

Heat-Assisted Argon Electrospray Interface for Low-Flow Rate Liquid Sample Introduction in Plasma Spectrometry

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A heated ($\approx 90^\circ\text{C}$) laminar flow interface has been designed to assist in the development of an argon electrospray sample introduction system for low-flow rate applications using inductively coupled plasma (ICP) spectrometry. Previously, the stability and robustness of the ICP were compromised by the entrainment of air, N_2 , or gas mixtures (e.g., $\text{Ar}-\text{N}_2$) from the electrospray source. Also, more concentrated organic solvents (e.g., 50% (v/v) methanol–water), typically introduced by electrospray, could generate carbon deposits that obstruct the entrance lens to an ICP optical emission spectrometer (ICP-OES) or the sampler/skimmer cone interface in an ICP mass spectrometer (ICP-MS), decreasing analyte sensitivity. With the new interface design, a stable spray of 5% (v/v) methanol–water in a pure argon environment is achieved, eliminating the aforementioned problems. The turbulence and the consequent droplet loss caused by high gas velocity around the electrospray capillary are mitigated by the use of a laminar-flow gas with the aid of a flow diffuser. The argon electrospray interface is successfully installed on an ICP-OES and an ICP-MS for the first time.

Inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) are among the most powerful elemental analysis techniques. Such an attribute has stimulated a broad interest in ICP based techniques that may be gauged by over 2000 ICP-related publications in 2008 and over 18 000 publications in the past 10 years (based on ISI Web of Science). The larger portion of these publications is based on ICP-MS studies, due to the excellent detection limits (in low femtogram per gram levels) and dynamic range of more than 8 orders of magnitude.¹ These characteristics have attracted interest in research areas such

as proteomics,^{2–5} metallomics,^{6–11} biomedical studies,^{3,7,8,10,12–23} and trace elemental speciation.^{24–28}

The constantly decreasing sample size within these areas of research along with the widespread application of low-flow separation techniques have led to an increasing demand for the

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development of highly efficient, low-flow, liquid sample introduction interfaces for ICP-MS.^{29–32} Recently, direct injection methods have been developed to meet these requirements.^{25,33,34} In most direct injection devices, the spray is formed pneumatically at the base of the plasma at solution flow rates of 1–100 $\mu\text{L min}^{-1}$, introducing 100% of the sample into the ICP. However, wide droplet size and velocity distributions as well as spatial scattering of the aerosol lower the percentage (<50%) of the sample mass contributing to the analytical signal.^{35–37}

Pneumatic generation of an aerosol with optimum characteristics at solution flow rates below 1 $\mu\text{L min}^{-1}$ is particularly challenging because high gas flow rates are needed in this regime, resulting in very fast traveling droplets that survive the plasma due to short residence time upon direct injection. A semidirect sample introduction technique has been introduced recently to alleviate the above-mentioned problems.²⁹ In this method, aerosol is generated inside a small spray chamber (≈ 3 mL total volume) using a very small solution capillary orifice (10 μm diameter) at high gas flow rates (>1.0 L min^{-1}). Such an arrangement results in near 100% transport efficiency at solution flow rates of 50–500 nL min^{-1} . The nebulizer gas serves as both the aerosol transport medium and the injector gas of the ICP, creating the axial channel inside the plasma. The axial channel flow directly influences the optimum position of atom/ion generation inside the plasma and, consequently, has a profound effect on the signal amplitude and precision.

Nonpneumatic nebulization offers an attractive alternative in the low-flow regime because aerosol generation and transport are decoupled, allowing independent optimization of the injector gas flow rate. Among nonpneumatic methods, electrospray is an efficient nebulization technique capable of operating at extremely low flow rates (nanoliters per minute). The successive desolvation and Coulombic fission of the charged droplets reduce the droplet sizes as they travel toward the plasma, a behavior highly favored in the interface design for ICP spectrometers. However, loss of the aerosol to the walls of the interface, as a result of its charged state, is more likely in comparison to pneumatically generated droplets. To increase the transport efficiency of the charged aerosol, one may neutralize the droplets using radioactive or electrical ionizers.^{38–42} However, radioactive ionizers produce both

negatively and positively charged particles, limiting the neutralization efficiency of unipolar charged electrospray aerosol compared with electrical ionizers.³⁹ Also, radioactive ionizers require strict regulation and have high replacement costs. For the introduction of a charged aerosol without neutralization, the spray chamber must be optimized to a minimum volume with the appropriate placement of a counter electrode to guide the aerosol through the interface, preventing interaction of the droplets with the walls of the interface and the counter electrode.⁴³

