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Electrospray-Differential Mobility Hyphenated with Single Particle Inductively Coupled Plasma Mass Spectrometry for Characterization of Nanoparticles and Their Aggregates

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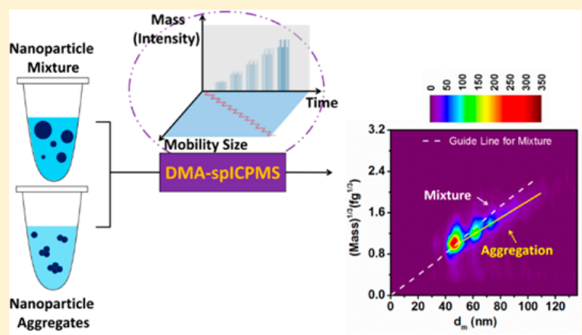
S *Supporting Information*

ABSTRACT: The novel hyphenation of electrospray-differential mobility analysis with single particle inductively coupled plasma mass spectrometry (ES-DMA-spICPMS) was demonstrated with the capacity for real-time size, mass, and concentration measurement of nanoparticles (NPs) on a particle-to-particle basis. In this proof-of-concept study, the feasibility of this technique was validated through both concentration and mass calibration using NIST gold NP reference materials. A detection limit of 10^5 NPs mL^{-1} was determined under current experimental conditions, which is about 4 orders of magnitude lower in comparison to that of a traditional ES-DMA setup using a condensation particle counter as detector. Furthermore, independent and simultaneous quantification of both size and mass of NPs provides information regarding NP aggregation states. Two demonstrative applications include gold NP mixtures with a broad size range (30−100 nm), and aggregated gold NPs with a primary size of 40 nm. Finally, this technique was shown to be potentially useful for real-world samples with high ionic background due to its ability to remove dissolved ions yielding a cleaner background. Overall, we demonstrate the capacity of this new hyphenated technique for (1) clearly resolving NP populations from a mixture containing a broad size range; (2) accurately measuring a linear relationship, which should inherently exist between mobility size and one-third power of ICPMS mass for spherical NPs; (3) quantifying the early stage propagation of NP aggregation with well-characterized oligomers; and (4) differentiating aggregated NPs and nonaggregated states based on the "apparent density" derived from both DMA size and spICPMS mass.



Engineered nanoparticles (NPs) in colloidal form have found a wide range of commercial applications.[1−4] However, when released into the environment, they are unlikely to remain in their pristine manufactured state throughout their lifecycle. Their transport properties and potential interaction with living organisms are highly dependent on their state of aggregation, complexation, and dissolution.[5−7] In order to evaluate the potential impact of nanotechnology on environmental and biological systems, validated analytical tools are critically needed which address challenges posed by real-world samples. This includes the analysis of environmentally relevant concentrations in the $\mu g\ L^{-1}$ to $mg\ L^{-1}$ range[8] and different NP states, including size polydispersity, aggregation, and adsorption of coatings. Ultimately, the ability to distinguish between naturally occurring and engineered NPs is highly beneficial.

In this regard, no single analytical tool is available that can fulfill the wide range of characterization needs. One method featured prominently in the area of environmental systems is inductively coupled plasma mass spectrometry (ICPMS). ICPMS provides rapid and quantitative elemental analysis, and a low limit of detection (LOD). More recently, single particle-ICPMS (spICPMS) has emerged as a powerful technique to quantify NPs on a particle-by-particle mass basis and to differentiate between dissolved and particulate forms. The potential of using spICPMS for simultaneous particle sizing, mass measurement, and particle number quantification at environmentally relevant concentrations has been demonstrated, and further method development and validation are ongoing.[9−12] Though promising, the technique has some significant limitations. First, ICPMS is a mass-based analytical tool; thus, unless chemical composition, density, and shape are known *a priori*, the size of NPs cannot be accurately determined. Additionally, spICPMS, without further size information, cannot be employed to distinguish between complex NP states, such as aggregate forms, heteroaggregates,

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or particles with coatings (such as proteins). In this respect, an upstream separation tool hyphenated with spICPMS to presort constituents in a complex sample has the potential to address such limitations by providing independent size information.

While chromatographic preseparation has been suggested, to our knowledge, the only method directly coupled to spICPMS to date is hydrodynamic chromatography (HDC). Pergantis et al.[13] utilized HDC online with spICPMS for the detection and characterization of metal-containing NPs in terms of number concentration, size, and metal content. Subsequent work by Rakcheev et al.[14] explored HDC-spICPMS to investigate morphology and temporal behavior of aggregation. While HDC has a very low LOD (≈ng L^{-1}) and can be applied to heterogeneous and complex samples, its resolution (the capacity to resolve multiple populations) was found to be insufficient to separate a mixture of NPs (5, 20, 50, and 100 nm); efforts must be made to improve resolution by, for example, optimization of flow rates and column length. Furthermore, to obtain size from retention time in HDC requires calibration with standards, and the influence of surface coatings on retention time complicates the accuracy for size determination.[15] Finally, we are aware of ongoing efforts to hyphenate asymmetric flow field-flow fractionation with spICPMS, but to date, published literature is limited to off-line analysis of collected fractions.[16]

