Agilent 8900 Triple Quadrupole ICP-MS

Technical Overview

Introduction

Agilent is the worldwide market leader in quadrupole ICP-MS, and the only supplier of triple quadrupole ICP-MS (ICP-QQQ).

Introduced in 2012, ICP-QQQ has transformed interference removal in ICP-MS, using MS/MS to control reaction chemistry and deliver consistent, reliable results in reaction mode. The Agilent 8900 ICP-QQQ builds on the success of the Agilent 8800 ICP-QQQ, with enhanced performance to improve the ultra-trace measurement of difficult analytes, coupled with ease of use and productivity tools to enable a wider range of applications to be run.

Interference control in quadrupole ICP-MS and ICP-QQQ

Agilent's 7800 and 7900 quadrupole ICP-MS instruments offer market-leading collision reaction cell (CRC) performance for controlling polyatomic interferences using helium (He) collision mode. This performance advantage is a key reason why Agilent is the worldwide market leader in quadrupole ICP-MS (ICP-QMS).

Agilent's He mode reduces common matrix-based polyatomic ions, improving accuracy for typical analytes in common sample types. But some analytes, sample types and interferences cannot be addressed adequately using collision mode. Examples include trace level measurement of elements such as silicon, phosphorus and sulfur, ultra-trace analysis of high purity materials and semiconductor process chemicals, and the resolution of doubly-charged and isobaric overlaps. In these cases, reactive cell gases may offer a superior approach to separating the interferences. However, reaction mode does not offer a reliable solution on conventional quadrupole ICP-MS, because such instruments do not have a mass filter before the CRC. This means that the ions that enter the cell will vary depending on the sample composition, so the reaction chemistry varies and therefore the measured ion/product ion spectrum is not consistent.

Se measurement in mass-shift reaction mode: conventional ICP-QMS vs. ICP-QQQ

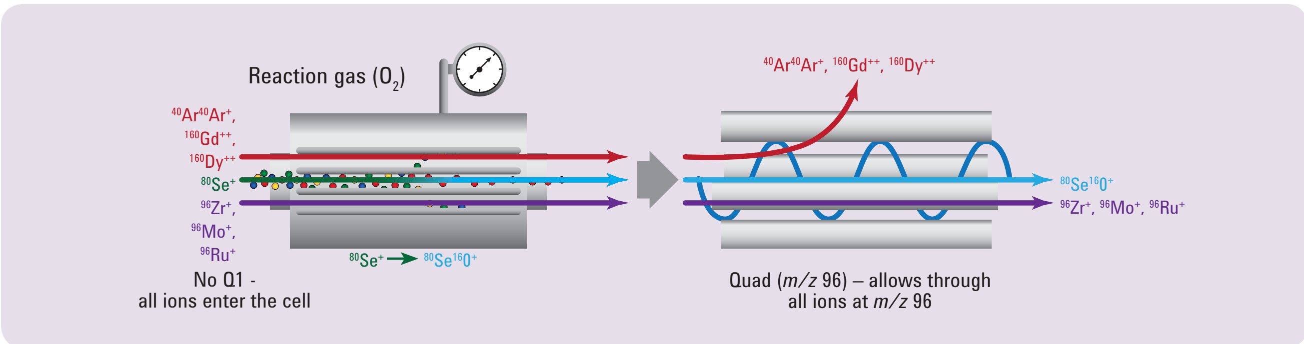

Figure 1A: Conventional ICP-QMS. Using O_2 reaction gas, Se is reacted away from interferences (Ar_2^+, Gd^{++} and Dy^{++}) at *m/z* 80. $^{80}Se^+$ is converted to $^{80}Se^{16}O^+$ in the cell and measured at *m/z* 96. However, Zr, Mo and Ru all overlap at *m/z* 96, leading to incorrect Se data