Due to several obstacles, very few studies have attempted to utilize electrospray for sample introduction in ICP-OES and ICP-MS. The most problematic is the gas incompatibility between the electrospray and the ICP.^{43–45} Electrospray is generally formed in air, nitrogen, carbon dioxide, or gas mixture environments (e.g., Ar–N₂, air–CO₂) and with solvents containing pure methanol, 50% (v/v) methanol–water, or 50% (v/v) acetonitrile–water.⁴⁶ The introduction of nitrogen or air into the ICP affects the plasma properties and kinetic energies of the ions sampled into the MS. For example, an Ar–N₂ plasma has a lower electron number density, electron temperature, and gas temperature compared to an Ar ICP,^{47–49} adversely affecting the analytical performance of the ICP instrument, especially for elements having higher ionization potentials (e.g., phosphorus and sulfur).¹ The presence of air in the plasma gas makes it difficult to ignite and sustain a stable plasma. Organic solvents can cause poor ICP-MS performance also, due to the deposition of carbon on the sampler/skimmer cones and torch. Additionally, these solvents require higher power levels and lower sample flow rates to reduce the effects of solvent loading.¹ Accordingly, the analytical performance of ICP spectrometries improves upon use of low organic content (<10% v/v) solvents and 100% argon gas. However, this approach compromises electrospray stability because of the high surface tension of water and the formation of a coronal discharge in the argon environment due to the applied high voltage (≈ 1 –2 kV in our setup).

The goal of this work was to design an electrospray interface that could establish a stable spray in a pure argon environment with little or no organic solvent in solution and could be coupled to ICP-OES and ICP-MS instruments for elemental detection. The first design investigated to electrospray pure water in 100% argon was a pressurized (138–207 kPa) interface.⁵⁰ Based on Paschen's Law (eq 1), this type of interface should increase the density of

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the argon gas (eq 2) and, thus, increase the breakdown voltage of the argon gas,^{51,52}

$$V = f(pd) \quad (1)$$

$$n = \frac{p}{kT} \quad (2)$$

where V is the breakdown voltage (V), p is the pressure (Pa), d is the gap distance (cm), n is the density (kg m^{-3}), T is temperature (K), and k is Boltzmann's constant (J K^{-1}). The gas density, n , is affected by both temperature and pressure. Therefore, the breakdown voltage of the argon gas can be increased to a level above that required for electrospray formation by elevating the pressure. This approach was successful in spraying pure water, requiring an applied voltage of 2.2 kV in a pressurized Ar environment of 207 kPa with the solution delivered at 500 nL min^{-1} . To pressurize the electrospray chamber to 207 kPa, the design required a $100 \text{ }\mu\text{m}$ gas outlet aperture. This small aperture reduced the transport of the aerosol to the ICP, eliminating any observable signal.⁵⁰

The high surface tension of water necessitates a high electrospray onset voltage, twice that of methanol,⁵³ easily leading to the formation of an electrical discharge, which leads to low analyte sensitivity and poor spray stability. A means of reducing the surface tension of water is the application of heat, as used in high temperature chromatography.⁵⁴ Investigators have reported the use of a heated electrospray interface for a variety of applications,^{55,56} including successfully electrospraying pure water.⁵⁷ However, none of these applications are conducted in argon, and the techniques utilize molecular MS. Most molecular MS-based bioanalysis techniques lack the ability of ICP-MS to provide highly accurate quantification.

As a result, a heated ($\approx 90 \text{ }^\circ\text{C}$) argon electrospray interface was investigated to reduce the surface tension of water, so that the required voltage for a stable electrospray is below the minimum breakdown voltage of argon ($\approx 2 \text{ kV}$ for this system) to prevent an electrical discharge from occurring in argon.⁵⁷ The design of this interface is important in minimizing the surface tension of water and maximizing transport efficiency of the aerosol to the plasma. The proposed interface is based on the design of a nitrogen laminar-flow electrospray device.⁵⁸ This design eliminates turbulence and consequent droplet loss caused by high gas velocity around the electrospray needle. Evaluation of the new design to assess the analytical performance of the electrospray was conducted using both ICP-OES and ICP-MS instruments. With

the heat-assisted argon electrospray interface, the establishment of a stable spray with 5% (v/v) methanol–water in a 100% argon environment is achievable. To the authors' knowledge, this is the first report of establishing a stable spray in pure argon and successfully coupling the device to both ICP-OES and ICP-MS instruments.

EXPERIMENTAL

Identification of commercial products in this paper was done in order to specify the experimental procedure. In no case does this imply endorsement or recommendation by the National Institute of Standards and Technology.