In the present work, we employ electrospray-differential mobility analysis (ES-DMA) as an ion-mobility-based size discrimination technique, coupled to spICPMS. DMA has been routinely used to characterize NPs across a broad size range from ≈3 nm to a few hundred nanometers, and was one of the primary analytical techniques for size value assignment of NIST gold NP reference materials. DMA has the advantage of superb resolution (capable of differentiating a 1% difference in mobility), fast measurement times (on the order of minutes), and size selectivity.[17] Furthermore, due to its ability to classify and separate ionic species from NPs, DMA shows great potential for reducing the ionic background for real-world samples. Prior work with ES-DMA has demonstrated its ability to separate discrete NP aggregates, characterize coating densities, and measure nonspherical geometries.[18−20] Recently, DMA was hyphenated online with ICPMS operating in conventional mode (i.e., nonsingle particle mode) for size differentiated elemental analysis[21,22] and quantification of a surface complexed cisplatin antitumor drug.[23] In this approach an independent measurement of number concentration was necessary to obtain the size distribution, and a condensation particle counter (CPC) was employed for this purpose.

In this proof-of-concept study, which builds on our previous work cited above, we have demonstrated, for the first time, the capabilities and advantages of coupling ES-DMA directly to ICPMS operated in time-resolved single particle analysis mode (i.e., spICPMS), for characterizing NP size, mass, and number concentration at environmentally relevant concentrations and on a particle-by-particle basis. The simultaneous and independent measurement of NP mass and size makes this coupled approach valuable for studying aggregation processes and for differentiating between mixtures of different sizes of NPs and aggregates of NPs.

■ EXPERIMENTAL SECTION

Chemicals. Gold NPs (AuNPs) were used as a test bed in this study as they can be readily obtained in a variety of monodisperse sizes, and are available as NIST reference materials. A series of AuNPs were employed in this study including NIST reference materials with nominal diameters of 30 and 60 nm (RM 8012 and RM 8013, respectively), and AuNP suspensions with nominal diameters of 40, 80, and 100 nm obtained from Ted Pella (Redding, CA). (The identification of any commercial product or trade name does not imply endorsement or recommendation by National Institute of Standards and Technology.) The sizes of AuNPs were validated by mobility measurement using a customized ES-DMA-CPC system and compared with reference values (Table S-1, Supporting Information, SI). Ammonium acetate (AmAc, Sigma, 99.9%) was used for the preparation of buffer solutions for electrospray and for inducing AuNP aggregation. The DMA was calibrated with NIST standard reference material polystyrene spheres (SRM 1963a) with a certified mobility diameter of 101.8 ± 1.1 nm. High purity filtered deionized (DI) water was used to prepare all solutions and suspensions. Formation of AuNP aggregates consisting of primary 40 nm monomers was induced by adjusting the ionic strength through addition of aqueous AmAc (for details refer to the SI).

Instrumentation. *Principles of Differential Mobility Analysis (DMA).* The electrical mobility of a particle Z_p is defined as

$$Z_p = \frac{v_r}{E} \tag{1}$$

where v_r is the drift velocity of a charged NP under the electric field with magnitude E. By balancing electric and drag forces on the particle with charge n, electrical mobility is also given by

$$Z_p = \frac{neC_c(d_m)}{3\pi\mu d_m} \tag{2}$$

where C_c (a function of d_m) is the Cunningham slip factor, which corrects for the nonslip boundary condition,[24] μ is the viscosity of the carrier gas, d_m is the electrical mobility diameter, and e is the elementary electric charge. For a spherical NP with $1e$, d_m is equal to the geometric diameter, while for a nonspherical NP, d_m is the equivalent diameter of a sphere having the same drag force.[20]

DMA classifies NPs based on mobility Z_p (i.e., d_m). In a cylindrical DMA, the inner electrode is maintained at a high voltage, and the outer cylinder is grounded (Figure 1c). A flow of polydisperse aerosol (called aerosol flow, Q_a) and a laminar sheath flow (Q_{sh}) enter the DMA, and the charged NPs traverse radially with velocity v_r, described by eqs 1 and 2, and are

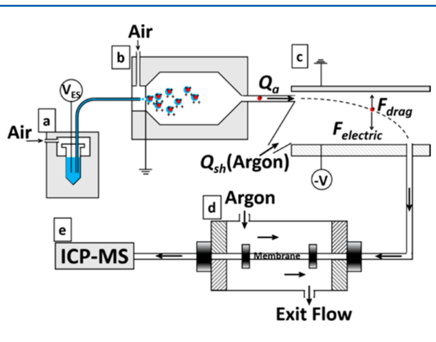

Figure 1. Experimental configuration for ES-DMA-spICPMS: (a) electrospray unit, (b) ^{210}Po neutralizer chamber, (c) differential mobility analyzer column, (d) gas exchange device to exchange air with argon for ICPMS compatibility, (e) ICPMS detector.

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classified by mobility Z_p, under a given applied voltage V, such that

$$Z_p = f(Q_{sh}, V, DMA_{configuration}) \quad (3)$$

Therefore, at a fixed sheath flow and DMA configuration, Z_p is strictly a function of applied voltage, and NPs of given mobility are selected by controlling the voltage. DMA is an aerosol technique, and therefore the analysis of colloidal suspensions is achieved by applying an electrospray process prior to DMA classification.