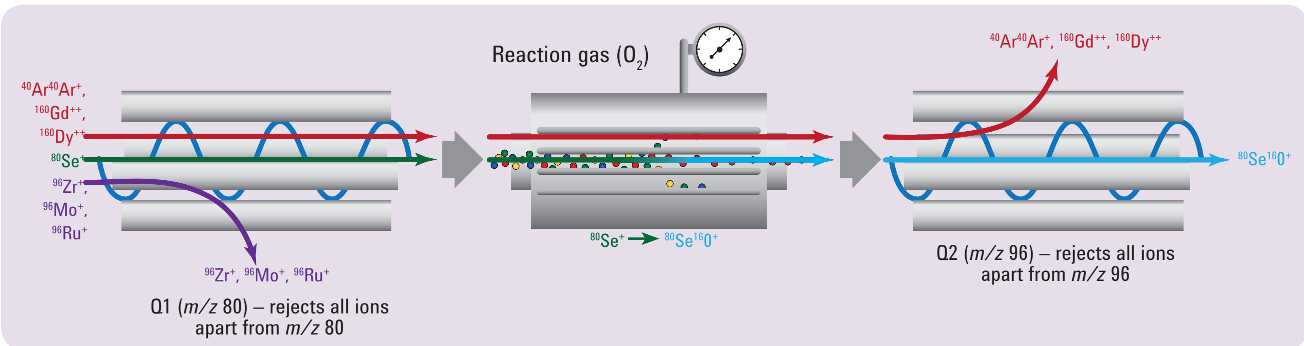

Figure 1B: ICP-QQQ. Q1 allows only ions at *m/z* 80 to pass to the cell – all other ions are rejected. $^{80}Se^+$ is converted to $^{80}Se^{16}O^+$ in the cell with O_2 reaction gas. Q2 measures SeO^+ at *m/z* 96. Zr, Mo and Ru cannot interfere since they were rejected by Q1.

The first triple quadrupole ICP-MS

In 2012, Agilent introduced the world's first triple quadrupole ICP-MS, the Agilent 8800 ICP-QQQ—a break-through instrument that extended the performance capability and scope of ICP-MS. The tandem mass spectrometer (MS/MS) configuration of ICP-QQQ uses two quadrupole mass filters, Q1 and Q2, separated by an Octopole Reaction System (ORS) CRC.

ICP-QQQ outperforms conventional quadrupole ICP-MS for established applications, and provides far superior control of interferences in reaction mode, due to the additional quadrupole (Q1) positioned before the CRC. This additional mass filter enables MS/MS operation, where both Q1 and Q2 are operated as unit mass filters; Q1 rejects non-target masses, so the ions that enter the cell are independent of the sample matrix composition. This means that ion-molecule reaction chemistry is predictable and consistent, so results are reliably accurate, and detection limits (DLs) are improved for challenging applications that require a reactive cell gas. The basic functional differences between ICP-QMS and ICP-QQQ are represented in Figures 1A and 1B, using the analysis of selenium as an example.

The selectivity of reaction chemistry enables ICP-QQQ to achieve some unique and remarkable performance capabilities. One example is the ability to use a reaction gas to separate direct isobaric overlaps, where isotopes of two different elements occur at the same mass, such as $^{204}Hg/^{204}Pb$. Many direct isobaric overlaps would require a mass resolution (M/ΔM) of several 100,000 to separate them, far beyond the capability of high-resolution sector field ICP-MS, which is limited to a maximum resolution of 10,000.

MS/MS mode is also fundamental to the superior peak separation of the QQQ configuration. Abundance sensitivity (AS) is a measure of the contribution that an intense peak makes to the adjacent masses. A typical quadrupole ICP-MS has an AS specification of 10^{-7}, but ICP-QQQ has two quadrupoles, and the AS is the product of Q1 AS x Q2 AS, so theoretically could achieve an overall AS of 10^{-14}. While this figure cannot be verified experimentally, as the sensitivity difference exceeds the dynamic range of the detector, ICP-QQQ has been shown to provide vastly superior peak separation in a range of applications including trace boron in organic solvents, ultra-trace manganese in iron and whole blood, and trace analysis of radio isotopes such as U-236 and I-129.

As a result of the range of unique performance capabilities demonstrated by the Agilent 8800, ICP-QQQ has been rapidly accepted and is now widely used in high-tech industries, research labs and for routine applications in various fields [1, 2, 3].

Second generation ICP-QQQ

Agilent's second generation triple quadrupole ICP-MS, the 8900, provides performance and productivity improvements compared to its predecessor. It offers increased matrix tolerance (up to 25% dissolved solids), higher sensitivity, lower backgrounds for S and Si, and more flexible cell gas options. The 8900 ICP-QQQ also has a new detector with fast Time Resolved Analysis (TRA) capability for single nanoparticle analysis, and a dynamic range of up to 11 orders of magnitude.

