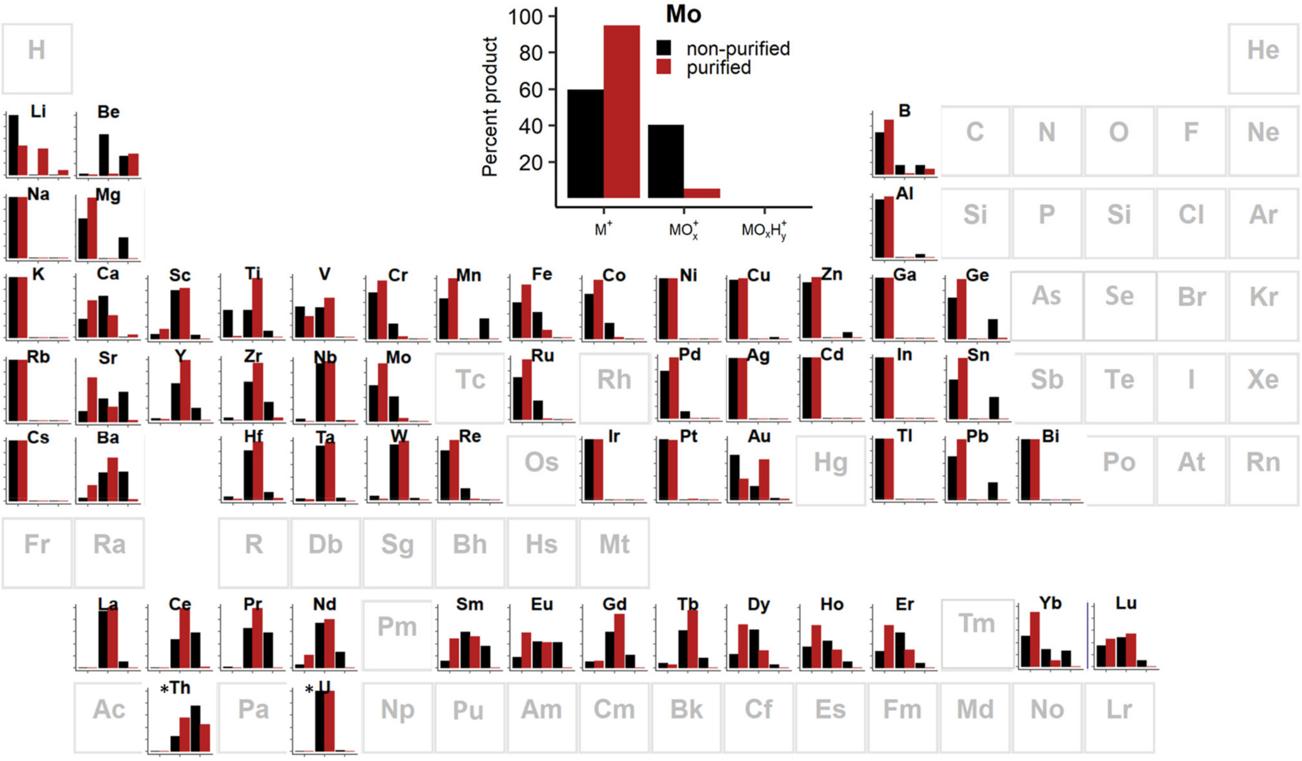

Fig. 3 Product distribution for M^+ analyzed using 0.89 mL min^{-1} NO. Results are shown as the percent product formed for M^+, a sum of the oxide products (MO_x; where x = 1, 2, 3, *etc.*), and a sum of the oxy-hydride products (MO_xH_y; where x and y = 1, 2, 3, *etc.*). MN^+ products were not included here as product formation was <2% for all elements (excluding Be, Mo, and Re [62%, 11%, and 6%, respectively] in the purified NO). The (*) notes that these ions may form higher order products that could not be analyzed fully based on the of max *m*/*z* of 275 on Q2. The Mo figure was expanded to show the axes labels; elements shown in grey text were not analyzed.