ES-DMA-spICPMS. A schematic of the instrumentation is shown in Figure 1, and is composed of four major components: (a, b) ES and neutralizer for aerosolizing colloidal nanoparticles, (c) DMA for particle mobility classification, (d) a gas exchange device (GED) to exchange air to ICP compatible argon [this requirement arises because the ES nominally requires some quantity of an electronegative gas (e.g., O_2) for stable operation], and (e) the ICPMS for elemental-specific particle counting and mass quantification.

The electrosprayed droplets were charge-reduced with a ^{210}Po neutralizer such that the aerosolized particles carry a known Boltzmann charge distribution (predominantly +1, 0, and −1 charges). Multiple charging is a concern for larger particles >50 nm, but is otherwise easily identified and excluded from analysis. Although only charged particles are size selected, with a known Boltzmann charge distribution, the total number of particles can be obtained after performing a "charge correction" (see Calculation of Number Concentration in the SI).[17] The DMA was operated with an aerosol flow Q_a of 1 L min^{-1} in air and a sheath flow Q_{sh} of 10 L min^{-1} in argon, for a theoretical resolution factor of 10.[25] This corresponds to a capacity for DMA to differentiate a 10% change in mobility and thus about 5% in diameter. The particles exiting the DMA (1 L min^{-1}) pass through the GED with 3 L min^{-1} of argon passing countercurrent to the direction of the particle-air flow, to exchange air with argon sufficient to sustain the plasma. The ICPMS was operated in time-resolved mode in order to monitor single particle signal intensity as DMA voltage was stepped up with respect to time, allowing a stream of single particles characterized by a specific d_m to exit the DMA at the selected voltage, ionize as single events in the plasma, and be detected by the mass spectrometer.

Unlike many liquid-based fractionation methods or chromatographic separations, the DMA offers flexibility in operation: enabling an arbitrarily chosen mobility size for a predetermined time by choosing voltage and DMA step time accordingly. Also, with the fixed voltage, the DMA operates as a band filter to allow one specific size of NPs to exit (see Figure S-2 in the SI).

Data Acquisition and Processing. *Distinguishing Particle Events.* In spICPMS, ^{197}Au was recorded with dwell time, t_{dwell}, defining the measurement window for particle events. With an appropriately chosen t_{dwell}, a single intensity pulse represents a single particle event. In the present study, 10 ms was chosen to minimize both particle splitting (a single particle event split over two adjacent dwell periods) and coincidence (more than one particle event occurring within a single dwell period). A five-sigma criterion (5σ) was applied to distinguish particle events from background[9] (for details refer to the SI). The Au background signal with DMA hyphenation is lower relative to direct analysis of aqueous NP suspensions (particularly in the presence of dissolved ionic forms). This is because there is no interference arising from dissolved ions in solution (e.g., Au^{3+}), as they form "salt" particles during the ES process and are subsequently separated from the NPs by DMA based on particle size; this yields a clean background for ICPMS detection of NPs. The sizes of "salt" particles are directly dependent on the concentration of nonvolatile dissolved ions/molecules and the droplet size produced by the electrospray process. However, under our experimental conditions, 6.5 mg L^{-1} of dissolved Au^{3+} is easily separated from the AuNP signal of interest. (see SI, Figures S-3 and S-4). As a result, the hyphenation of DMA with spICPMS offers the advantage of reduced background and better detection of NP populations relative to conventional stand-alone spICPMS. This is true for any type of NP and dissolved ions/molecules, even though interference by ICPMS only occurs when dissolved species are of the same composition as NPs.

Particle Mobility Size Determination. In our experiments, by stepping the applied voltage, the DMA is operated in a stepwise mode with respect to DMA scanning time, t, so that singly charged NPs are selected as shown on the y-axis in Figure 2, inset. Operationally, a mobility step size, $d_{m,step}$ = 2 nm, and a

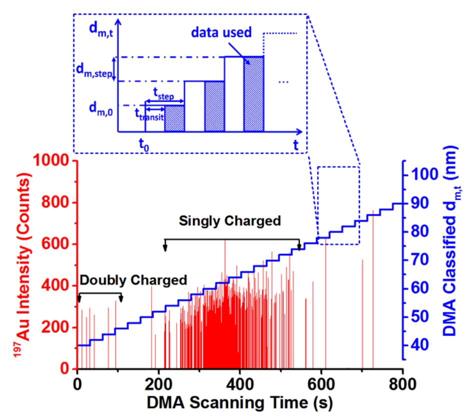

Figure 2. spICPMS intensity spectrum as a function of DMA scanning time for 60 nm AuNPs. Single particle events are presented as red spikes. The $d_{m,t}$ selected by the DMA with respect to time is represented by the stepped blue line following eq 4 ($d_{m,0}$ = 40 nm, $d_{m,step}$ = 2 nm, and t_{step} = 31 s). Two major populations representing singly and doubly charged 60 nm AuNPs are highlighted by the black brackets. Inset shows operational features of DMA-spICPMS relevant to data acquisition (eq 4).