The 8900 ICP-QQQ consists of a single, high-performance mainframe with one standard configuration and two application-specific configurations, to address the wide range of customer requirements from research to routine applications:

- Agilent 8900 Standard configuration—provides higher performance than quadrupole ICP-MS for typical applications in food, environmental, nanoparticle characterization, geological and clinical-research laboratories.
- Agilent 8900 #100 Advanced Applications configuration—suitable for materials analysis, life science, low level Si and S analysis, and research. This instrument offers higher sensitivity specification; improved cell performance; low Si and S background; wider dynamic range.
- Agilent 8900 #200 Semiconductor configuration—includes inert sample introduction; Pt interface cones; highest sensitivity; lowest DLs and cool plasma capability providing the highest performance for high purity semiconductor reagents.

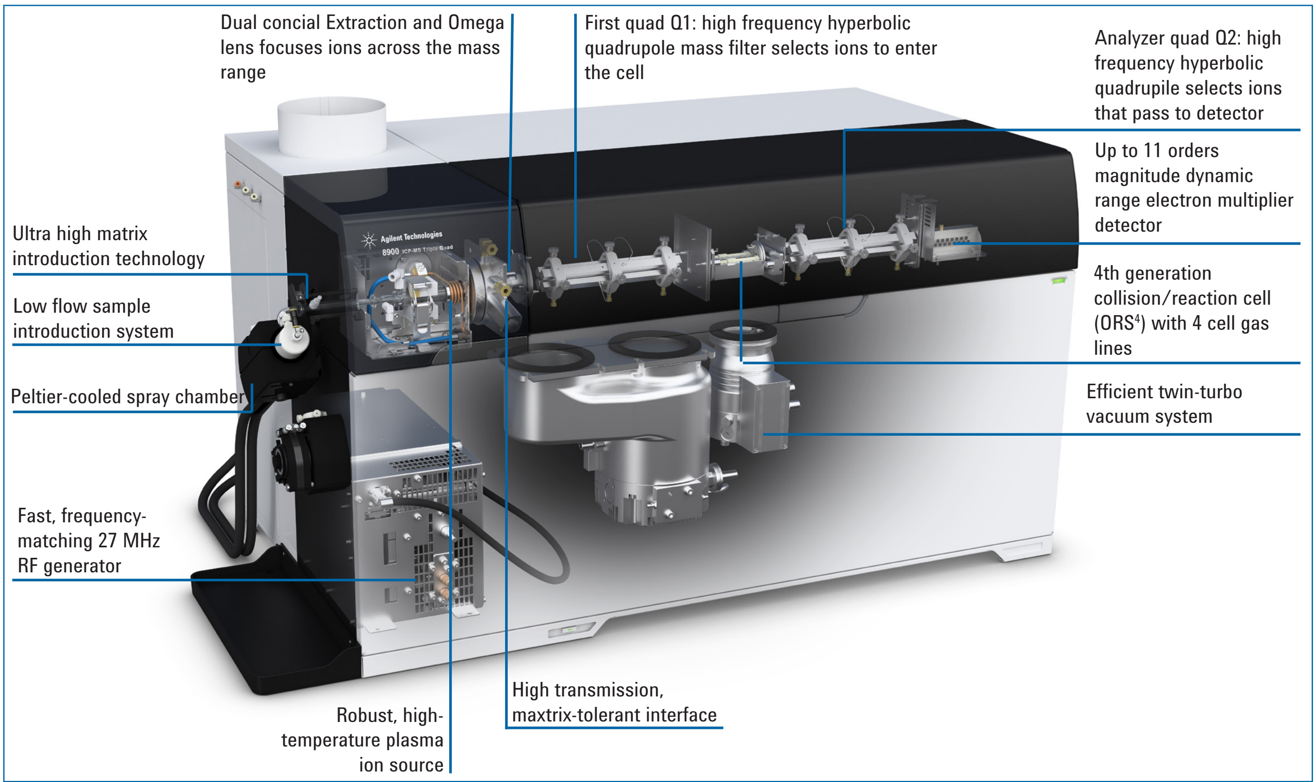

Figure 2. Schematic showing key hardware components of the Agilent 8900 ICP-QQQ

Technology advancements deliver improved performance for many applications

The Agilent 8900 ICP-QQQ builds on the success of the previous 8800 model, improving key performance capabilities and extending the range of applications that can be addressed.

