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Environmental Significance Statement

Aerosols act as a surface for heterogeneous reactions and multiphase processes in the atmosphere, which impacts their climate-relevant properties (scattering, absorption, and cloud droplet and ice crystal nucleation). Raman microspectroscopy is able to probe organic and inorganic functional groups at ambient temperature and pressure, but is challenging to apply to aerosols critical to climate since the most abundant sizes by number in the atmosphere (~100 nm) are smaller than the diffraction limit of visible light. We show that surface enhanced Raman spectroscopy (SERS) can extend analysis of atmospheric particles down to 150 nm, revealing new chemical detail about accumulation mode particles in the atmosphere and the potential to enable future studies of the complex chemistry occurring at aerosol surfaces.

Extending Surface Enhanced Raman Spectroscopy (SERS) of Atmospheric Aerosol Particles to the Accumulation Mode (150-800 nm)

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Abstract (50-250 words)

Due to their small size, measurements of the complex composition of atmospheric aerosol particles and their surfaces are analytically challenging. This is particularly true for microspectroscopic methods, where it can be difficult to optically identify individual particles smaller than the diffraction limit of visible light (~350 nm) and measure their vibrational modes. Recently, surface enhanced Raman spectroscopy (SERS) has been applied to the study of aerosol particles, allowing for detection and characterization of previously undistinguishable vibrational modes. However, atmospheric particles analyzed via SERS have primarily been > 1 μm to date, much larger than the diameter of the most abundant atmospheric aerosols (~100 nm). To push SERS towards more relevant particle sizes, a simplified approach involving Ag foil substrates was developed. Both ambient particles and several laboratory-generated model aerosol systems (polystyrene latex spheres (PSLs), ammonium sulfate, and sodium nitrate) were investigated to determine SERS enhancements. SERS spectra of monodisperse, model aerosols between 400-800 nm were compared with non-SERS enhanced spectra, yielding average enhancement factors of 10^2 for both inorganic and organic vibrational modes. Additionally, SERS-enabled detection of 150 nm size-selected ambient particles represent the smallest individual aerosol particles analyzed by Raman microspectroscopy to date, and the first time atmospheric particles have been measured at sizes approaching the atmospheric number size distribution mode. SERS-enabled detection and identification of vibrational modes in smaller, more atmospherically-relevant, particles has the potential to improve understanding of aerosol composition and surface properties, as well as their impact on heterogeneous and multiphase reactions involving aerosol surfaces.

1 Introduction

Atmospheric aerosol particles impact climate by scattering and absorbing solar radiation and acting as cloud condensation and ice nuclei, which modify cloud properties and precipitation.[1–8] However, these impacts are difficult to quantify due to the complex physicochemical properties of aerosols,[8–10] particularly in terms of chemical composition and mixing state.[9,11–19] This is complicated by the fact that individual particles can contain hundreds to thousands of different chemical species from difference sources and atmospheric aging.[8] An important example of aerosol chemical complexity is secondary organic aerosol (SOA), which forms when low volatility oxidation products of volatile organic compounds (VOCs) condense onto or heterogeneously react with existing aerosol particles containing inorganic salts (e.g. ammonium sulfate).[20–22] Though it is known that these particles contain both organic and inorganic components, particle-to-particle variability in chemical composition and mixing state due to different multiphase processes in the atmosphere are not well understood.[20,23,24] In addition, aerosols can have intraparticle chemical variability through processes such as liquid-liquid phase separations.[24–28] More detailed investigations of particle chemical composition and surface properties are needed to improve understanding of multiphase processes,[29,30] such as heterogeneous reactions occurring on surfaces,[31–33] water uptake,[34,35] viscous particles,[36–38] phase transitions,[39,40] and gas-particle partitioning.[41,42]

Over the past decade, Raman microspectroscopy has been increasingly applied as an analytical technique for chemical characterization of aerosol particles.[9,43–46] This technique uses inelastically scattered light to detect vibrational modes present within a sample, which can then be used to identify functional groups and chemical species. Raman microspectroscopy has been applied to characterize many different particle types, such as sea spray and other marine

aerosol,[44,47–49] soot and elemental carbon (EC) particles,[50–53] mineral dust,[53–56] and SOA,[46] as well as specific compounds commonly found in aerosols, including biological molecules[57] and various organic compounds like organic nitrates,[58] organosulfates,[59] and glyoxal oligomers.[60] Raman analysis has also been used to study hygroscopic properties,[61–65] phase separations,[66–68] heterogeneous reactions,[49,69,70] ice nucleation,[71] and acidity of aerosols.[72,73] Advantages of this technique include minimal sample preparation and non-destructive analysis under ambient temperature and relative humidity (RH) conditions. However, detection limits in terms of both particle size and analyte concentrations can make Raman microspectroscopic studies of aerosol particles challenging. The majority of aerosol particles, particularly those with long atmospheric lifetimes that react and undergo atmospheric processing, are smaller than 1 μm, but Raman microspectroscopy has been applied mostly to the study of individual particles larger than 1 μm, often 10-30 μm, because it is difficult to optically distinguish smaller particles due to the wavelengths commonly used for Raman analysis (532 or 640 nm) and the diffraction limit of optical microscopy (300-400 nm). Furthermore, even in supermicron atmospheric particles, chemical species are often present in very low concentration, making it difficult to detect Raman signal with enough intensity to determine the identity of vibrational modes and corresponding functional groups. Lastly, important particle properties, such as deliquescence relative humidity can be size-dependent, limiting the ability to translate studies on large particles to atmospherically relevant sizes.[74] If SERS can be used to overcome the detection limit challenges associated with small particle sizes, the potential for Raman microspectroscopic analysis of aerosol particles to improve understanding of chemical composition and mixing state will greatly increase.