Interface Design. A schematic of the heat-assisted argon electrospray interface is illustrated in Figure 1. The solution is passed through a stainless steel (SS) union (Valco Instruments, Houston, TX) that is connected to a SS threaded rod (McMaster-Carr, Atlanta, GA) using a conductive polymer ferrule (Upchurch Scientific, Oak Harbor, WA). The ferrule holds the fused silica electrospray needle ($360 \text{ }\mu\text{m}$ o.d., $50 \text{ }\mu\text{m}$ i.d. tapered to $30 \text{ }\mu\text{m}$ tip, Standard Coated, New Objective Inc., Woburn, MA) at the center of the $1/16 \text{ in.}$ channel drilled through the SS rod. In the previous design, a noncoated, electrospray needle was used; however, this required a 2.2 kV potential to establish a successful electrospray. This potential often increased after a few experiments, increasing the probability of a coronal discharge. With the new design, the standard (platinum) coated needle reduced the required potential to 1.3 kV, further decreasing the likelihood of an electrical breakdown in the argon environment, for longer periods of time. The SS rod screws into the PEEK assembly, which has another threaded inlet perpendicular to the SS rod for the argon carrier gas. A copper wire is used to apply the high voltage from the power supply to the SS rod and, eventually, to the solution via the conductive ferrule. Two glass shells are contained in this interface assembly as well. Glass shell (1) (2 cm long, 11.5 mm i.d., 14 mm o.d.) is inserted into the PEEK assembly and secured using an O-ring that serves as a window to monitor the spray with an optical microscope (model ZST, Unitron, Bohemia, NY) equipped with a charge-coupled device (CCD) camera. A 115 mm Delrin flow diffuser disk (fabricated in house), consisting of eight outer holes with a diameter of 2.0 mm and a 1.6 mm center hole, is fitted into the glass shell to center the electrospray needle and ensure a laminar gas flow inside the interface. The glass shell also connects to a second PEEK cylinder which houses the grounded platinum ring electrode (Fisher Scientific, Hampton, NH). This electrode is used to focus and guide the charged droplets through glass shell (2) (tapered from $1/2 \text{ in.}$ to $1/4 \text{ in.}$ o.d.) to an injector nozzle (Meinhard Glass Products, Golden, CO) via a grounded brass union. To couple the electrospray device to ICP-OES and ICP-MS instrumentation, the injector nozzle fits into a modified ICP torch adapter fabricated in-house. The axial positioning of the electrospray needle can be changed by turning the threaded SS rod. The distance between the needle tip and the grounded ring electrode is adjusted to 15 mm for the formation of a stable spray. To reinforce the electrospray interface, three threaded rods (McMaster-Carr) are passed through and bolted to two Delrin disks that are fastened to either side of each PEEK assembly. This helps to anchor and seal the electrospray interface, preventing any gas leaks.

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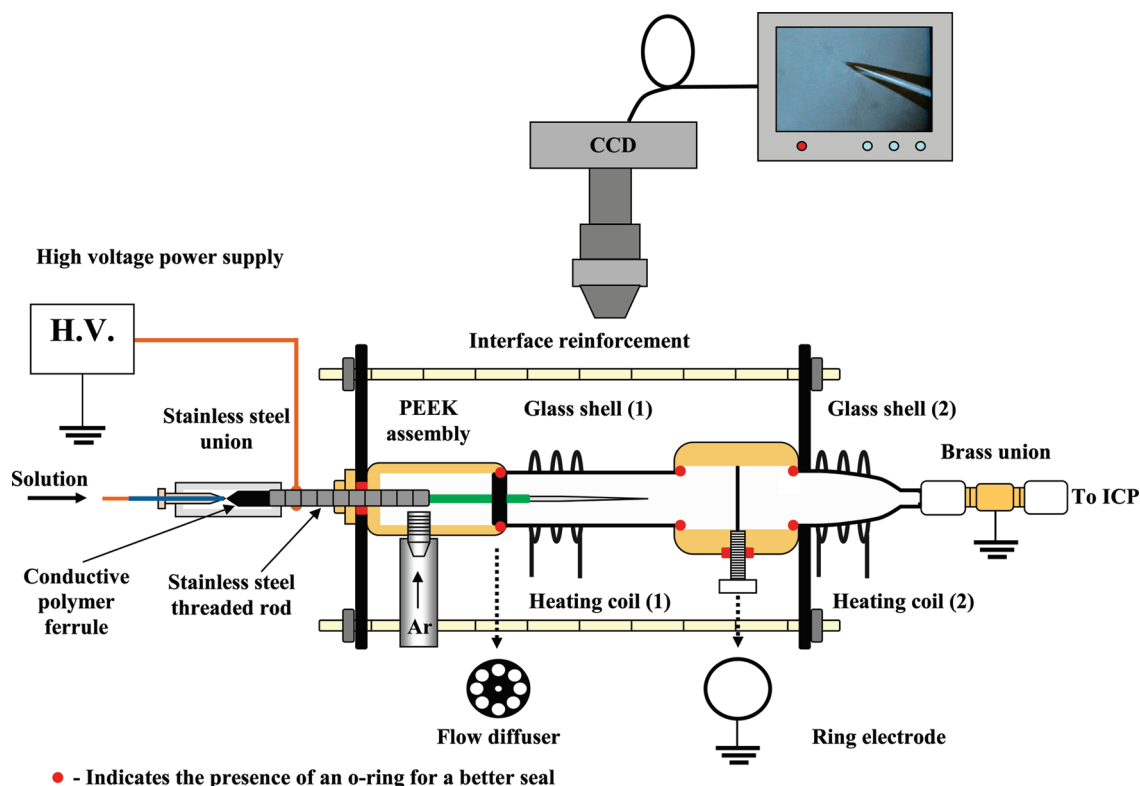