that resulted in an increased signal on the M^+ and/or MO_x^+ (where x = 1, 2, 3) products. Notably, many of the MO_xH_y products (*e.g.*, MOH^+, MO_2H^+, $MO_2H_2^+$, $MO_2H_3^+$, $MO_3H_3^+$, and MO_4H^+) were greatly reduced with the use of the purifier (Fig. 2). These products are suspected to be a result of M^+ reacting with H_2O present as an impurity in the NO gas as H_2O is the only hydride contaminating impurity expected in NO from the manufacturer's specifications. Notably, these oxy-hydride products can account for >30% of the product distribution (Fig. 2 and 3). This is a significant amount of signal distributed over multiple products, potentially decreasing the sensitivity of the product used for calibration/quantitation. Ratios of M + 17/M + 16, M + 33/M + 32, M + 34/M + 32, and M + 35/M + 32 (Table S4†) were assessed to determine if the species observed were primarily due to the natural isotopic abundance of oxygen or a result of the MO_xH_y product. In most cases, the oxy-hydride product was greatly reduced, and signal ratios approached the expected natural isotopic distribution of pure oxygen adducts. The absence of these products with the use of the purifier implies that these oxy-hydride species are only observed when higher concentrations of H_2O (and perhaps other constituents) are present as impurities within the NO.

Several elements (Be, V, Cr, Zr, Mo, Nb, Ru, Ce, La, Pr, and Re) had a larger percentage of MN^+ product in the purified NO as compared to the non-purified gas. V, Cr, Mo, and Ru had no detectable MN^+ product in the non-purified NO, but MN^+ was formed (<2%) when using the purified NO. The presence of impurities (presumably H_2O as this is the only impurity removed with the purifier used) may decrease the production of MN^+ by providing a more favorable reaction pathway for M^+, ultimately allowing the M^+ to react with the impurity(ies) rather than form the MN^+ product. Additionally, the impurities present in the non-purified gas can cause greater dispersion of the reactant ion kinetic energy, as compared to the purified gas, which can result in a shift of the product distribution. In this case, M^+ may retain more kinetic energy (or there is less dispersion in ion energy) which can result in increased MN^+ formation.

Several elements show a large shift in the product distribution when using the purified NO that have potential utility for a number of applications. For example, Au^+ has relatively low reactivity;[7–10] however, with the purifier added, additional AuO^+ is formed (Fig. 3). This suggests that Au^+ reactivity is suppressed by the impurities within the NO. Alternatively, PtO^+ was detectable in the non-purified NO but not with purified NO. Thus, the resulting increase in Pt on-mass sensitivity (M^+) was primarily due to the removal of the PtO^+ production, likely resulting from Pt^+ reacting with the impurities within the NO.

Increased sensitivity on a product used for analysis and a reduction in unwanted products may result in a novel analytical method previously determined unviable. For example, the on-mas sensitivity for Co increased by 12× when using the purifier. When examining the full spectra, it was found that a charge transfer reaction ($M^+ + NO \rightarrow NO^+ + M$) was occurring in the non-purified NO and, when using the purifier, the signal at NO^+ decreased by 7× along with a slight decrease in the CoO^+ product (~20%). Thus, purified NO reduced the number of unwanted products (NO^+ and CoO^+) and on-mass sensitivity was retained. This combination of the increased total ion sensitivity and product distribution shift is not unique to the analytes mentioned here and can provides improved detection limits for many analytical methods (Fig. 3).

There are limited reports for the use of NO in ICP-MS/MS applications,[10,13,14] with one paper specifically stating that NO (99.5%) produced excess hydrides that were problematic for the analysis of Pu isotopes.[14] Previous work from our group showed the utility of NO (99.5%) for Pu isotopes, despite the potential purity issues.[10] Variation in impurities in NO employed across studies may be reason for variations seen in analytical outcomes. Such analytical discrepancies may also be true for other gases of various source purity. Based on the product distribution shifts and the decreased production in hydride species observed when using purified NO, the ^{239}Pu measurement is likely to be improved by using NO with a purifier, which we will investigate in a future study.