Surface enhanced Raman spectroscopy (SERS) has been used to improve the limit of detection of low concentration chemical species,[75] all the way to single molecules.[76] Through SERS, weak Raman signals are enhanced via interactions with localized surface plasmon resonances (LSPRs), which are generated by excited electrons in metallic substrates.[75,77–80] The metallic substrates are often silver, gold, or copper and can be in the form of foils, geometric nanoparticles, and colloids.[78,80,81] SERS has applications in many different fields, from biosensing to art preservation, and enhancement factors (EFs) for vibrational intensities of analytes are reported that range from $10^2 - 10^{10}$.[75,77–80,82,83] The volumes that experience SERS enhancements are small and typically located less than 5-10 nm from a hotspot, which shows the potential to measure submicron particles that are challenging to identify optically, since a detected SERS-enhanced spectrum originates from a such a small area, it most likely corresponds to an individual particle at low substrate loadings (e.g. no particle overlap). In the future, SERS hotspots could be used to probe phenomena localized near aerosol surfaces. With SERS, limitations of optically distinguishing particles for analysis and detection of chemical species present in trace amounts within aerosol particles can be overcome.

Prior to 2015, only a few preliminary, qualitative studies had used SERS for aerosol analysis, with a focus on bioaerosols.[84–86] Since 2015, SERS has been applied to the study of aerosol particles more broadly and in a more quantitative manner. In 2015, Craig et al. used silver nanoparticle coated quartz substrates to investigate both ammonium sulfate and sodium nitrate aerosol particle standards as well as ambient aerosol.[87] In 2016, Fu et al. used Klarite, a commercially available Au substrate of structured gold inverted pyramids, to study mixed ammonium sulfate and naphthalene particles.[88] A few variations of SERS, such as tip-enhanced Raman spectroscopy (TERS),[89] electrospray SERS (ES-SERS),[90] and surface-enhanced

resonance Raman spectroscopy (SERRS) of trapped and suspended particles,[91] have also been applied to study aerosol particles. Reported EFs ranged from 2.0 – 70 for $\nu_s(SO_4^{2-})$, $\nu_s(NO_3^-)$, ν(C-H), ν(O-H), and δ(C-C) vibrational modes[87,88,90] and 10^5 for vibrational modes of Rhodamine 590 chloride (R6G), a dye with a large scattering cross-section commonly used for SERS studies.[91] However, most particles probed in these studies were supermicron, not in the submicron size range most abundant for ambient aerosol, and further work is needed to increase EFs for vibrational modes corresponding to more atmospherically-relevant chemical compounds.

In this study, silver SERS substrates, including Ag nanoparticles and commercial Ag foil, were tested with both organic and inorganic species commonly observed in aerosols. Additionally, laboratory-generated and ambient aerosol particles <1 μm were analyzed to explore the lower limit in terms of particle size for SERS using these simple methods. The results of this study highlight the potential for SERS analysis of aerosol particles with atmospherically-relevant sizes (down to 150 nm) to improve understanding of chemical composition, mixing state, and reactions occurring on aerosol surfaces that impact aerosol climate effects.

2 Experimental

2.1 Materials and Reagents

Quartz slides (Ted Pella, Inc.) and silver foil (ESPI Metals) were purchased and used as substrates. Silver nitrate ($Ag(NO_3)_2$) (Sigma-Aldrich), hydroxylamine hydrochloride (Sigma-Aldrich), and sodium hydroxide (Fischer) were used for silver nanoparticle (AgNP) synthesis (described below). Polystyrene latex sphere (PSL) standards (Polysciences, Inc.), ammonium sulfate ($(NH_4)_2SO_4$) (Alfa Aesar), and sodium nitrate (Sigma Aldrich) were used as model aerosol systems. All chemicals were >98% purity and used without further purification.

2.2 Substrate Preparation

Quartz coverslips were cut and cleaned prior to use as either directly as substrates or as a base for a silver nanoparticle (AgNP) SERS substrates. AgNPs were synthesized by reducing silver nitrate with hydroxylamine hydrochloride, according to the method by Leopold and Lendl.[92] The resulting colloidal solution of AgNPs was drop-coated onto clean quartz slides and dried in a desiccator to create SERS substrates in the same manner as Craig et al.[87] Size distribution data collected via Nanoparticle Tracking Analysis (NTA)[93–95] for the AgNPs prior to dropcoating is included in the Supplementary Information. Silver foil (0.002" thick, ESPI Metals) was cut for use as SERS substrates. Microscopy characterization of the Ag foil is included in the Supplementary Information.