Figure 1. Schematic diagram of the laminar flow heat-assisted argon electrospray interface for ICP spectrometry.

Table 1. Operating Conditions for Heat-Assisted Argon Electrospray Interface Utilizing ICP-OES

ICP-OES system	Optima 5300 DV
RF power (W)	1500
plasma gas flow rate (L min ⁻¹)	15
auxiliary gas flow rate (L min ⁻¹)	0.5
carrier gas flow rate (L min ⁻¹)	0.45
viewing	axial
on-chip integration time (s)	1.024
total read time (s)	8.192
injector nozzle (tip i.d., μm)	500
sample introduction	heat-assisted argon electrospray
solution flow rate ($\mu\text{L min}^{-1}$)	2–4
solution delivery	syringe pump ^a
electrospray needle ^b	360 μm o.d., 50 μm i.d., 30 μm tip, standard platinum coated
electrospray chamber temperature ($^{\circ}\text{C}$)	≈ 90
needle tip–ring electrode distance (mm)	15
voltage (kV)	1.3
solvent	5% (v/v) methanol–water

^a Model KDS100, KD Scientific, New Hope, PA. ^b New Objective, Woburn, MA.

Table 2. Operating Conditions for the Argon ICP-MS

ICP-MS system	Elan DRC II
RF power (W)	1100
sampler (orifice diameter, mm)	nickel, 1.1
skimmer (orifice diameter, mm)	nickel, 0.9
plasma gas flow rate (L min ⁻¹)	15
auxiliary gas flow rate (L min ⁻¹)	1.2
carrier gas flow rate (L min ⁻¹)	0.55
injector nozzle (tip i.d., μm)	500
ICP-MS data acquisition parameter	
scan mode	peak hopping
points/mass	1
resolution (amu)	0.7
sweeps/reading	20
readings/replicates	1
replicates	10
dwell time/mass (ms)	100
integration time (ms)	2000

solution. The electrospray was operated under the same optimum spraying conditions on both the ICP-OES and ICP-MS instruments (Table 1).

Instrumentation. The Optima 5300 DV ICP-OES (PerkinElmer, Inc., Shelton, CT) and ELAN DRC II ICP-MS (PerkinElmer Sciex, Inc., Thornhill, ON) instrumentation details are listed in Tables 1 and 2. The solution was delivered at 2–4 $\mu\text{L min}^{-1}$ using a 1000 μL syringe (Hamilton Company, Reno, NV) and a syringe pump (Model KDS100, KD Scientific, New Hope, PA). For flow injection analysis, a 100 nL microbore internal sample injector was used with a microelectric actuator (Model C4–1344.10 EH, Valco Instruments). The connections between the pump, the valve, and the stainless steel union were made using a fused silica capillary (75 μm i.d., 150 μm o.d., Polymicro Technologies, Phoenix, AZ) to minimize the dead volume, thereby reducing peak broadening. The injector/carrier gas flow was controlled by the instrument software.