When assessing the product distribution for ICP-MS/MS analyses, the largest gain is the improvement in total ion sensitivity and the product distribution shift that can increase sensitivity on a given product. For high resolution CRC-based instruments (*e.g.*, multi-collector (MC)-ICP-MS variations such as the Thermo Neoma or the Nu Sapphire), the impurities in a reaction gas can produce unfavorable products which can cause added interferences in the mass spectrum and greatly reduce the utility of reaction gases. Unlike the quadrupole-based instruments, the MC-ICP-MS variations do not mass filter at 1 amu resolution prior to the CRC. Thus, an increased background can be observed at unexpected masses when there are reactions occurring with gas impurities. Additionally, the higher extraction voltages used in MC-ICP-MS instrument results in more ions being extracted into the mass spectrometer and the use of non-purified gas may result in additional side reactions causing an increase in spectral interferences. Based on the purified NO data collected on the quadrupole ICP-MS/MS, it is predicted that spectral interferences on CRC-containing MC-ICP-MS may suffer from increased backgrounds resulting from reaction gas impurities. Thus, using purified reaction gases with MC-ICP-MS may be vitally important.

For NO specifically, the backgrounds are greatly reduced in the spectra across the entire mass range when using the purified form. The reduction in oxy-hydride species results in a product distribution favoring the major expected products (*e.g.*, M^+, MN^+, MO^+ and MO_2^+), which alone can increase signal by as much as 40% and significantly improve detection limits. The use of purified NO enables analyses that were not previously obtainable by removing additional background interferences and improving product sensitivity as a result of fewer products being produced.

Pressure (flow rate) effects

To examine the effects of pressure (flow rate), four M^+ (V, Ce, Tl, and Th) were analyzed at four flow rates (0.00, 0.22, 0.45, 0.89, and 1.49 mL min^{-1}) and the resulting spectra were compared (Fig. 4). Calculations were performed using previously reported methods[7–10] to predict the number of non-reactive M^+ collisions feasible within the CRC. Table S5† reports the percent probability of M^+ experiencing 0 to 40 collisions within the CRC and notes the most probable number of collisions. Previous reports have provided discussions on the importance of the number of ion collisions within the CRC.[7–10] In short, when the focus is on M^+ collisions with the bulk gas (NO in this case), the number of unreactive collisions is directly related to the ion energy within the collision reaction cell.[2] With each collision, the ion loses energy which can ultimately affect whether a reaction is observed. The maximum number of collisions with NO has been estimated to be ~40 at 1.49 mL min^{-1} (Table S5†). Using the hard sphere model, the number of collisions with H_2O as a gas impurity at 20 mg L^{-1} would then be assumed to be <1 collision; however, the experimental results in the previous sections show that this is not the case. The hard sphere model does not account for parameters such as dipole moment or polarity; thus, for molecules like H_2O the hard sphere model may be greatly under reporting the number of expected collisions. In general, the collisional cross section of H_2O is much larger than the geometric cross section due to the polarity and the number of collisions is expected the be greater than predicted using the hard sphere model. Additional modelling of the impurities within the CRC gases should look to include additional parameters to more accurately predict the reactions of the impurities, like H_2O, in the CRC.[2]

At low flow rates there are subtle differences observed in product formation which become more pronounced as gas flow/pressure increases (Fig. 4). For example, CeO^+ formation is 16% greater with the purified gas compared to non-purified at 0.22 mL min^{-1}, while at the higher flow rate (1.49 mL min^{-1}) CeO^+ formation is 38% greater for the purified gas (Fig. 4a). A greater quantity of MO_xH_y species is formed as gas flow increases both with and without using the purifier (Fig. 4b). Similarly, previous work using selection-ion flow tube mass spectrometry (SIFT-MS), where total pressure in the flow tube is 0.3–0.5 Torr of He with trace reaction gas, has shown that Ce readily reacts with D_2O to form both CeO^+ and higher order products ($CeO^+(D_2O)_{1-5}$) in subsequent collisions.[15] The conditions in SIFT-MS are similar to the work presented here where H_2O is a trace impurity within the NO gas, except NO is more reactive than He. Nevertheless, at higher flow rates the ions in ICP-MS/MS are expected to thermalize so the reaction with NO likely only proceeds when the reaction is exothermic. Under these conditions, ICP-MS/MS and SIFT-MS are likely very similar, so reactions with a trace impurity do occur. For other M^+ that are still reactive with NO, the increased oxy-