step time, t_{step} = 31 s, are fixed. The lag time for NPs exiting the DMA to reach the ICPMS interface was determined to be approximately 15 s ($t_{transit}$ = 15 s) (see Figure S-5 in the SI). Although recorded continuously by ICPMS with respect to t, this transit time of 15 s has to be subtracted from 31 s yielding 16 s for actual data analysis for an individual step, as indicated by the dashed zone in Figure 2, inset. With a spICPMS dwell time of 10 ms, about 1600 measurements can be performed at each selected mobility size using the current experimental setup. Therefore, $d_{m,t}$ for the singly charged state is correlated with DMA scanning time t (i.e., spICPMS recording time) by eq 4:

$$d_{m,t} = d_{m,0} + \left\lfloor \frac{(t - t_0)}{t_{step}} \right\rfloor \times d_{m,step} \quad (4)$$

where $d_{m,t}$ is the spherical equivalent mobility diameter of NPs selected by the DMA at t, and $d_{m,0}$ is the initial stepped diameter at t_0. The bracket in eq 4 represents the *greatest integer*

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function such that the DMA selects particle size in a stepwise mode (the greatest integer function rounds to the nearest smaller whole number). For a nonspherical particle (e.g., clusters of NPs), $d_{m,t}$ is the equivalent spherical mobility diameter with the same drag force as the measured particle.

■ RESULTS AND DISCUSSION

ES-DMA-spICPMS Spectrum. A typical time-resolved intensity (^{197}Au) spectrum for nominal 60 nm AuNPs obtained by DMA-spICPMS is presented in Figure 2 (raw data before removing background). The detection by spICPMS yields element-specific intensity spikes, each representing a single particle event generating an ion plume in the plasma. Thus, each spike should be directly relatable to the mass of a specific element in one particle. In our case, since the particles comprise single component Au, the spike represents the total mass of the metallic core (excluding citrate capping agent). Unlike raw intensity spectra obtained in stand-alone spICPMS, time on the *x*-axis is the DMA scanning time, which corresponds to the selected mobility size for singly charged particles (step mode following eq 4: blue line in Figure 2). Therefore, a correlated size and mass measurement is achieved by the coupling of DMA to spICPMS. Closer examination of the spectrum shows that the majority of event spikes are narrowly distributed between 200 and 600 s, which corresponds to a mobility size ranging from 50 to 75 nm (i.e., the singly charged nominal 60 nm AuNP population). The doubly charged states of this population have a greater mobility, corresponding to a theoretical mobility diameter from 35 to 52 nm. Hence, the small number of single particle events below 100 s is attributed to doubly charged particles. As expected, the nominal intensity of the single particle events are of similar magnitude, with an average of 280 counts, regardless of the charged state of the particle.

Overall, there are three independent types of information that can be extracted from the spectrum: particle mobility size determined by DMA, intensity of each event spike, and frequency of spikes. In the following section, we establish two calibration curves that correlate (1) the intensity to the NP mass, and (2) the frequency of spikes to the NP number concentration. The two calibration curves combined with the known DMA classified size can be used for simultaneous determination of NP mass, size, and particle concentration for unknown samples.

Proof-of-Concept Studies. *Measurement of Number Concentration.* In order to explore the capacity of DMA-spICPMS to measure NP concentration and its sensitivity range, we utilized 60 nm AuNPs, serially diluted to yield a final number concentration ranging from 3.1 × 10^6 to 7.9 × 10^7 mL^{-1} (mass concentration of 6 to 160 μg L^{-1}). The number concentration was calculated on the basis of the mass concentration (51.86 μg g^{-1}) given on the RM certificate combined with an assumption of spherical shape with a Gaussian fit DMA measured diameter. Figure 3a illustrates a linear relationship between the number of particles in the aerosol phase detected by spICPMS and the concentration of NPs in solution (i.e., $N_{spICPMS}$ and [NP], respectively, in Calculation of Number Concentration, SI) with an R^2 value of 0.99999, indicating a high degree of linearity. This demonstrates the capacity of DMA-spICPMS to quantitatively measure NP concentration in solution for unknown samples with appropriate calibration. For our ES-DMA-spICPMS configuration and acquisition parameters, we find that the upper range of concentration for which single particle events are statistically meaningful without significant (≥5%) particle coincidence is ≈10^8 mL^{-1}. An LOD of 3.7 × 10^5 NPs mL^{-1} was determined under our experimental conditions from the calibration curve: $Y_{NspICPMS} = 2.6 \times 10^{-5} X_{[AuNP60nm]} + 46.4$ (LOD = 3.3σ/S, where σ = standard deviation of *y*-intercept from regression line, *S* = slope of the calibration curve).[26] This leads to a mass LOD of 0.8 μg L^{-1} for 60 nm AuNPs. In comparison, the LOD for stand-alone spICPMS was reported to be 100 NPs mL^{-1} (theory)[27] and about 1000 NPs mL^{-1} (observed).[28] LOD is about 3 orders of magnitude higher for hyphenation of ES-DMA-spICPMS relative to stand-alone spICPMS. This can be attributed to the lower sample flow rate into the ES (≈400 nL min^{-1}) versus into the nebulizer (≈500 mL min^{-1}) for stand-alone spICPMS. The slope of the calibration curve represents the transport efficiency, which takes into account particle loss associated within ES, DMA (including GED), and ICPMS (see *k* in Calculation of Number Concentration, SI). We experimentally evaluated these losses and concluded that the total particle transport efficiency is 12% (i.e., 88% total particle loss) with the majority loss associated with the front-end ES-DMA which accounts for approximately 94% of the total particle loss.