Drawing on the experience of several hundred 8800 users, and taking account of emerging and developing application requirements, the 8900 introduces new hardware and software developments to enhance performance for a wider range of applications:

- Ultra high matrix introduction (UHMI) capability on the 8900 Standard and Advanced Applications configurations. UHMI uses Agilent's proprietary aerosol dilution technique to extend matrix tolerance up to 25% total dissolved solids (TDS), matching the market-leading robustness of Agilent's quadrupole ICP-MS systems.
- The 8900 Advanced Applications and Semiconductor configurations use a new argon gas flow system which utilizes materials that minimize silicon and sulfur background. This enables a detection limit specification of 50 ppt to be achieved for both of these elements, which were previously difficult to measure at trace levels using ICP-MS.
- Sensitivity is increased through a new interface vacuum stage, which improves ion transmission, increasing sensitivity by up to a factor of two compared to the 8800.
- A new, fourth generation, four channel ORS^4 collision reaction cell increases flexibility by supporting a wider range of reaction gases. On the 8900 Advanced Applications and Semiconductor configurations, the ORS^4 includes axial acceleration, which further enhances sensitivity by increasing the axial energy of slow-moving product ions and suppressing the formation of higher-order product ions.

- A new on-axis, high-gain electron multiplier detector supports fast TRA acquisition, with minimum dwell times of 0.1 ms to enable single nanoparticle characterization (spICP-MS). The detector dynamic range is extended up to 11 orders for the 8900 Advanced Applications and Semiconductor configurations (10 orders dynamic range for the 8900 Standard configuration).
- High throughput routine applications are supported on the 8900 ICP-QQQ, with increased productivity delivered by Agilent's optional ISIS 3 Integrated Sample Introduction System accessory.
- Agilent's ICP-MS MassHunter 4.3 software platform, used for all current quadrupole ICP-MS and ICP-QQQ systems, includes an improved Method Wizard to simplify and accelerate method setup. A wider range of Pre-set Methods is provided, and additional method-specific report templates are included. ICP-MS MassHunter's optional Intelligent Sequencing QA/QC software module now supports ICP-QQQ, as well as quadrupole ICP-MS.

Key features of the Agilent 8900 ICP-QQQ instrument are shown in Figure 2.

Performance characteristics of the Agilent 8900 ICP-QQQ

High sensitivity

Sensitivity and signal-to-noise (S/N) are fundamental performance parameters for ICP-MS. The 8900 ICP-QQQ is equipped with a high sensitivity vacuum interface (the first vacuum stage), which has been field-proven on Agilent's 7900 quadrupole ICP-MS. The extraction lens system has also been optimized to maximize ion transmission with the new vacuum interface, so the 8900 ICP-QQQ Advanced Applications and Semiconductor configurations now deliver double the sensitivity of the equivalent 8800 models.

Recognizing the application requirements of different industries, the 8900 Semiconductor configuration uses a special design of extraction lens that is suitable for the high-sensitivity, low detection limit requirements of the semiconductor industry. This "s-lens" provides higher sensitivity under normal hot plasma conditions than the "x-lens" used on the Standard and Advanced Applications configurations, and also supports reliable cool plasma performance. The x-lens is suitable for general applications which require good sensitivity under the robust, hot plasma conditions used for measuring high matrix samples (typical $CeO^+/Ce^+ \leq 1\%$).

