Single particle ICPMS for characterizing metal-based nanoparticles and monitoring transformation processes in surface water

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Introduction

- The U.S. EPA is developing and validating methods for measuring and characterizing engineered nanomaterials (ENMs) in environmental matrices. These methods will be used to:
  - –assess occurrence of ENMs in the environment and temporal trends in their distribution.
  - –support laboratory studies of transformations, transport, and fate of ENMs.
  - –provide input parameters for environmental models, and validate those models.
- Current methods for measuring and sizing metal-based ENMs in surface and ground water are challenged by the low concentration of ENMs and the presence of non-target NP containing the metal of interest. The most commonly used approaches are hyphenated techniques, such as field-flow fractionation (FFF) with inductively coupled plasma mass spectrometry (ICPMS) detection. Such techniques are very useful for screening-level assessments.
  - –Hyphenated methods measure analyte metal concentration associated with size fractions of particles and, therefore, they can identify samples that potentially contain target ENMs.
  - –However, they do not measure the number density of nanoparticles or the metal content of individual nanoparticles and, therefore, they do not distinguish the metal content of the ENMs from the metal contents associated with other naturally nanoparticles (e.g., minerals, natural organic matter).
- Single particle (SP)-ICPMS, introduced by Degueldre, et al. (2003), and expanded on by others (see references), provides data that are complementary to those provided by hyphenated methods.
  - –SP-ICPMS measures the number density of individual nanoparticles containing the analyte metal, as well as the metal content of each particle.
  - –It does not measure the size of the nanoparticles.
  - –Stand-alone SP-ICPMS could be used as a screening technique for identifying water samples potentially containing metal-based ENMs. It has the advantage of sample throughput potentially an order of magnitude greater than hyphenated methods.
  - –SP-ICPMS could be used in concert with particle sizing methods, such as FFF, for selective determination of metal-based ENMs.
  - –SP-ICPMS could be used to monitor transformation processes that are too rapid to monitor by hyphenated methods.
- The research goal of the Environmental Sciences Division is to develop SP-ICPMS as a practical analytical technique for environmental metal-based ENM measurements.
- The objective of the work presented here is to characterize the performance of SP-ICPMS, and to determine the major experimental parameters affecting that performance.

Materials and Methods

- Gold was chosen as the model analyte for these investigations because of the availability of well characterized, monodisperse suspensions that are stable for long periods.
- Suspensions of Au ENMs in water (20, 50, 80, 100, 150, and 200 nm diameter, C.V. < 8%) were obtained from Corpuscular, Inc. (www.microspheres-nanospheres.com).
- ENM sizes were confirmed by transmission electron microscopy.
- Most SP-ICPMS measurements and all measurements with individual measurement windows (i.e., dwell times) of less than 10 ms were performed on a DRC-e ICPMS (Perkin Elmer, Waltham, MA, USA).
- Some measurements with 10-ms dwell time were performed on a 7500 cx (Agilent Technologies, Santa Clara, CA, USA).
- Unless otherwise indicated, the ICPMS was tuned for optimal Au sensitivity with an appropriate dissolved gold standard.

Results and Discussion

Principles of SP-ICPMS detection

- Analyte ion flux is contained in ion plumes from individual nanoparticles vaporized by the plasma. The flux of nanoparticles in the plasma is:

  $q_p = c_p\, q_s\, \varepsilon_n / 60$

  c_p = nanoparticle concentration in sample (mL^{-1})
  q_s = sample flow rate (mL/min)
  ε_n = nebulization efficiency
- Analyte ions are detected only during the time ($\tau_p \approx 10^{-4}$ s) an ion plume transits to the detector; otherwise, intensity at the detector, I_b, is due to background.
- The key to SP-ICPMS is to measure the signal with high temporal resolution (i.e., dwell time, t_d, >>1 second) so the number of background ions detected in each data point is much less than the number of ions produced by a nanoparticle ion cloud.
- The number of particles counted per second, is equal to the particle flux given in the equation above (i.e., every particle entering the plasma is counted).
- The number of ions detected for each plume transit is proportional to the analyte mass in the particle and is:

  $n_{i,p} = m_{a,p} N_A (A_i / A_r) \varepsilon_{v,a,i} \varepsilon_d$

  $m_{a,p}$ = average analyte mass in nanoparticle (g)
  N_A = Avogadro's number
  A_i = relative abundance of monitored analyte isotope
  A_r = atomic weight of analyte metal
  $\varepsilon_{v,a,i}$ = vaporization, atomization, and ionization efficiency
  ε_d = mass spectrometer detection efficiency, including factors related to ion plume dimensions
- There are two sets of metrics in SP-ICPMS, **nanoparticle concentration metrics** and **single particle analyte mass metrics**, and they are controlled by different factors. For both metrics, the following figures of merit apply:
  - precision
  - accuracy
  - dynamic range
    - detection limit
    - upper linear range

Nanoparticle Concentration Metrics

- **Precision** is controlled by counting statistics:
  - $\sigma \cong p^{0.5}$
  - $\sigma \cong (q_b T_t)^{0.5}$
    - p = total particles counted
    - T_t = total counting time
- **Accuracy** is controlled by **nebulization efficiency**
  - –Changes in viscosity and surface tension affect accuracy.
- **Detection Limit** is ultimately determined by background nanoparticle concentration. When this is negligible, the detection limit is only limited by reasonable signal acquisition time. Assuming 1 nanoparticle can be counted in 30 seconds, with a typical sample flow of 1 mL/min and a nebulization efficiency of 0.02:

  $C_{p,DL} = (60\, q_p / q_s\, \varepsilon_n) = 100\ mL^{-1}$
- However, a **practical quantification limit** (PQL) is often defined as the concentration giving less that 1% false negatives (zero particles detected ≈ three standard deviations below the mean total particle count at the practical quantification limit). Using counting statistics:

  $0 = p_{POL} - 3\sqrt{p_m}$

  $p_{POL} = 9$

  So, the practical quantitation limit for q_p is about 0.3 s^{-1} for the above 30 second acquisition time and assuming the conditions for the detection limit:

  $C_{p,POL} = (60\, q_p / q_s\, \varepsilon_n) = 900\ mL^{-1}$

  Alternatively, PQL can be defined by the maximum acceptable relative standard deviation (RSD). If an RSD ≤ 15% is specified, the minimum q_p is 1.5 s^{-1} and $C_{p,POL}$ = 4500 mL^{-1}.
- **Upper linear range** (ULR) is determined by the need to avoid multiple ion plumes transiting the detector during a detector dwell time t_d (the sampling time per data point in seconds). To avoid unacceptable numbers of these events (~10% of total counts):

  $q_{p,ULR} \leq 0.1 / t_d$
- SP-ICPMS to date has been limited to dwell times of ≥10 ms so the plasma particle flux should be less than about 10 s^{-1}.
- As a result, the upper linear range is often in the low ng/L (part-per-trillion) in terms of total metal mass concentration.
- **Practical dynamic range with 10 ms dwell time ($q_{p,ULR}$/ $q_{p,POL}$) is 30 or less.** This makes SP-ICPMS impractical for ENM monitoring in real environmental samples.
- The practical dynamic range was increased in this study by using dwell times less than 10 ms. An aqueous suspension of 50 nm Au ENMs at a particle concentration of 1.25×10^5 mL^{-1} was analyzed. The resulting q_p was 40-50 s^{-1} or about 4-5 times the maximum recommended for 10 ms dwell. Figure 1 shows the effect of decreasing the dwell time from 10 ms in Fig. 1(a), to 1 ms in Fig. 1(b). At 10 ms dwell, individual pulses cannot be distinguished and many dwell times have apparent $n_{i,p}$ much greater than the actual value of 40.

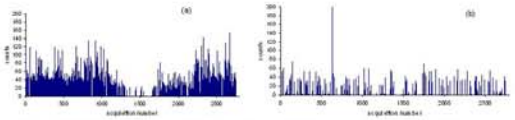

Figure 1. SP-ICPMS of 50 nm Au at 1.25×10^5 particles mL^{-1}. (a) 10 ms dwell time, (b) 1 ms dwell time.

- Linear dynamic range for 0.3 ms and 0.1 ms dwell times in this study extended over at least two orders of magnitude (1.25×10^4 mL^{-1} to 1.25×10^5 mL^{-1}).

Single Particle Analyte Mass Metrics

- **Accuracy** and **precision** of the particle analyte mass were both detrimentally affected by deceasing the dwell time below about 3 ms in this study. Figure 2 shows the cumulative distributions of $n_{i,p}$ at 10, 3, 0.3, and 0.1 ms dwell time. The distributions produced by 10 ms and 3 ms dwell times have calculated particle diameter relative standard deviations of 16% and 18%, respectively. This is consistent with counting statistics and a relative standard deviation of particle diameters of 7% being the sole sources of error. The distribution produced by 1 ms dwell is significantly degraded, and the 0.3 ms distribution does not show any significant number of whole particles ($n_{i,p} \approx 40$).

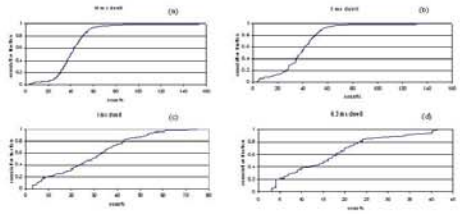

Figure 2. Cumulative distributions of number of analyte ions detected per particle for (a) 10 ms, (b) 3 ms, (c) 1 ms, and (d) 0.3 ms dwell times.

- This degraded particle analyte mass characterization is an **artifact** of the limitation of current ICPMS signal handling. Even instruments that can sample at dwell times less than 10 ms cannot do so continuously. **Dead times** of at least 1 ms, during which no signal is detected, occur between each data point collected. This results in partial acquisition of particle ion plumes, depending on where the ion plume transit time intersects the active dwell time. The effect becomes manifest when the transit time (indirectly measured to be ca. 0.4 ms in these experiments) approaches the dwell time.
- **The degradation of the accuracy and precision of particle analyte mass would not occur if ICPMS instrumentation capable of continuous sampling at 0.1 ms dwell times were available.**

Conclusions

- The upper dynamic range of SP-ICPMS nanoparticle concentration determinations is inversely proportional to the dwell time.
- Discontinuous sampling of current commercial ICPMS instruments at short dwell times degrades the accuracy and precision of the measurement of analyte mass in nanoparticles.
- Dwell times less than 3 ms with current instrumentation and operating conditions used in this study are not suitable for particle analyte mass measurement.
- A dwell time of 0.3 ms, in conjunction with a size-selective separation technique, could be useful to distinguish analyte nanoparticles from analyte adsorbed to other particles (i.e., where the analyte mass per particle differs by a large amount).

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