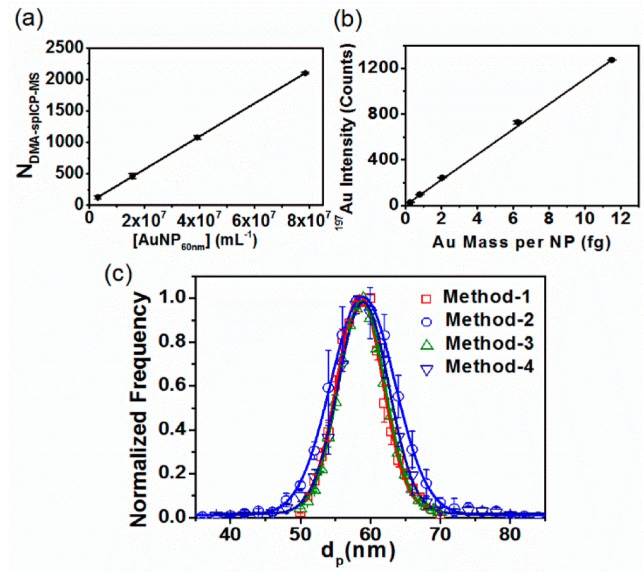

Figure 3. (a) Number concentration calibration curve (60 nm AuNP). (b) Mass calibration curve based on AuNPs of various sizes (30 and 60 nm, and 40, 80 and 100 nm AuNPs). Au mass per NP was calculated on the basis of DMA mobility equivalent spherical size. (c) Comparison of PSD for 60 nm AuNPs measured by DMA-spICPMS and other conventional methods: Method-1, by summation of particle spikes over each DMA step by DMA-spICPMS; Method-2, by single particle event intensity from DMA-spICPMS; Method-3, by conventional DMA-CPC; Method-4, by single particle event intensity from conventional stand-alone spICPMS. Lines represent Gaussian fits applied to each set of data. Error bars, if not visually apparent, are smaller than the symbols and are based on one standard deviation from at least two replicate runs.

Measurement of Nanoparticle Mass. In order to demonstrate the capability for accurate mass measurement, NPs of different nominal diameters were utilized: 30, 40, 60, 80, and 100 nm. The mass of each NP was calculated by assuming that AuNPs have a density equal to bulk gold (19.3 g cm^{-3}) and are spherical in shape. The geometric diameter (equivalent to mobility diameter for spheres) was obtained by a Gaussian peak

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fit to the particle size distribution measured by DMA-CPC (see Table S-1 in SI). The reader should keep in mind that because the DMA resolution is much higher than the width of the size distribution for these nominally monodisperse AuNPs, the DMA must be scanned/stepped over the entire size distribution to obtain a full representation of the population by event spikes. AuNPs of different sizes were measured, and the averaged intensities of each size were used to construct a mass calibration curve versus the mass of a NP calculated from the diameter.

Within the size range studied, a linear relationship is demonstrated between the averaged ^{197}Au intensity, and the Au mass per AuNP as shown in Figure 3b: $Y_{^{197}\text{AuIntensity}} = 110.5X_{\text{AumassperNP}} + 3.3$; $R^2 = 0.99995$ This mass calibration curve demonstrates the capacity for the determination of metal mass of unknown NPs from detected spike intensity of an appropriate element. From the calibration curve, an LOD of 0.1 fg (4×10^{35} Au atoms) is obtained, which converts to a AuNP size of about 23 nm. This detection limit (dependent on sensitivity to noise of the ICPMS instrument) is comparable to the smallest detectable size of 15 nm for AuNPs reported by Hu et al.[29] and the theoretical calculated size of 13 nm obtained by Lee et al.[30]

Measurement of Particle Size Distributions. Next we compare the particle size distribution (PSD) of 60 nm AuNPs obtained by DMA-spICPMS with that obtained from the standard ES-DMA-CPC method. The latter technique was applied as one of the primary tools for development of traceable NIST AuNP reference materials.[31] The CPC detects particles by light scattering from droplets that nucleate and grow on the particles themselves, and the LOD for ES-DMA-CPC is reported to be $>10^9$ NPs mL^{-1}.[32]

Using the raw data obtained by DMA-spICPMS (Figure 2), the spikes representing particle events were first resolved from the background based on a 5σ criteria as discussed previously. Then two different methods were applied to obtain particle size distributions. In one approach, where the ICPMS was used exclusively as a particle counter, the number of particle spikes occurring over the step time of a mobility size were summed, and this process was repeated for each size step to yield a number-based PSD as shown in Figure 3c (designated as Method-1). In the second method, the intensities of all particle spikes were converted to mass using the mass calibration curve (Figure 3b). On the basis of spherical geometry and the density of Au, the mass was converted to size, and the distribution was obtained and designated as Method-2, in Figure 3c. The PSDs obtained from DMA-spICPMS, either by counting NP frequency at a specific size, or by converting NP mass to diameter, are internally consistent and consistent with the PSD obtained by the traditional ES-DMA-CPC (Method-3, in Figure 3c). This clearly demonstrates that, for a near monodisperse PSD of the NPs examined here, the mass resolution and counting ability of the DMA-spICPMS yield accurate size distributions.