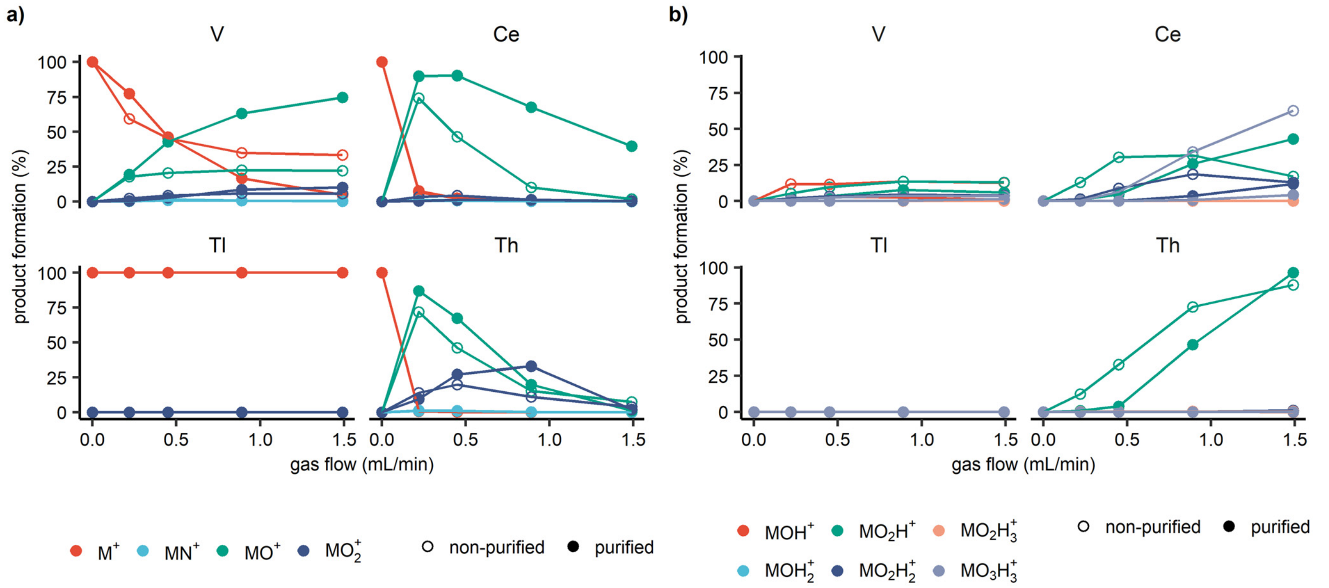

Fig. 4 Percentage of product species formed for ^{51}V, ^{140}Ce, ^{205}Tl, and ^{232}Th as a function of NO flow (mL min^{-1}) with (filled points) and without (open points) the gas purifier. (a) Shows the primary, expected products to be formed with NO (M^+, MN^+, MO^+, and MO_2^+), while (b) shows the formation of the impurity-reacted products (MOH^+, MOH_2^+, MO_2H^+, $MO_2H_2^+$, $MO_2H_3^+$, and $MO_3H_3^+$). Note that the ThO_3 and respective oxy-hydrides are not measured due to the Q2 *m*/*z* limitations.

hydrides at higher flow rates suggest that even at <100 pptV H_2O remaining in the NO reaction gas. For some elements (*e.g.* Ce and Th), the reaction kinetics of M^+ with the impurities (primarily expected to be H_2O) can still be favored over NO because of the strong H_2O dipole moment. Nitric oxide has a weaker dipole moment that H_2O; thus, the collision radius of H_2O will be much larger than that of NO. Further discussion of the effect of the dipole moment on collision rates can be found elsewhere.[16,17] Furthermore, H_2O is also favored thermodynamically by ~1.5 eV for oxidation reactions.