2.3 Laboratory-Generated Aerosol Particle Samples

Organic particle standards were generated by aerosolizing colloidal solutions of PSLs of varying size (400 nm, 600 nm, and 800 nm). Prior studies have analyzed PSLs with SERS going back to the 1990's,[96] providing useful reference points for Raman studies focused on aerosol particles. Inorganic aerosol particle standards were generated by aerosolizing solutions of 30 mM $(NH_4)_2SO_4$ or 30 mM $NaNO_3$. All solutions were made with 18.3 MΩ Milli-Q water. Aerosolization was conducted with a Collison nebulizer operated with HEPA-filtered air and the generated aerosol was passed through two diffusion dryers to remove excess water before being impacted onto substrates with a microanalysis particle sampler (MPS-3, California Instruments, Inc.). Prior to impaction, the inorganic standard particles were size-selected at 400 nm, 600 nm, or 800 nm (electrical mobility diameter) with an electrostatic classifier (Model 3080, TSI Corporation) equipped with a long differential mobility analyzer (Model 3082, TSI Corporation) at sample to sheath flow ratio of 1:8.3 (0.3 to 2.5 lpm)

2.4 Ambient Aerosol Particle Samples

Ambient samples were collected from outside the University of Michigan Chemistry Building (42.2783° N, 83.7372° W). Samples were size selected at 150 nm (electrical mobility diameter) with an electrostatic classifier (Model 3080, TSI Corporation) and then collected on Ag foil via impaction with the MPS-3. Each sample was collected for ~1 hour.

2.5 Raman Microspectroscopy

Raman analysis was performed with a Horiba Labram HR Evolution Raman spectrometer (Horiba Scientific) coupled to a confocal optical microscope (100x Olympus objective, 0.9 N.A.). The spectrometer was equipped with a Nd:YAG laser source (50mW, 532nm) and a CCD detector. A 600 groove/mm diffraction grating yielded spectral resolution of 1.8 cm^{-1}. Calibration was carried out daily against the Stokes Raman signal of a pure silicon standard at 520 cm^{-1}. Laser power was attenuated with neutral density (ND) filters ranging from 1 to 100 to prevent sample damage. Spectra were collected for the range of 500 to 4000 cm^{-1} for 3 accumulations with 15 s acquisition time. 8-15 particles were analyzed for each sample. Raman maps were collected with computer-controlled XY Raman mapping, with spectra recorded using a point-by-point scanning mode with a 0.25 μm step size. Map spectra were also collected from 500 to 4000 cm^{-1} for 3 accumulations with 15 s acquisition time. Each spectrum collected during a map acquisition was matched to its corresponding location in an optical image to determine if it represented an aerosol particle. Samples were exposed to ambient relative humidity and temperature conditions during Raman analysis (~23ºC and 40-60% RH).

SERS EFs were calculated for vibrational modes of interest according to Equation 1, I_{SERS} and I_{RS} are the Raman signal under SERS and non-SERS conditions, respectively, and c_{SERS} and c_{RS} are the analyte concentration under SERS and non-SERS conditions, respectively.[97]

Eq. 1 $$\mathrm{EF} = \frac{I_{SERS}/c_{SERS}}{I_{RS}/c_{RS}} = \frac{I_{SERS}}{I_{RC}}$$

Since sample preparation for SERS and non-SERS conditions was identical, the concentration c_{SERS} can be assumed to be equal to c_{RS} and the equation to calculate EFs can be simplified to a comparison of I_{SERS} and I_{RC}. I_{SERS} and I_{RC} are represented by the integrated peak area for the respective vibrational modes. Integrated peak areas were determined along the natural baseline of the spectra using a multipeak fitting software package (Igor Pro, WaveMetrics). The average integrated peak area for Raman spectra collected under non-SERS conditions was used for I_{RC}.

3 Results and Discussion

Laboratory-generated aerosol particle standards were used to investigate enhancement from various Ag SERS substrates, including AgNP coated quartz and Ag foil, and their application to aerosol particle studies, specifically particles <1 μm. Raman spectra of standard PSL particles sized 400 nm, 600 nm, and 800 nm collected from each substrate showed that, while both Ag SERS substrates enhanced the Raman signal across all vibrational modes, Ag foil yielded significantly higher EFs (Figure 1). Raman spectra were successfully collected for PSL particles of all sizes on the Ag foil and quartz substrates, but due to low intensity and the resulting small enhancement, only the 800 nm PSLs were tested with the AgNP substrate. Even though Raman