The electrospray chamber was heated by means of resistive heating using a nichrome alloy wire (1.038 Ω , Driver-Harris Company, Harrison, NJ) that was shaped into a 3-turn design that wrapped each glass shell as shown in Figure 1. The electrospray solution and argon gas were heated by means of heat transfer from the wire-wrapped glass shells (Figure 1). The voltage applied to the wire was controlled by a Powerstat variable autotransformer (0 to 140 V, Superior Electric Co., Bristol, CT). The voltage was optimized to obtain an electrospray chamber temperature of approximately 90 $^{\circ}\text{C}$. This temperature was required to achieve a stable spray in pure argon with only a 5% (v/v) methanol–water

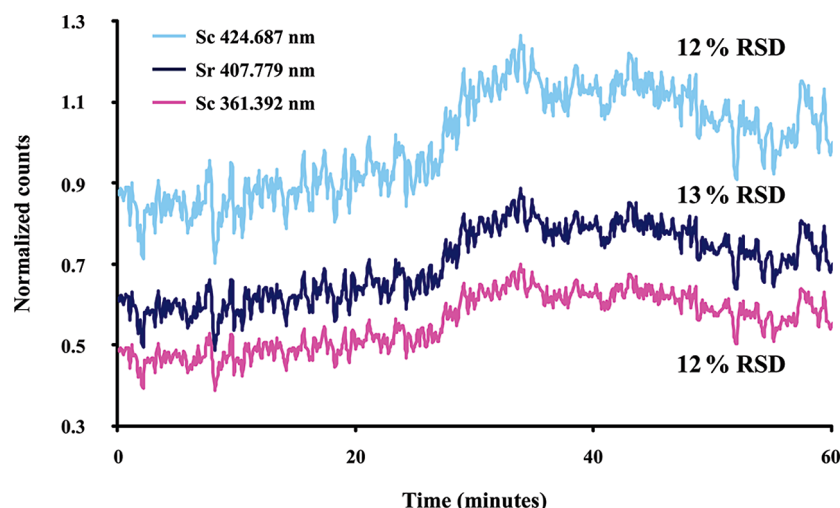
Table 3. Intensities and Precisions as a Function of Sample Uptake for Heat-Assisted Argon Electrospray Interface Utilizing ICP-OES

analyte	wavelength (nm)	2 $\mu\text{L min}^{-1}$		3 $\mu\text{L min}^{-1}$		4 $\mu\text{L min}^{-1}$	
		mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD	mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD	mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD
Sr	407.779	2.9	2.1	4.0	2.5	4.3	2.7
Sr	421.552	1.2	2.4	1.7	2.4	1.9	2.8
Sr	460.752	0.096	3.6	0.13	2.8	0.14	4.3
Sc	361.392	1.8	2.1	2.7	2.5	2.9	2.9
Sc	357.253	0.64	4.1	1.1	3.8	1.2	4.0
Sc	424.687	3.6	2.0	5.1	2.5	5.5	2.8
Sc	357.634	0.54	2.1	0.78	2.5	0.85	2.8
Y	371.029	1.4	2.2	2.0	2.6	2.2	3.1
Y	324.227	0.38	2.4	0.56	2.3	0.61	2.6
Y	360.073	0.79	2.2	1.2	2.7	1.3	3.1

Table 4. Intensities, Precisions, and Detection Limits for a Heat-Assisted Argon Electrospray Interface and d-DIHEN Utilizing ICP-OES

analyte	wavelength (nm)	heat-assisted argon electrospray interface (4 $\mu\text{L min}^{-1}$)			d-DIHEN ^b (4 $\mu\text{L min}^{-1}$)		
		mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD	detection limit ^a (ng g^{-1})	mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD	detection limit ^a (ng g^{-1})
Sr	407.779	0.43	2.7	14	32	1.2	0.60
Sr	421.552	0.19	2.8	38	14	1.1	1.5
Sr	460.752	0.014	4.3	570	0.46	2.0	91
Sc	361.392	0.29	2.9	11	26	1.0	0.60
Sc	357.253	0.12	4.0	140	16	1.0	16
Sc	424.687	0.55	2.8	17	47	1.1	0.60
Sc	357.634	0.085	2.8	68	8.0	0.95	2.4
Y	371.029	0.22	3.1	26	19	1.1	0.90
Y	324.227	0.061	2.6	80	5.9	1.0	3.6
Y	360.073	0.13	3.1	28	11	1.0	3.0

^a Based on 3 s of the blank mass fraction measured at the analyte wavelength. ^b Nebulizer dimensions taken from ref 25 and operated at a nebulizer gas flow rate of 0.16 L min^{-1} .

**Figure 2.** Heat-assisted argon electrospray ICP-OES 1 h stability test, spraying a 10 $\mu\text{g g}^{-1}$ multielement solution at 4 $\mu\text{L min}^{-1}$.