The fwhm (full width at half maximum) was calculated for the Gaussian fits. The fwhm (7.7) for the PSD obtained by counting single particle event spikes (Method-1) was essentially equivalent to that (7.8) obtained by DMA-CPC (Method-3). This is reasonable, since in the case of single particle event counting the size binning is determined by the DMA; in this case the spICPMS is utilized as an ultrasensitive particle counter, and thus functionally similar to a CPC. The PSD obtained on the basis of DMA-spICPMS particle intensity (Method-2) has a slightly wider breadth (fwhm = 10.8) in comparison to the other two methods (Method-1 and Method-3). The fwhm in PSD obtained from the single particle intensity by conventional stand-alone spICPMS (Method-4) is 8.6, which is intermediate between that for the DMA-size-based methods (Method-1 and Method-3) and that for Method-2.

Results indicate that the nature of determining size (either by DMA or by conversion from spICPMS particle intensity) has an influence on the resulting width of the PSD. For the case examined here, DMA yields a narrower PSD in comparison to a single particle intensity-based method (i.e., better resolution). The reason for the difference in fwhm, in a comparison of Method-2 to Method-4, is not clear at this point. One likely attribution is the different operating condition in ICPMS, which influences single particle intensity for each event (e.g., gas introduction for DMA-spICPMS in comparison to liquid introduction for conventional stand-alone spICPMS). With the consideration of the error bars (precision) from the PSD, the PSDs with the exception of Method-2 are essentially indistinguishable. The upper size limit for our study is around 150 nm, which is primarily limited by the breakdown voltage of argon used as sheath flow in the DMA. An improvement in efficiency for the GED would permit the use of air (with higher breakdown voltage) as the sheath flow, and thereby expand the applicability to sizes of several hundred nanometers.

Resolving Mixed Populations. In order to evaluate the robustness of DMA-spICPMS, we turn to a problem of more practical relevance, that of particle mixtures, using a 5-component AuNP sample with sizes ranging from 30 to 100 nm. For these experiments the number concentrations of NPs of various sizes were adjusted to a nominally equivalent basis, based on independent spICPMS measurements. Figure 4a is a 3-D contour map and heat map showing simultaneously the measurement of NP mobility size, NP mass, and NP concentration (frequency of NPs). Populations of AuNPs of different sizes are clearly distinguishable from each other, demonstrating the superb resolution obtained by coupling DMA with spICPMS.

For spheres one would predict a linear relationship between mobility diameter (d_m) and 1/3 power of ^{197}Au mass. This is clearly apparent in the heat map of Figure 4a, as the five NP populations lie on a diagonal. The off-diagonal populations, which are obviously fewer in number, located above the diagonal correspond to doubly charged NPs, while the populations below the diagonal are indications of split particle events.

This pattern if obtained for an unknown sample should also indicate that the particles in the mixture are largely spherical and in an unaggregated state (as will be shown in Analysis of Discrete Aggregates and Apparent Density for Aggregates sections). Furthermore, the diagonal also implies that there is no significant coating on the particle, because otherwise, the coating would bias particles of the same ^{197}Au mass toward a larger mobility size and would appear below the diagonal line. Therefore, independent and simultaneous quantification of both size and mass provides rich information regarding the NP state (e.g., shape, state of aggregation, and coating information), which is not possible using stand-alone spICPMS. Utilizing 60 nm AuNPs for single-point calibration of concentration, the measured particle number concentrations for all five populations are consistent with the known concentration initially in the mixture (Figure 4b). This implies high fidelity of the system in measuring number concentration,

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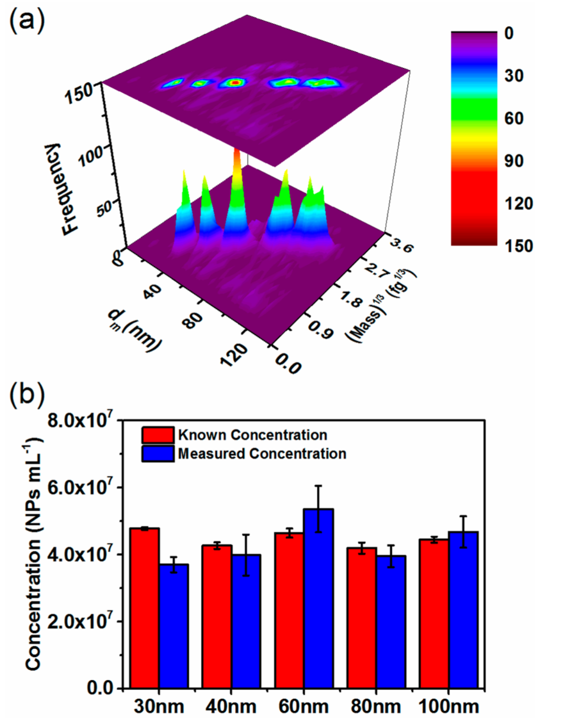

Figure 4. (a) Plot of size, mass$^{1/3}$, and concentration (frequency of NPs) for mixtures containing five sizes of AuNPs as obtained by ES-DMA-spICPMS. (b) Comparison between measured and known NP concentration initially mixed for five different sizes. Error bars represent one standard deviation for three replicate measurements. The known concentration initially mixed was based on independent relative number concentration measurement for all five different sizes by stand-alone spICPMS and normalized to known 60 nm AuNPs concentration from certificate.