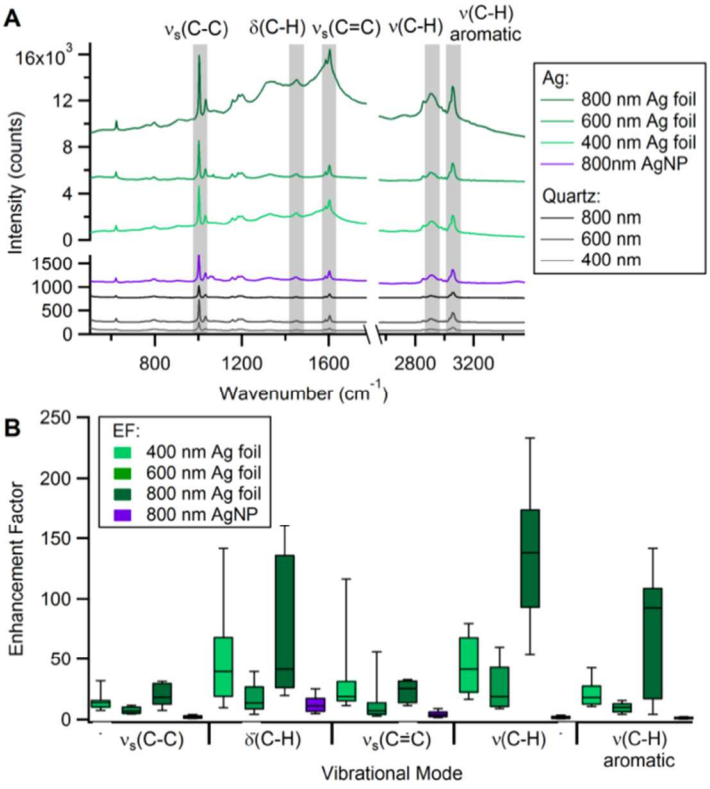

Figure 1. (A) Average Raman spectra for 400 nm, 600 nm, and 800 nm PSL particles on quartz, Ag foil, and AgNP substrates. (B) Box and whisker plot of calculated EFs for vibrational modes of interest for all particle sizes. The center line represents the median, the box outlines the inner quartiles, and the whiskers represent the 10th and 90th percentile.

signal was detected for PSL particles on plain quartz substrate, intensity was very low and vibrational modes were difficult to distinguish from background noise, particularly for the 400 nm sized particles. For the 800 nm PSL particles, EFs for the symmetric ring stretching modes, ν_s(C-C)[98–100] at 1000 cm^{-1} and ν_s(C=C)[98–100] at 1602 cm^{-1}, ranged for 7 to 32 and 11 to 33, respectively, for the Ag foil and 1 to 4 and 2 to 9 for the AgNP substrate, respectively. In comparison to the ring stretching modes, C-H bending and stretching modes showed greater enhancement in response to the SERS effect. EFs for the C-H bending mode (δ(C-H), 1452 cm^{-1}),[98,99] C-H stretching mode (ν(C-H), 2908 cm^{-1}),[98,99] and aromatic C-H stretching mode (ν(C-H) aromatic, 3054 cm^{-1})[98,99] ranged from 20 to 161, 54 to 233, and 4 to 142, respectively, for the Ag foil and 5 to 26, 1 to 4, and 1 to 3, respectively, for the AgNP substrate. The EF values for the AgNP substrate samples are consistent with previously reported EF values for $(NH_4)_2SO_4$ and $NaNO_3$ standard particles analyzed with SERS using similar substrates.[87] SERS enhancement was observed for the 400 and 600 nm sized particles on Ag foil and EFs for the five PSL vibrational modes ranged from 4 to 151, with the δ(C-H) and ν(C-H) modes again exhibiting the largest enhancements. All Raman spectra, for PSL particles on both quartz and Ag foil, are provided in the Supplementary Information. It should be noted that both the 400 nm and 600 nm particles are smaller than the 721 nm diameter of the laser spot (for a 532 nm laser with 0.9 N.A. objective).

The large variability in EFs, particularly evident for the Ag foil samples, could be attributed to varying degrees of coupling between LSPRs with analytes depending on location of the particle with respect to the SERS-enhanced volume on the rough surface of the Ag foil or inconsistent distribution of AgNPs. Preliminary work testing several other Ag SERS substrates is included in the Supplementary Information and results were, at best, comparable to the AgNP

enhancement shown here. Despite the variability in enhancement, the Ag foil substrate yielded the highest EFs and thus, was used as the SERS substrate for all subsequent experiments in this work.

Across all vibrational modes, there was no clear relationship between particle size and enhancement. Enhancement was expected to increase with increasing particle size, as the higher number of analyte molecules present in the larger particles could enable more opportunities for coupling to LSPRs and lead to greater enhancement of the Raman signal. This was observed somewhat for the largest and smallest sized PSL particles analyzed, as the 800 nm particles were consistently more enhanced than the 400 nm particles, but the 600 nm particles exhibited the lowest levels of enhancement. The cause for the low enhancement observed for the 600 nm PSL particles is unclear at this time, but could possibly be due to PSL quality, crowding effects, or the arrangement of PSL molecules hindering coupling between LSPRs and analyte molecules. The cause of the low enhancement for the 600 nm PSL particles remains unclear, as the inorganic particles investigated as part of this study (discussed below) were more consistent with the 400 nm and 800 nm PSL particles, with larger sized particles yielding more enhanced spectra.