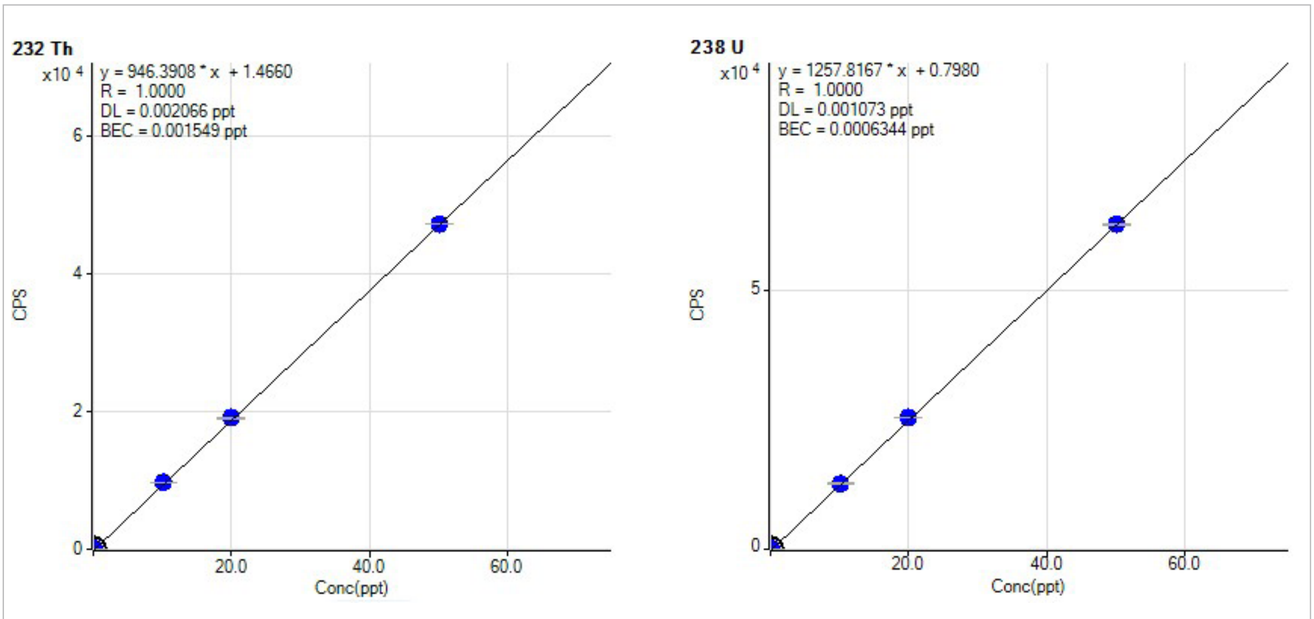

Figure 3. Calibration curve of ^{232}Th (left) and ^{238}U (right). The DLs were calculated as three times the standard deviation of 10 replicate analyses of the calibration blank with a 3 s integration time

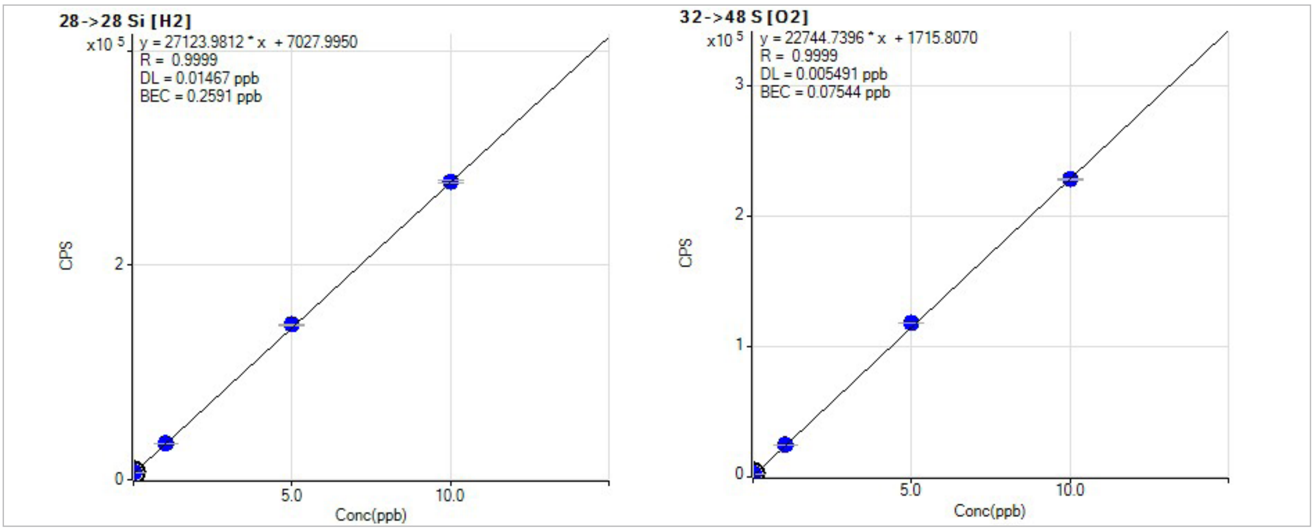

Figure 4. Left: calibration curve of silicon in in MS/MS on-mass mode using H_2 cell gas; a DL of 15 ppt was achieved. Right :calibration curve of sulfur in MS/MS mass-shift mode using O_2 cell gas; a DL of 5 ppt was achieved.