Non-reactive elements like Tl (>99% remains at M^+) retain total ion sensitivity across all gas flows used; while the more reactive elements (V, Ce, and Th) lose sensitivity as the gas flow increases (Fig. S1†). When comparing the total ion sensitivity for the lowest (0.22 mL min^{-1}) and highest (1.49 mL min^{-1}) pressure, Tl sensitivity only decreased by ~1.5× regardless of whether the purifier is used, while Th sensitivity decreased by ~22× with the purifier and by ~130× without the purifier (Fig. S1†). The purifier had a greater impact on total ion sensitivity at 1.49 mL min^{-1} (Fig. 5), while at 0.22 mL min^{-1} limited improvement was observed. This is in agreement with Tanner *et al.*, 2002 who reported that under multiple-collision conditions (*i.e.*, higher gas flows/pressures) gas purity becomes exceedingly important as trace impurities can impact the observed reactions if the reaction pathways favor the impurity reaction over the reaction gas.[2]

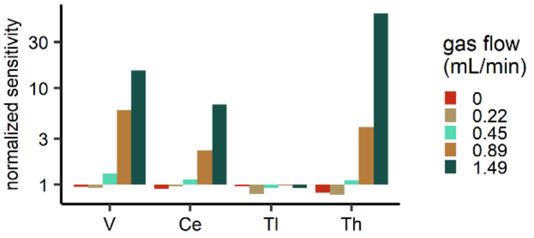

Fig. 5 Normalized total ion transmission (sum of all Q2 products; cps) as a function of NO flow for ^{51}V, ^{140}Ce, ^{205}Tl, and ^{232}Th, when using purified NO normalized to non-purified NO signal. Elements > 1.0 show enhanced ion transmission, elements < 1.0 show decreased ion transmission.

The number of collisions, and thus the gas pressure, is an important driver of the reactions occurring within the CRC. Previous work with NO (0.22 mL min^{-1}) has shown the collisional probability distribution using the hard sphere model, which does not account for polarizability or dipole moment.[10] With each (non-reactive) collision, the kinetic energy (KE) of the reactant ion decreases which effects the probability a given reaction will occur. At low flow rates (fewer collisions) in the ICP-MS/MS the hard sphere model provides a reasonable estimate of the number of collisions and the subsequent energy of each ion after collision. Previous work with CO_2 has shown that the Langevin Gioumousis Stevenson (LGS) model (which accounts for polarizability) provides a more accurate explanation of the expected chemistry, especially at lower energies (<1 eV).[18] Specifically, Cox *et al.*, found that the collisional probability distribution is bimodal with the LGS model which leads to a higher energy ion population with few collisions and a thermalized ion population from many collisions. As the gas pressure increases the distribution shifts to favors a thermalized distribution. Note that CO_2 is not polar, but both H_2O

and NO are. The Su–Chesnavich trajectory model incorporates the dipole into the LGS model. The polarizability of NO and H_2O are 1.7 and 1.45 Å^3, respectively. The dipole moments are 0.16 and 1.84 D.[16,19] The theoretical probability of collision for H_2O will increase at a greater rate than that of NO due to the size and polarizability of H_2O. For reference, the trajectory cross sections at 300 K (*i.e.* thermal distribution) for NO and H_2O are 120 and 390 Å^2. Therefore, as the NO pressure increases, additional collisions with H_2O impurities are expected to be greatly increased. When weighted against prevalence, the advantage of H_2O is diminished, but reactions with H_2O are ~1.4 eV more favorable thermodynamically based on differences in neutral bond energies. Furthermore, as seen in the SIFT-ICP-MS reactions, H_2O tends to form clusters that further increase contact and subsequent collisions. This is clearly observed in Fig. 4, where the impurity-reacted products exceed that of the NO-reacted products.