In addition to PSL particles, which are primarily organic, $(NH_4)_2SO_4$ and $NaNO_3$ particles were also tested since atmospheric aerosol particles often contain these inorganic components.[101] $(NH_4)_2SO_4$ and $NaNO_3$ particles were generated from solution and size-selected at 400 nm, 600 nm, and 800 nm for SERS analysis. For $(NH_4)_2SO_4$, the $\nu(SO_4^{2-})$ and the ν(N-H) stretching mode of NH_4^+ were studied (Figure 2). The $\nu_1(SO_4^{2-})$[44,46,47,102,103] mode at 963 cm^{-1} had EFs ranging from 30 to 841, which is up to ~420 times greater than the average EFs reported by Craig et al. using AgNP SERS substrates.[87] There was a red shift in peak location for the SERS enhanced $\nu_1(SO_4^{2-})$ mode, shifting from 975 cm^{-1} to 963 cm^{-1}, along with an increase

in peak broadness. This shift is possibly attributed to charge-transfer interactions between Ag and the $(NH_4)_2SO_4$ molecules and is consistent with earlier work studying SERS enhancement of $(NH_4)_2SO_4$/sucrose particles.[90] The ν(N-H)[102,103] mode centered at 3130 cm^{-1} had EFs ranging from 33 to 730. It should be noted that ν(N-H) is broader due to hydrogen bonding and can be difficult to quantify in low-intensity spectra. For $NaNO_3$, three stretches corresponding to NO_3^- were studied (Figure 3). $\nu_1(NO_3^-)$[47,103,104] at 1067 cm^{-1} had EFs ranging from 8 to 48, which is up to ~16 times greater than the average EFs reported by Craig et al. using AgNP SERS

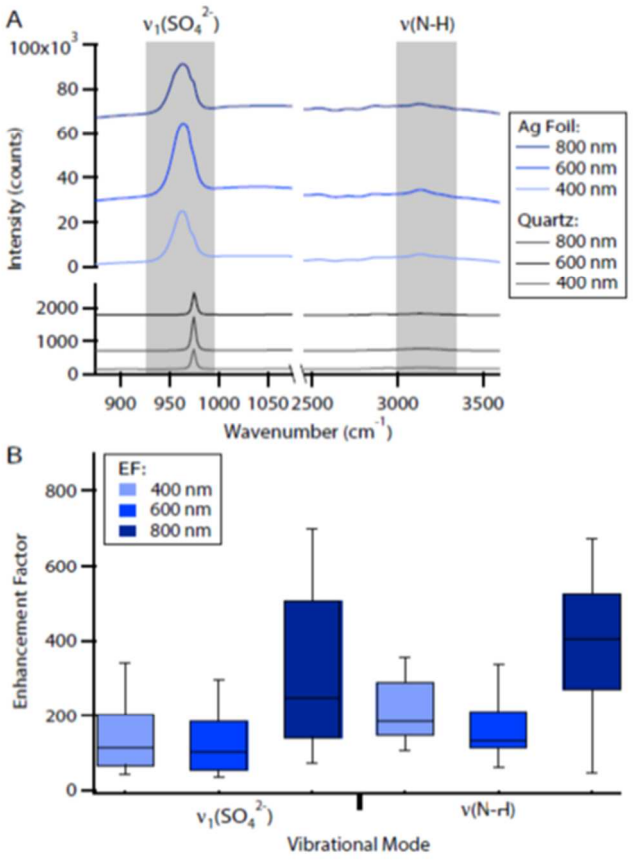

Figure 2. (A) Average Raman spectra for 400 nm, 600 nm, and 800 nm $(NH_4)_2SO_4$ particles on quartz and Ag foil substrates. (B) Box and whisker plot of calculated EFs for vibrational modes of interest for all particle sizes. The center line represents the median, the box outlines the inner quartiles, and the whiskers represent the 10th and 90th percentile.

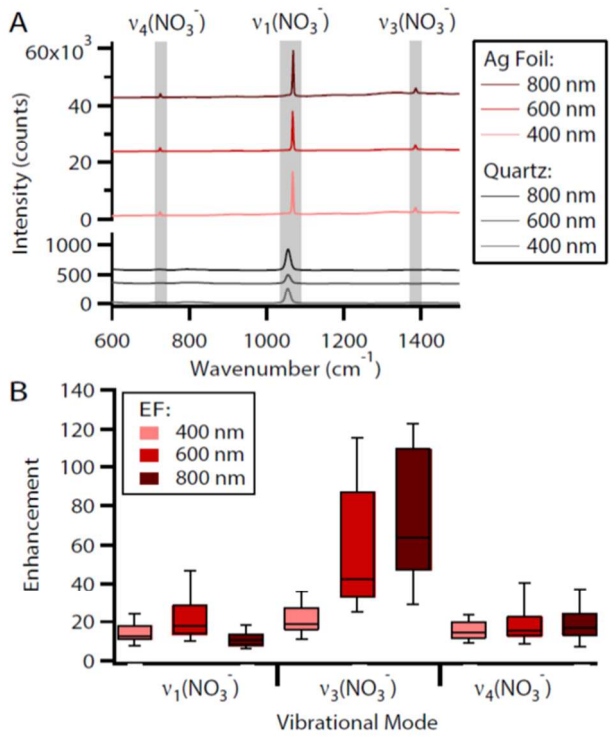

Figure 3. (A) Average Raman spectra for 400 nm, 600 nm, and 800 nm $NaNO_3$ particles on quartz and Ag foil substrates. (B) Box and whisker plot of calculated EFs for vibrational modes of interest for all particle sizes. The center line represents the median, the box outlines the inner quartiles, and the whiskers represent the 10th and 90th percentile.