The sensitivity specifications for yttrium on the 8900 Advanced Applications and Semiconductor configurations are 700 Mcps/ppm and 1.2 Gcps/ppm, respectively. Figure 3 shows calibration curves for Th and U with standards at 10, 20 and 50 ppt obtained using the 8900 Advanced Applications configuration. The calibration curves demonstrate how the combination of high sensitivity and ultra-low background noise (specification of < 0.2 cps) allow the 8900 ICP-QQQ to achieve DLs of 1–2 ppq.

Low sulfur and silicon analysis capability

While quadrupole ICP-MS achieves sub-ppt level DLs for most commonly-measured elements, trace analysis of certain unusual elements remained challenging for ICP-MS until the introduction of ICP-QQQ. Elements such as Si and S suffer severe spectral interferences from CO^+ & N_2^+ and O_2^+, respectively. ICP-QQQ can utilize MS/MS methods to resolve the spectral interferences efficiently, but the DLs achievable remain relatively high due to background contamination.

Si and S are ubiquitous in laboratory consumables, supplies, and many of the materials used in instrument components, leading to a high background. To minimize the contribution from the ICP-MS hardware, key components of the 8900 Advanced Applications and Semiconductor configuration ICP-QQQ have been replaced using more inert materials. This has successfully reduced the background signal for S and Si, allowing a DL specification of < 50 ppt for S, Si and P to be set; this limit is verified on every Advanced Applications and Semiconductor configuration instrument during factory testing. This DL performance is unprecedented in ICP-MS, and provides a major breakthrough for applications where trace Si and/or S analysis is required, including life science, pharma/biopharma, petrochemical and other applications. Figure 4 shows calibration curves for Si and S in ultra-pure water (UPW), demonstrating DLs of 15 ppt for Si and 5 ppt for S [4].

ORS[4] CRC with axial acceleration

All of Agilent’s current ICP-MS and ICP-QQQ instruments use an octopole-based CRC, known as the Octopole Reaction System (ORS). The fourth generation ORS[4] used in the current 7800 and 7900 quadrupole ICP-MS and the 8900 ICP-QQQ provides unmatched cell mode performance.

An octopole ion guide is the optimum ion guide for He mode, as the octopole has a very small internal diameter combined with a wide stability region, so the ion beam is well-focused within the octopole, and ion transmission is high. This means that the cell can have a small volume, and kinetic energy discrimination can achieve effective interference removal at low cell gas pressure, minimizing signal loss by scattering. The same benefits of high transmission and high collision number also apply to methods that use reactive cell gases, which is one of the reasons for the superior DL performance of the 8900 ICP-QQQ.

In the Agilent 8900 Advanced Applications and Semiconductor configurations, the ORS[4] has a new axial acceleration function which allows a voltage gradient to be applied along the length of the octopole. This can be used to accelerate ions along the ion guide axis, providing two analytical benefits:

- **Enhanced sensitivity in reaction cell mode.** Reaction product ions are relatively slow due to their comparatively large size. The low speed can result in reduced ion transmission due to collisional scattering or space charge repulsion. Axial acceleration gives these product ions more energy to enable them to overcome these effects and proceed along the axis of the ion-guide, increasing sensitivity. This is illustrated in Figure 5, which shows the effect of axial acceleration on the measurement of sulfur as the SO^+ product ion using MS/MS mass-shift with O_2 cell gas. The overlaid spectra demonstrate that axial acceleration increases transmission of the SO^+ product ions by reducing the effects of back-scattering, thereby increasing the signal for SO^+ and improving DLs for sulfur analysis.
- **Suppression of higher order product ion formation.** The additional acceleration-energy can also be used to enhance sensitivity for lower-order product ions by suppressing the formation of higher order cluster ions, since the increased collisional energy exceeds the weak bond energy of potential high-order cluster ions.