Additionally in Fig. 4, there is a large increase in the MO_2H^+ product for Ce and Th in the purified gas at 1.49 mL min^{-1}, which was not anticipated. Upon closer investigation, there is a potential reaction pathway for the removal of an H_2O adduct from the higher order product ($MO_3H_3^+$) upon additional collisions, resulting in increased MO_2H^+. Due to the increased number of collisions there would be a higher probability of removing this H_2O adduct at the higher flow rates. Another potential pathway could be through the increased formation of MO_2^+ when the purifier is used, which collides with a H-containing gas impurity, resulting in the MO_2H^+ formation. Understanding the fundamental chemistry and how the gas impurities effect the chemistry occurring within the CRC is important to interpreting the resulting spectra and ultimately finding ways to mitigate unwanted side reactions and exploit advantageous chemistry.

Conclusions

The use of purified NO (<100 pptV H_2O) in the CRC of an ICP-MS/MS was shown to completely mitigate several MO_xH_y interferences, improve total ion sensitivity (especially notable at high gas flows), and shift product distributions. Previous reports on the use of NO have suggested that hydride formation, as a result of gas purity, can be problematic for NO to be useful as a reaction gas.[14] Thus, utilizing a gas purifier may allow for lower purity gases to be assessed for various analytical applications. While gas purity for CRC-based single quadrupole ICP-MS instruments was evaluated in the early 2000s with initial suggestions on how gas purity may impact a measurement,[1–3] the advent of instrument designs with mass filtering capabilities between the ion source (plasma) and before the CRC creates conditions within the cell that can be well-controlled. As such, gas purity and its effects on ion reactivity can be studied with much greater sensitivity. Thus, gas purity has become vitally important to understanding fundamental reactions occurring within the CRC and to investigate additional gases for use in analytical applications.

The gas purifier used in this experiment is anticipated to reduce H_2O to <100 pptV, while typical 5N pure gases are specified to have <1 ng g^{-1} H_2O. This difference in specifications may mean that even gases with 5N purity can benefit from using a gas purifier. Further, it is important to note that the reproducibility of ICP-MS/MS results across different systems/labs may vary depending on the purity of the gas being used. This can be especially true when looking at general reactivity experiments and methods comparing separation factors amongst different labs.

Gas purity may be more important in single quadrupole instruments since additional interferences are being directed into the CRC, which suggests that higher resolution ICP-MS instruments that are beginning to utilize CRC technology (*e.g.*, Thermo Neoma, Nu Sapphire) may also be greatly affected by collision/reaction gas purity. These higher resolution instruments are more sensitive to the impurity reactions that may occur within the CRC as ions from the CRC are extracted at a high voltage prior to mass separation.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

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References

1 D. R. Bandura, V. I. Baranov and S. D. Tanner, Reaction chemistry and collisional processes in multipole devices for resolving isobaric interferences in ICP-MS, *Fresenius' J. Anal. Chem.*, 2001, 454–470.
2 S. D. Tanner, V. I. Baranov and D. R. Bandura, Reaction cells and collision cells for ICP-MS: A tutorial review, *Spectrochim. Acta, Part B*, 2002, **57**(9), 1361–1452.
3 S. D. Tanner, V. I. Baranov and U. Vollkopf, Dynamic reaction cell for inductively coupled plasma mass spectrometry (ICP-DRC-MS). Part III. Optimization and analytical performance, *J. Anal. At. Spectrom.*, 2000, **15**(9), 1261–1269.
4 Agilent Technologies, Agilent 8800 Triple Quadrupole ICP-MS Hardware Maintenance Manual, pp. 1–178.

5 N. Yamada, J. Takahashi and K. Sakata, The effects of cell-gas impurities and kinetic energy discrimination in an octopole collision cell ICP-MS under non-thermalized conditions, *J. Anal. At. Spectrom.*, 2002, **17**(10), 1213–1222.

6 M. A. Dexter, P. K. Appelblad, C. P. Ingle, J. H. Batey, H. J. Reid and B. L. Sharp, The effect of adventitious water in hexapole collision cell inductively coupled plasma mass spectrometry, *J. Anal. At. Spectrom.*, 2002, **17**(3), 183–188.