substrates.[87] There was a slight blue shift in peak location for the SERS enhanced $\nu_1(NO_3^-)$ mode, shifting from 1056 cm^{-1} to 1067 cm^{-1}, along with an increase in peak sharpness. The 1054 cm^{-1} mode corresponds to aqueous, free NO_3^-, while the 1067 cm^{-1} mode corresponds to Na^+-bound NO_3^-.[69,103] Interestingly, this result is inconsistent with previous work that observed a red shift from 1067 cm^{-1} to 1054 cm^{-1} for $\nu_1(NO_3^-)$.[87,105] Previous work proposed that $NaNO_3$ cannot couple as effectively as NO_3^- with the Ag substrate due to interaction with sodium or incorporation into a $NaNO_3$ amorphous solid or crystal, leading to a red shift occurring with increased enhancment.[87] Experimental conditions, such as RH impacts on particle phase, could play a role, but further work is needed to characterize this phenomenon and reconcile the discrepancy in observed peak shifting. Other modes, $\nu_3(NO_3^-)$[103,104] at 1386 cm^{-1} and $\nu_4(NO_3^-)$[103,104] at 725 cm^{-1}, had larger EFs, ranging from 5 to 116, and no observable peak shifts. All Raman spectra, for $(NH_4)_2SO_4$ and $NaNO_3$ particles on both quartz and Ag foil, are provided in the Supplementary Information.

Qualitative observation shows that EFs increased with increasing particle size for the vibrational modes studied for the 400 nm and 800 nm $(NH_4)_2SO_4$ particles. As discussed

previously, this could be attributed to the higher number of analyte molecules present in the larger particles and the greater probability that a portion of the particle would be within the enhanced region of a LSPR after impaction leading to greater observed enhancement. An alternate explanation for increased enhancement is the accumulation of crystals or ions at the foil interface as aqueous particles spread upon impaction. This effect applies only to the $(NH_4)_2SO_4$ and $NaNO_3$ particles, as the PSL particles are solid. Similar to the PSL particles, the 600 nm $(NH_4)_2SO_4$ particles exhibited the lowest enhancement. There is no apparent trend for the EFs for the vibrational modes studied for all sized $NaNO_3$ particles. Also, as with the PSL particles, there was a high level of variability in enhancement for all of the $(NH_4)_2SO_4$ and $NaNO_3$ vibrational modes. Further testing with more samples, both in terms of particle sizes studied and number of particles analyzed, is necessary to resolve any trends or relationships between particle size and enhancement.

Thus far in this study, through SERS, the smallest particle size shown has been 400 nm, which is about 2-3 times smaller than the size of aerosol particles typically characterized through Raman analysis. However, SERS is capable of single molecule detection and so, should allow for Raman analysis of aerosol particles < 400 nm. To test this limit, 150 nm PSL particles were collected on Ag foil. It should be noted that a 150 nm sized particle is well below to the diffraction limit of visible light and the Raman spectrometer used in this study (300-400 nm and 361 nm, respectively), making individual particle identification challenging. Automated point-by-point mapping with a step size of 0.25 μm was used over a larger region of the substrate, enabling spectra to be collected for the 150 nm particles that were difficult to distinguish optically due to spatial resolution limitations. A representative spectrum for a 150 nm PSL particle and its corresponding location are shown in Figure 4. The five vibrational modes focused