Reagents and Sample Preparation. The performance evaluations of the heat-assisted argon electrospray interface using ICP-OES and ICP-MS were carried out with 10 $\mu\text{g g}^{-1}$ (Sc, Sr, and Y) and 2 $\mu\text{g g}^{-1}$ (Mg, Ag, Cd, In, Au, Tl, and Pb) multielement solutions, respectively. These solutions were prepared from 10 000 $\mu\text{g mL}^{-1}$ single element standard solutions (Inorganic Ventures, Lakewood, NJ) and contained 5% (v/v) methanol–water. Deionized water (18.3 M Ω cm) and HPLC grade methanol (Fisher Scientific, Hampton, NH) were used to

prepare the diluent and blanks. As an additional precaution, all solutions were filtered with a 0.22 μm filter (Fisher brand, Fisher Scientific) to remove small particulates that could clog the electrospray needle.

RESULTS AND DISCUSSION

Optimization of Electrospray Interface. The optimization of the electrospray interface temperature was the most important parameter for achieving a stable spray. At temperatures below 60

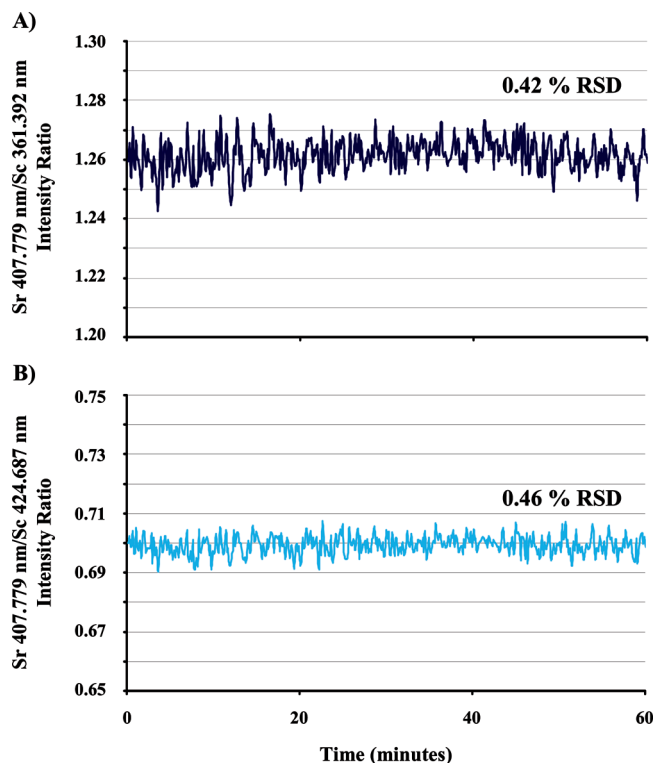


Figure 3. Use of internal standardization to minimize instrumental drift from the heat-assisted argon electrospray ICP-OES signal during a 1 h stability test. Analyte to internal standard precision, spraying a $10 \mu\text{g g}^{-1}$ multielement solution at a solution flow rate of $4 \mu\text{L min}^{-1}$: (A) Sr 407.779 nm/Sc 361.392 nm and (B) Sr 407.779 nm/Sc 424.687 nm.

$^{\circ}\text{C}$, a stable spray could not be achieved in the argon environment. A typical observation would be sputtering or a collection of sample on the electrospray needle. Above 100°C , the solvent would evaporate within the needle, preventing any type of spray formation. Using a variable autotransformer in the current setup, temperatures of $\approx 60^{\circ}\text{C}$ (corresponding to 2 V) and $\approx 90^{\circ}\text{C}$ (corresponding to 2.5 V) could be obtained. Only these two temperature settings could be achieved due to the sensitivity of the variable autotransformer. At a temperature of $\approx 90^{\circ}\text{C}$ compared to $\approx 60^{\circ}\text{C}$, the analyte sensitivity increased by a factor of ≈ 3 on average for most of the emission lines. The carrier gas flow rate was optimized at 0.45 and 0.55 L min^{-1} , respectively, for ICP-OES and ICP-MS. If the carrier gas flow rate were too low ($<0.35 \text{ L min}^{-1}$), there was insufficient energy to transport the aerosol to the ICP. Above the optimum carrier gas flow rate, the optimum temperature of the electrospray interface would decrease, reducing aerosol transport and/or destabilizing the spray. The applied voltage to the electrospray needle was held at the minimum voltage (1.3 kV) required for the onset of a stable electrospray to prevent a coronal discharge in the argon environment and premature degradation of the electrospray needle. The minimum voltage was determined on the basis of the stability of the spray monitored via an optical microscope with a CCD camera and the ICP signal precision. The distance from the counter electrode was established in prior work,⁵⁸ based on electrospray stability. Under the optimum experimental conditions listed in Tables 1 and 2, the electrospray interface was successfully installed on ICP-OES and ICP-MS instruments, and the performance of the device is shown in Tables 3–5.