7 A. D. French, K. M. Melby, R. M. Cox, E. Bylaska, G. C. Eiden, E. W. Hoppe, *et al.*, Utilizing metal cation reactions with carbonyl sulfide to remove isobaric interferences in tandem inductively coupled plasma mass spectrometry analyses, *Spectrochim. Acta, Part B*, 2023, **207**, 106754.

8 K. Harouaka, C. Allen, E. Bylaska, R. Cox, G. Eiden, M. L. di Vacri, *et al.*, Gas-phase ion-molecule interactions in a collision reaction cell with QQQ-ICP-MS: Investigations with N_2O as the reaction gas, *Spectrochim. Acta, Part B*, 2021, 106309.

9 K. Harouaka, K. M. Melby, A. D. French, R. M. Cox, E. J. Bylaska, G. C. Eiden, *et al.*, Gas-phase ion-molecule interactions in a collision reaction cell with QQQ-ICP-MS: Investigations with CO_2 as the reaction gas, *Geostand. Geoanal. Res.*, 2022, **46**, 387–399.

10 K. P. Hobbs, A. D. French, K. M. Melby, E. J. Bylaska, K. Harouaka, R. M. Cox, *et al.*, Assessing Gas-Phase Ion Reactivity of 50 Elements with NO and the Direct Application for ^{239}Pu in Complex Matrices Using ICP-MS/MS, *Anal. Chem.*, 2024, **96**, 5807–5814.

11 A. Kafle and P. B. Armentrout, Mechanism and Energetics of the Hydrolysis of Th^+ to Form $Th(OD)_3^+$: Guided Ion Beam and Theoretical Studies of ThO^+, ThO_2^+, and $OThOD^+$ Reacting with D_2O, *J. Phys. Chem. A*, 2019, **123**(28), 5893–5905.

12 P. B. Armentrout and K. A. Peterson, Guided ion beam and quantum chemical investigation of the thermochemistry of thorium dioxide cations: Thermodynamic evidence for participation of f orbitals in bonding, *Inorg. Chem.*, 2020, **59**, 3118–3131.

13 S. D. Tanner, C. Li, V. Vais, V. I. Baranov and D. R. Bandura, Chemical resolution of Pu^+ from U^+ and Am^+ using a band-pass reaction cell inductively coupled plasma mass spectrometer, *Anal. Chem.*, 2004, **76**(11), 3042–3048.

14 M. Matsueda, T. Kawakami, K. Koarai, M. Terashima, K. Fujiwara, K. Iijima, *et al.*, Using CO_2 Reactions to Achieve Mass-spectrometric Discrimination in Simultaneous Plutonium-isotope Speciation with Inductively Coupled Plasma-Tandem Mass Spectrometry, *Chem. Lett.*, 2022, **51**(7), 678–682.

15 P. Cheng, G. K. Koyanagi and D. K. Bohme, Gas-phase reactions of atomic lanthanide cations with CO_2 and CS_2: Room-temperature kinetics and periodicities in reactivity, *J. Phys. Chem. A*, 2006, **110**(47), 12832–12838.

16 T. Su, Parametrization of kinetic energy dependences of ion–polar molecule collision rate constants by trajectory calculations, *J. Chem. Phys.*, 1994, **100**(6), 4703.

17 T. Su and W. J. Chesnavich, Parametrization of the ion–polar molecule collision rate constant by trajectory calculations, *J. Chem. Phys.*, 1982, **76**(10), 5183–5185.

18 R. M. Cox, K. Harouaka, M. Citir and P. B. Armentrout, Activation of CO_2 by Actinide Cations (Th^+, U^+, Pu^+, and Am^+) as Studied by Guided Ion Beam and Triple Quadrupole Mass Spectrometry, *Inorg. Chem.*, 2022, **61**(21), 8168–8181.

19 Computational Chemistry Comparison and Benchmark Database [Internet], 2022, available from: **https://cccbdb.nist.gov/**.