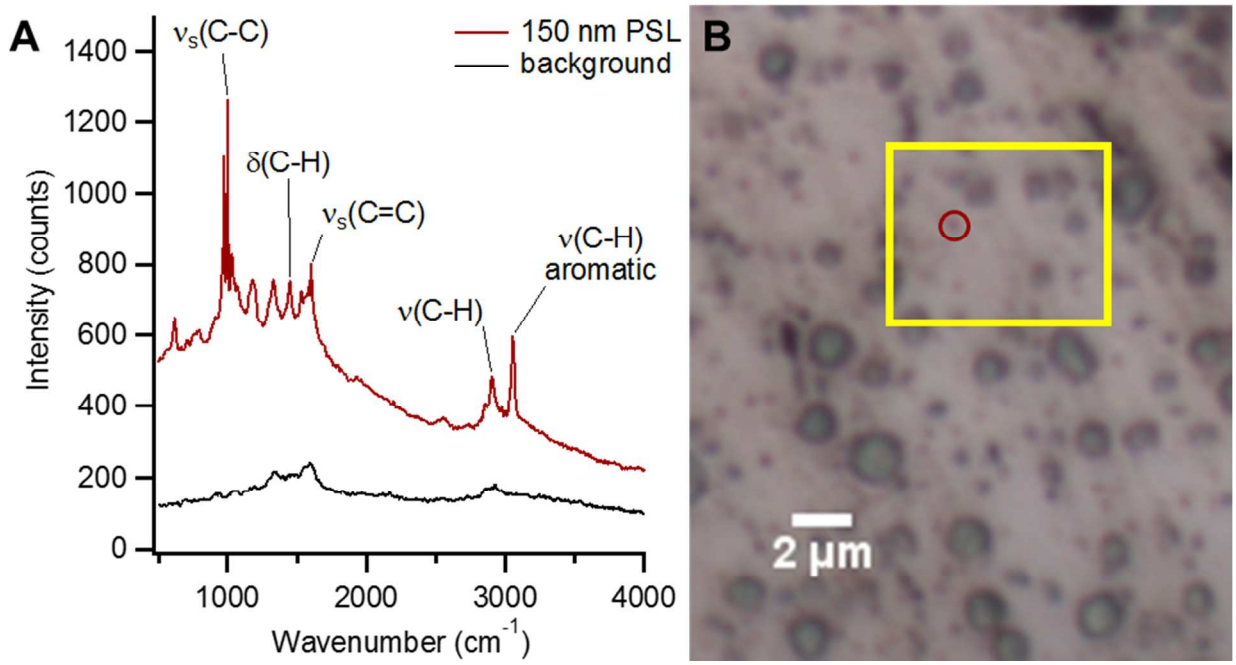

Figure 4. (A) SERS spectrum collected via automated point-by-point mapping of a 150 nm PSL particle on Ag foil substrate. (B) Optical image of 150 nm PSL sample on Ag foil, with the yellow box highlighting the mapped area and the red circle indicating the location of the Raman spectrum shown in (A).

on in the earlier analysis are indicated, though other vibrational modes were also enhanced and present. In the optical image, the yellow box highlights the mapped region, while the red circle indicates the point corresponding to the SERS PSL spectrum. The small, dark spots are individual 150 nm PSL particles, while the larger spots are most likely agglomerates and were avoided for this analysis. It should also be noted that marks and scratches to the Ag foil can lead to intensity in the Raman spectra that make it difficult to identify vibrational modes corresponding to the particles. To reduce substrate interference, smooth regions of the Ag foil were selected for mapping analysis.

In addition to testing SERS with laboratory-generated aerosol standards below the diffraction limit, ambient aerosol particles were also sampled, size-selected at 150 nm, and impacted in a same manner (Figure 5). Based on the sampling time and aerosol concentrations, the substrate has primarily individual particles with minimal overlap. While it is difficult to

definitively identify vibrational modes in ambient aerosol due to their complex chemical composition and overlapping regions where modes can be present, tentative assignments are proposed. Peaks in the 500-900 cm^{-1} region could correspond to ν(Si-O-Si), δ(Si-O-Al), and other lattice vibrations of fly ash or silicon and aluminosilicate minerals,[54,98,106–108] δ(C-O) of carbonates and carboxylic acids,[54,87,98] or "breathing" modes of aromatic rings.[57] The peaks at 963 – 988 cm^{-1} most likely correspond to $\nu_1(SO_4^{2-})$,[44,46,47,102,103] and are exhibiting the same red shift observed for the $(NH_4)_2SO_4$ standard particles discussed earlier.[90] Peaks in the 1000-1700 cm^{-1} region could correspond to a range of vibrational modes of organic functional groups, including stretching modes, such as ν(C-O), ν(C-C), ν(C=C), ν(COO^-), and ν(C-OH), and bending and twisting modes, such as δ(CH_2), δ(CH_3), δ(C-C), δ(O-C-O), and δ(O-H).[44,47,54,57–60,67,98,109,110] Peaks in the higher energy 2700-3000 cm^{-1} region correspond to symmetric and asymmetric ν(CH_2) and ν(CH_3) modes.[44,47,54,57,59,98] Specific compounds present in the ambient aerosol particles related to these functional groups could include long chain aliphatics, glyoxal oligomers, peroxides, organic sulfates, and minerals associated with dust.[47,54,59,60,70] To our knowledge, this is the first SERS-enhanced spectroscopic analysis of aerosol particles that have a smaller diameter than the visible light diffraction limit, an important step towards measurements of aerosol particles in a key size range for atmospheric surface chemistry. Additionally, for these