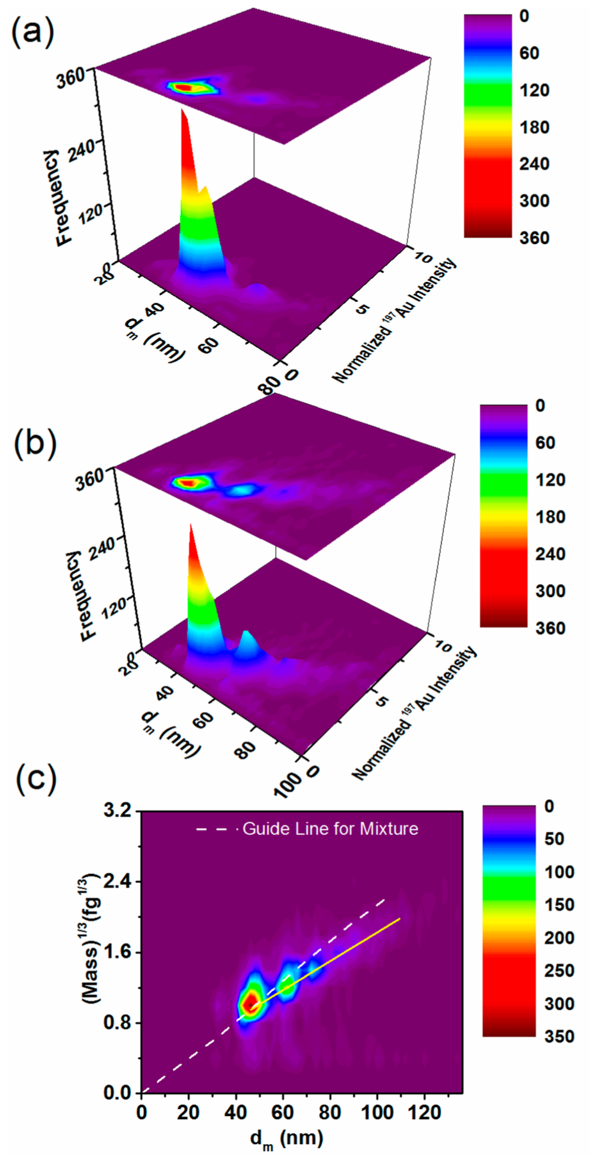

Figure 5. Heat map showing aggregation of 40 nm AuNPs occurring over 9 days [(a) day 1 and (b) day 9]; ^{197}Au intensity was normalized to that of the first monomer peak. (c) Comparison of discrete aggregates with the expected results for a mixture of solid spheres.

size, and mass simultaneously as well as providing NP states information.

Analysis of Discrete Aggregates. Here, we examine a fundamental issue frequently encountered in colloidal systems, that of particle aggregation and the ability to quantify both the process and the products. In Figure 5, we present results clearly demonstrating the capacity of DMA-spICPMS to differentiate discrete aggregates, and track aggregation temporally, in this case over a 9 day period. As singlet primary 40 nm AuNPs aggregate, the mass for N-mers (discrete aggregates composed of N primary particles) increases linearly with N; similarly, for DMA the mobility size will increase, but will follow a nonlinear function of N (i.e., independent confirmation of aggregate number is required).

Distinguishable populations of NP oligomers are presented as islands (heat map) associated with the peaks in Figure 5. For day 1 after initiation of aggregation, two populations are clearly resolved and distinguished from each other (Figure 5a). As the aggregation process propagates, aggregates with larger size and mass appear, forming a continuum of discrete aggregation states in solution. In Figure 5b, three peaks are clearly resolved on day 9 of aggregation, while two additional low height peaks appear at larger sizes forming a tail (see Figure S-6 in the SI). The first (smallest size) peak (in bin 44−46 nm) with maximum height is identified as the monomer 40 nm AuNPs (d_m = 42.8 nm, see Table S-1 in the SI). In order to assign the remaining peaks, each spike intensity contributing to the peak was normalized to the intensity of 40 nm monomers, resulting in normalized intensities of 1, 2, 3, 4, and 5. In other words, the normalized intensities correspond to monomers, dimers, trimers, tetramers, and pentamers of the aggregating AuNPs, since intensity (correlating to particle mass) linearly increases with the number of primary NPs associated with a given aggregate. In these studies the samples were first diluted to appropriate concentration to avoid particle coincidence. However, as aggregation proceeds number concentration decreases, and thus by day 9, the dilution employed was 8× lower than day 1 so as to obtain similar spICPMS spike frequency. This difference in dilution factor would need to be accounted for if the objective were quantitative kinetic information.