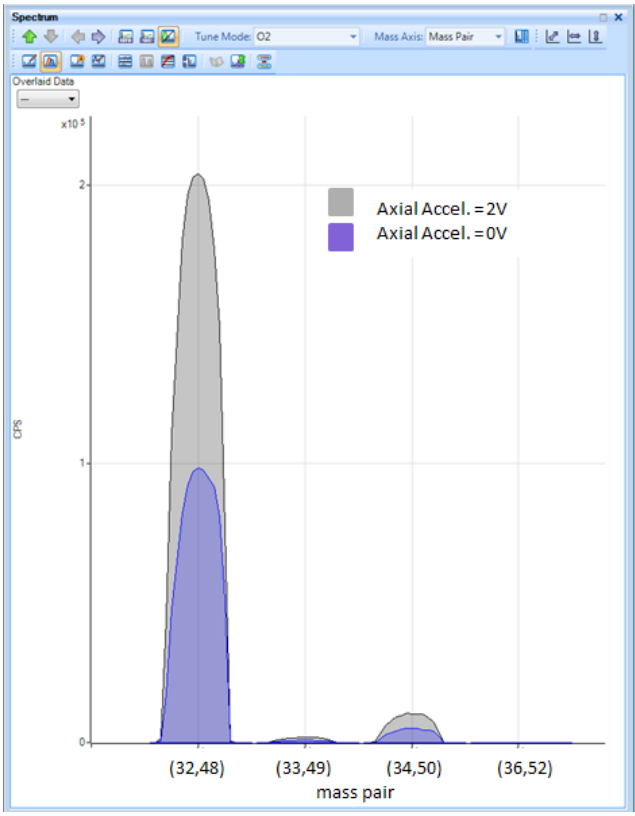

Figure 5. Spectrum of 10 ppb sulfur with and without axial acceleration, showing significant signal enhancement with axial acceleration voltage

Single nanoparticle analysis capability

Nanoparticle (NP) characterization is of growing and urgent interest across many industries and in various sample types. Toxicology research, the study of cycling in ecosystems and characterization of engineered nanoparticles are just three examples of emerging applications where ICP-MS is already used for NP analysis.

One approach used to characterize NPs is to measure the signal for each individual NP as it passes through the ICP and is atomized and ionized. This technique is called single particle ICP-MS (spICP-MS). The signal generated from a single NP typically lasts for only a few milliseconds or less, so successful analysis requires a very fast detector, to capture the signal and ensure that each NP signal is measured without overlap from the next particle.