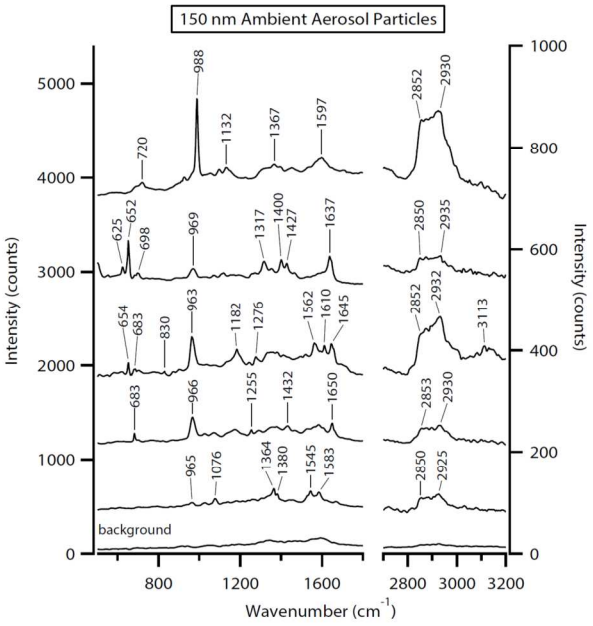

Figure 5. SERS-enhanced spectra obtained from Raman mapping of 150 nm size-selected ambient aerosol particles.

ambient spectra, vibrational modes attributed to organic species exhibited greater enhancement in the lower frequency region (1000 – 1800 cm^{-1}) than the higher frequency region (2700 – 3000 cm^{-1}), which is consistent with previous work with SERS of ambient particles.[87] This demonstrates the potential for SERS to enable the study of vibrational modes that are not as well characterized in the literature due to the difficulties associated with detecting them in aerosol particles via traditional microspectroscopic methods.

4 Conclusions

SERS was applied to the study of atmospheric aerosol particles to improve the limit of detection in terms of particles size. 400 nm, 600 nm, and 800 nm size-selected laboratory-generated aerosol particle standards of PSLs, ammonium sulfate, and sodium nitrate were collected on Ag foil SERS substrates and analyzed. Average enhancement factors for a range of inorganic and organic vibrational modes were calculated to be on the order of 10^2 and as large as 530. SERS enhancements may increase with increasing particle size, as observed with the 400 nm and 800 nm PSL and $(NH_4)_2SO_4$ standards, but the 600 nm PSL and $(NH_4)_2SO_4$ had the lowest EF values and there was no observed consistent trend between SERS enhancement and particle size for the $NaNO_3$ standard. These results are likely due to variability in LSPRs on the foil surface and subsequent coupling with analyte molecules. Further testing with more particle sizes and increased number of particles analyzed is necessary to resolve a definitive relationship between particle size and enhancement. Ag foil substrates were also used for SERS analysis of 150 nm PSL and ambient aerosol particles via automated Raman mapping. All five PSL vibrational modes characterized with the larger sized particles were identified in the SERS enhanced spectra of the 150 nm particles. For the ambient aerosol, a range of inorganic and organic vibrational modes were detected, and corresponding functional groups were proposed.

To our knowledge, this is the first vibrational spectroscopic analysis of aerosol particles approaching the mode of the atmospheric number size distribution (~100 nm). These results show the potential for SERS to enable improved analysis of aerosol particle chemical composition and mixing state for the most atmospherically abundant particle sizes. The ability to detect chemical species in these small volume particles also shows the potential for future SERS work to probe differences in composition at aerosol surfaces due to phase separation, the presence of surfactants, or surface-level reactions. Overall, future SERS studies of atmospheric aerosol composition could lead to improved understanding of multiphase atmospheric processing and aerosol impacts on climate and human health.

Conflicts of Interest

There are no conflicts to declare.

Acknowledgments

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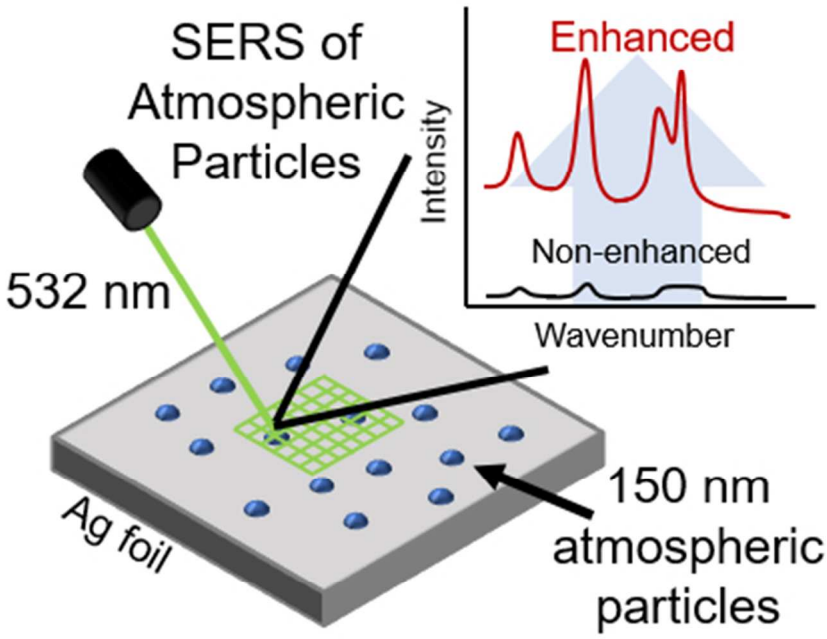

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