A more challenging test of DMA-spICPMS is to explore its suitability to differentiate NP aggregates from mixtures of solid spherical NPs that vary in size. This is a substantial challenge for either stand-alone spICPMS or DMA. However, due to the fact that DMA-spICPMS offers an independent measurement

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of both mass and size (i.e., density), the approach offers a unique capability to differentiate NP states. As mentioned previously, the mixture of spherical NPs lies diagonally on a graph of mass$^{1/3}$ versus d_m. In contrast, the aggregated sample clearly exhibits a deviation from the diagonal (indicated by the dashed white line in Figure 5c). More specifically, the peak trail in the heat map for the aggregated sample lies below the diagonal for mixtures of spheres, indicating that, for particles with the same mass as spheres, a larger d_m is observed. This is due to the fact that the nonspherical and less compact structure of aggregates presents a larger drag force relative to a sphere of equivalent mass.

These results show that the hyphenation of DMA with spICPMS can be used to track aggregation temporally, resolve aggregate distributions, and distinguish solid spheres from aggregates. The following section will demonstrate quantitative differentiation of aggregates and spheres by defining an apparent density parameter.

Apparent Density for Aggregates. One can also apply a more quantitative approach by defining a "mobility-based apparent density" (ρ_α) to characterize the state of aggregation:

$$\rho_a = \frac{m_a}{\frac{\pi}{6}(d_{m,a})^3} \propto \frac{I_a}{{d_{m,a}}^3} \quad (5)$$

Here, m_a represents the mass of NP aggregates measured by spICPMS intensity I_a for each particle event calibrated using spherical 60 nm AuNPs. $d_{m,a}$ is the measured mobility diameter as previously defined, and the function $\pi/6(d_{m,a})^3$ represents the volume of a sphere that has the same mobility as the aggregate. Equation 5 represents an apparent density for the measured particle. Thus, for a particle with an apparent density less than the theoretical solid bulk density, we conclude that this particle must be an aggregate. Figure 6a shows the apparent density for a mixture of differently sized spherical solid AuNPs.

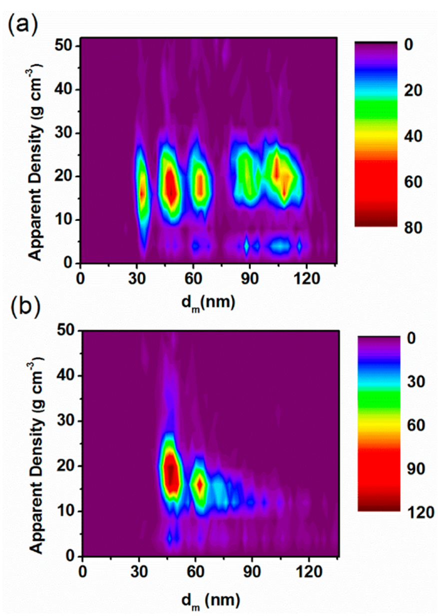

Figure 6. Heat maps for mobility-based apparent density: (a) NP mixtures containing 30, 40, 60, 80 and 100 nm AuNPs. (b) Aggregates consisting of 40 nm primary AuNPs. The map indicates a small population with apparent density of 40 g cm^{-3}, which we attribute to particle coincidence, and that around 4 g cm^{-3} is due to particle splitting.

Five distinct populations are clearly resolved with similar apparent density centered just below 20 g cm^{-3}, which is close to the expected density based on the known bulk density of Au (19.3 g cm^{-3}). By contrast, Figure 6b shows a decreasing apparent density with respect to size for aggregates of primary 40 nm AuNPs. As aggregates form, the apparent density decreases from just less than 20 g cm^{-3} for spherical monomers to approximately 12.5 g cm^{-3} for discrete aggregate states. The decreasing apparent density results from the formation of less compact NP aggregates. A decreasing relative density for agglomerates has been observed using hyphenation of HDC with spICPMS.[14] However, that work presents the results as an average over the whole distribution, while in this work we are able to both identify aggregates and assign an apparent density to each oligomer state. In this way ES-DMA-spICPMS offers the opportunity to quantitatively assess the state of aggregation and the aggregation number of discrete populations. The apparent density could potentially be useful to extract complementary information for unknown particles, such as porosity or coating; it may also be possible to distinguish between these two conditions by using complementary techniques.

■ CONCLUSIONS

The capacity of ES-DMA-spICPMS for simultaneous determination of NP size, mass, and concentration and the analysis of complex mixtures and aggregated samples were demonstrated using AuNPs. The high size resolution and tunability associated with DMA, combined with the low LOD, single particle detection, and elemental specificity of spICPMS, permit not only resolution of different NP populations, but also the detection of different aggregate states (oligomers) with a defined apparent density at environmentally relevant concentrations. Meanwhile, the operational flexibility of ES-DMA allows for selection of a specific particle size and step time, both simplifying and expanding the capabilities of stand-alone spICPMS as it has been implemented to date. The concurrent improvements in the spICPMS technique (both data processing and hardware capabilities), leading to increased sensitivity and faster acquisition, are pushing the lower size limit downward and improving the overall statistical quality of data. Overall, the coupling of mobility analysis with spICPMS offers what we believe to be a substantial and novel advancement in the characterization of NP populations.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.analchem.6b01544.

Additional information as noted in the text (PDF)

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Notes

The authors declare no competing financial interest.

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