ICP-OES Performance Evaluation. The effect of solution flow rate on the ICP-OES signal for the heat-assisted argon electrospray interface is shown in Table 3. The sensitivity increase is proportional to the increase in the solution uptake rate from 2 to $3 \mu\text{L min}^{-1}$ for most of the emission lines. However, the sensitivity declines slightly in proportionality with a solution uptake rate at $4 \mu\text{L min}^{-1}$. This could be due to a loss of larger droplets to the walls of the electrospray interface chamber. The short-term precision ($n = 5$) achieved at each flow rate ranges from 2.0% to 4.3% (RSD), which is higher than that achieved with a conventional sample introduction system (typically $\leq 1\%$). The recommended maximum solution flow rate for these electrospray needles is $1 \mu\text{L min}^{-1}$. However, at flow rates less than $2 \mu\text{L min}^{-1}$, the solvent was evaporating too quickly at the needle tip as a consequence of the high temperature required to maintain a stable spray in the argon environment. In Table 4, the analyte signals, precisions, and limits of detection for the heat-assisted argon electrospray-ICP-OES are compared to values obtained with a demountable, direct injection high efficiency nebulizer (d-DIHEN) both operated at a flow rate of $4 \mu\text{L min}^{-1}$. The d-DIHEN is approximately 70–85 times more efficient than the heat-assisted argon electrospray interface in terms of the mean ICP-OES signal intensity. However, with modifications to the current electrospray interface, signal intensities, detection limits, and precisions should improve. To do so will require a shorter travel distance from the electrospray needle to the plasma and more precise control of the chamber temperature to ensure efficient heating.

To examine the long-term stability of the heat-assisted argon electrospray interface, the ICP-OES signals for Sc 424.687 nm, Sr 407.779 nm, and Sc 361.392 nm were monitored for an hour (Figure 2), resulting in an average RSD of 12–13% for the three wavelengths. With the use of internal standardization (Sr 407.779 nm/Sc 361.392 nm or Sr 407.779 nm/Sc 424.687 nm) to minimize instrumental drift in the ICP-OES analyte signal, the precision was dramatically improved, decreasing the ratio RSD to 0.42% and 0.46%, respectively (Figure 3).

Flow injection analysis at reduced solution flow rates offers an attractive approach when the amount of sample is limited. The possibility of the analysis of nanoliter size samples using the heat-assisted argon electrospray interface was examined by utilizing a 100 nL internal sample loop. In Figure 4, the average maximum signal ($n = 6$) for the analytes is observed in $\approx 30 \text{ s}$, and the washout times for the analytes closely agree. The peak dispersion is most likely due to a small amount of the analyte colliding with the interface walls and gradually being carried to the ICP. This will be addressed in future work regarding the modification to the electrospray interface size and design. However, with the current setup, a washout time of $\approx 30 \text{ s}$ should be acceptable to eliminate any carryover from replicate injections for the analytes observed. The precision (RSD) for peak area determinations of Sc 424.687 nm, Sr 407.779 nm, and Sc 361.392 nm were 2.7%, 5.1%, and 4.0%, respectively.

ICP-MS Performance Evaluation. The majority of the heat-assisted argon electrospray interface performance tests were carried out on the ICP-OES instrument. However, eventual development of an efficient sample introduction method that operates at solution flow rates of 300 nL min^{-1} to $1 \mu\text{L min}^{-1}$ will

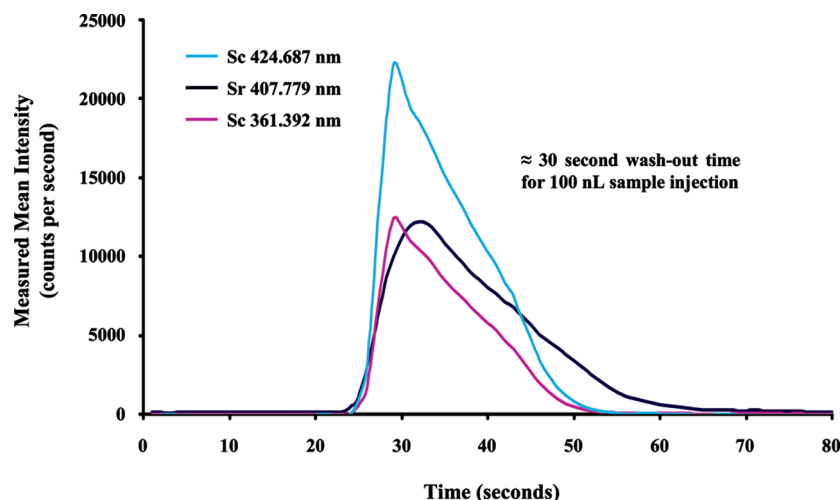


Figure 4. Heat-assisted argon electrospray ICP-OES profile for a 100 nL injection of $10 \mu\text{g g}^{-1}$ multielement solution at a solution flow rate of $4 \mu\text{L min}^{-1}$. The profile represents the average of six replicate 100 nL injections.