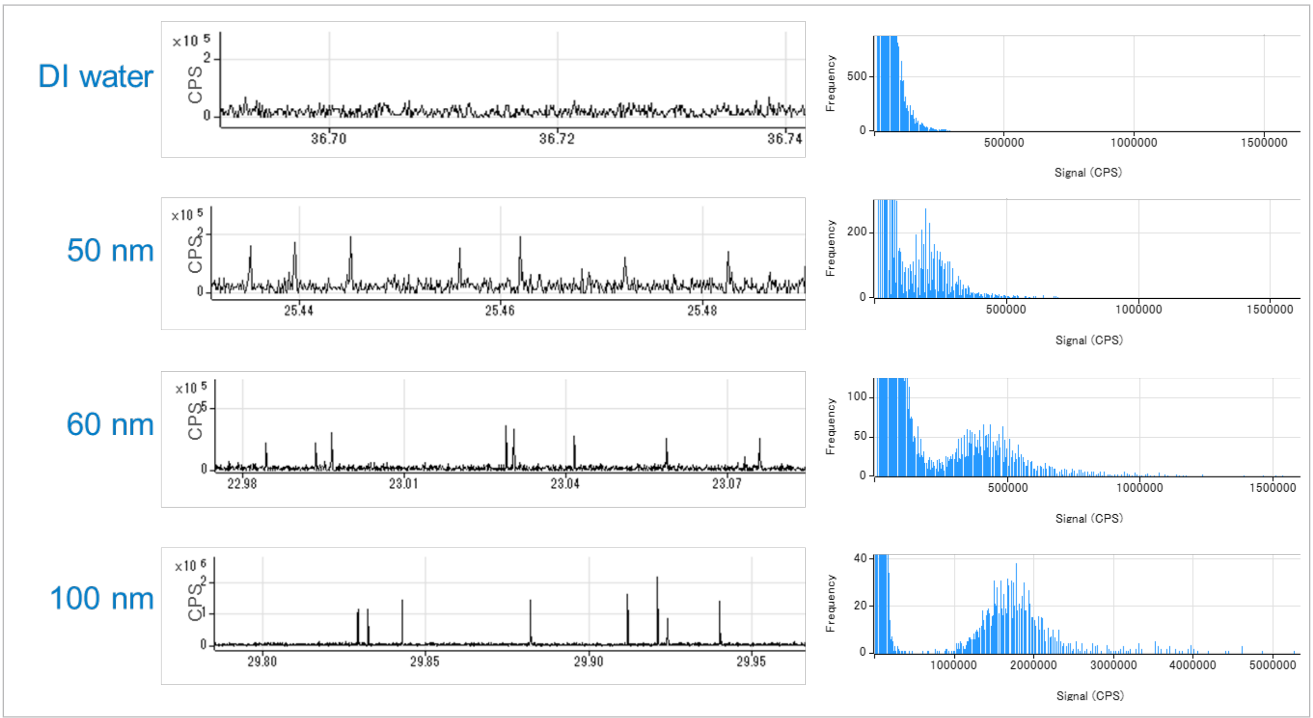

Figure 6. Left: single particle analysis of blank and SiO_2 NP standards in fast TRA mode. Right: particle size distribution plots calculated for SiO_2 NPs from the TRA data

The 8900 ICP-QQQ uses a new detector with fast TRA capability, allowing a dwell time of 0.1 ms to be used. The fast detector is combined with specialized software to process the signals and reveal the particle size and size distribution. The 8900 ICP-QQQ is arguably the most suitable ICP-MS for the study of NPs for two reasons:

- **Highest sensitivity and ultra-low background.** The ability to distinguish small particles from the background signal is fundamental to the ability to characterize the NP content of real-world samples. The 8900 ICP-QQQ offers the highest signal-to-noise of any quadrupole-based ICP-MS, with ultra-low background and high ion transmission. This means that NPs based on easily-measured elements such as Ag and Au can be measured at very small particle diameters of 10 nm or less [5].

- **Efficient removal of elemental backgrounds and spectral interferences.** The control of Si and S backgrounds, combined with the unmatched control of interferences in MS/MS mode enable the 8900 ICP-QQQ to characterize NPs based on more difficult elements such as Fe, S, Ti and Si. SiO_2 NPs are widely used in manufactured goods, food and consumer products, and their fate in the environment and potential toxicological effects are receiving urgent attention. However, spectral interferences from N_2^+ and CO^+ hamper the low level detection of Si by ICP-MS. TiO_2 NPs are also difficult to measure at small sizes using quadrupole ICP-MS, due to spectral overlap from ^{48}Ca on the major Ti isotope at *m/z* 48. The 8900 ICP-QQQ uses MS/MS mode to remove these spectral interferences, allowing accurate measurement of Si and Ti at low levels. This ensures that small particles (50 nm or less) can be distinguished from the background signal, allowing unprecedented accuracy for SiO_2 and TiO_2 NP analysis.

The performance of the 8900 ICP-QQQ for SiO_2 NP analysis is illustrated in Figure 6 [6]. This figure shows the measured signal collected using fast TRA (100 µs dwell time) for a blank deionized water and SiO_2 NP standards with reference particle sizes of 50 nm, 60 nm and 100 nm. The particle events in the 50 nm standard can clearly be distinguished above the low and stable baseline signal. Using ICP-MS MassHunter's Single Nanoparticle Application Module, the measured signals were calibrated and converted to particle size distribution plots, also shown in Figure 6. From the measured data, the background equivalent particle diameter (BED) was calculated as < 25 nm.

Conclusions

The world's first commercial ICP-QQQ, the Agilent 8800, has been rapidly accepted as the most powerful and flexible ICP-MS by users from high-tech industries and research institutions through to analytical service providers.

Its successor, the Agilent 8900, further advances the capability of ICP-QQQ, improving analytical performance and productivity, and extending the scope of ICP-QQQ to address a wider range of sample types and applications.

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