Table 5. Intensities, Precisions, and Detection Limits for a Heat-Assisted Argon Electrospray Interface Utilizing ICP-MS

analyte	mass	heat-assisted argon electrospray interface ($3 \mu\text{L min}^{-1}$)		
		mean intensity (counts $\text{s}^{-1} 10^3$)	% RSD	detection limit ^a (ng g^{-1})
Mg	24	17	5.6	1.7
Ag	107	4.2	8.9	3.6
Cd	111	4.8	4.5	4.2
Cd	114	12	6.0	2.3
In	115	54	7.0	2.9
Au	197	3.9	7.1	1.2
Tl	205	21	10	1.3
Pb	208	15	4.1	38

^a Based on 3 s of the blank mass fraction measured at the mass of the analyte.

require the sensitivity and detection limit capabilities of the ICP-MS. Recently, Pergantis et al.⁵⁹ developed a method directly coupling an electrospray with a differential mobility analyzer (DMA) to an ICP-MS. Their technique shows promise for sizing various types of nanoparticles, including biomolecules, and simultaneously providing the elemental composition via ICP-MS. However, as mentioned previously, there are technical challenges involving the coupling of an electrospray to an ICP instrument due to the presence of air or nitrogen typically being required for the electrospray. To overcome such limitations, they implemented an argon sheath gas. However, only a portion of the nanoparticles generated from the electrospray-DMA were carried into the sheath gas, leading to losses in transport efficiency to the ICP-MS.

The implementation of a heat-assisted argon electrospray interface could overcome such limitations. Mean intensity, limits of detection, and precision for the heat-assisted argon electrospray-ICP-MS are summarized in Table 5. The heat-assisted argon electrospray interface was optimized at a flow rate of $3 \mu\text{L min}^{-1}$ based on mean ICP-MS signal intensities and % RSD. With superior detection limits ($<100 \text{ pg g}^{-1}$ for the given analytes)¹

and sensitivity capabilities, it was assumed that the ICP-MS would offer significantly better analytical performance in comparison to the ICP-OES; however, this was not observed likely due to the transport efficiency of the current electrospray interface. In the future, the goal will be to operate the heat-assisted argon electrospray interface at a solution flow rate in the range of 300 nL min^{-1} to $1 \mu\text{L min}^{-1}$, which will generate finer droplets that can easily be evaporated via the heat source. This improvement along with modifications to the size and shape of the electrospray chamber are expected to decrease the occurrence of analyte loss to the chamber walls and counter electrode, leading to increased transport efficiency and sensitivity, while lowering detection limits. The initial success of the heat-assisted argon electrospray interface shows great promise, and with the possibility of coupling this device to a DMA and ICP-MS, a potential tool for proteomic and metallomic studies is provided.

CONCLUSIONS

This work describes the preliminary evaluation of a heat-assisted argon electrospray interface developed for plasma spectrometry. A heated ($\approx 90^\circ\text{C}$) laminar flow interface has been designed to spray 5% (v/v) methanol–water in a 100% argon environment. This device has been successfully coupled to both ICP-OES and ICP-MS instruments, providing observable signal with acceptable initial precision. A 1 h stability test proves the device can operate for long periods of time without breakdown, and the use of an internal injection valve allows for future work with flow injection analysis. However, to make this a viable tool for plasma spectrometry, the transport efficiency of the current device must be improved.

At present, research efforts are focused on (1) modification of the current heat-assisted argon electrospray interface to allow for a shorter travel distance from the electrospray needle to the plasma, (2) operation at less than $1 \mu\text{L min}^{-1}$ in order to produce a finer spray (i.e., smaller droplet size), and (3) more precise control of the chamber temperature and efficient heating to ensure that the small aerosol droplets are all evaporated and analyte loss to the chamber walls is minimized. If these improvements are successful, the heat-assisted argon electro-

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spray interface will be coupled to a DMA and eventually interfaced with an ICP-MS to potentially detect, size, and chemically characterize metal, metalloid, and halogen containing biomolecules. Additionally, the heat-assisted argon electrospray interface could be utilized as an alternative low-flow liquid sample introduction system to conventional systems that are inadequate for analyses limited in sample volume, such as DNA mass determination.^{60,61}

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