

Chapter 1. Introduction

1.1. Overview

In the past twenty years, charged droplets and strong electric fields have quietly revolutionized chemistry. In combination with an atmospheric-sampling mass spectrometer, charged droplets containing biomolecules or polymers become a source for desolvated, gas-phase ions of these analytes. The process by which charged droplets evaporate is remarkably “soft” in that the process imparts little to no energy to the resulting ions. This thesis explores two techniques for generating these charged droplets. One technique, electrospray ionization (ESI), is commonly employed for biomolecule mass analysis. In the second technique, jets of charged progeny droplets are emitted from neutral parent droplets in strong electric fields in a process we call field-induced droplet ionization, or FIDI.

A cartoon of the electrospray process is shown in Figure 1.1. Here an analyte-containing liquid is pumped through a capillary needle. A high voltage source establishes an electric field between the needle and a plate. Sufficiently high voltages produce strong fields within the liquid itself drawing the liquid to a tip as it exits the needle. From this tip, the liquid sprays outward as charged droplets that are accelerated in the electric field toward the plate. When the plate contains an inlet to a mass spectrometer, analyte within the charged droplets may be mass analyzed.¹ Although Malcolm Dole is commonly credited with the first application of electrospray to mass spectrometry in the

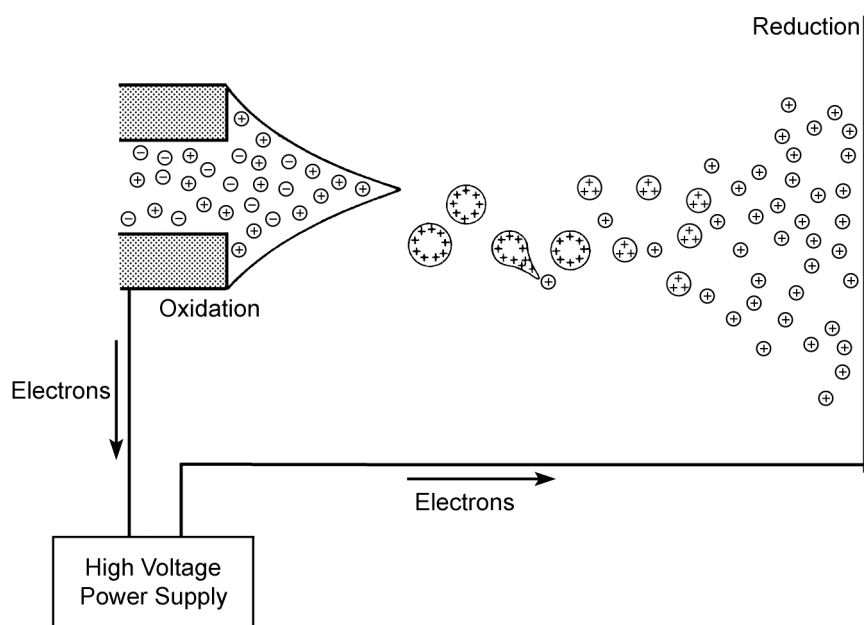


Figure 1.1. Electro spray ionization cartoon. A high voltage power supply establishes an electric field between a solution-filled capillary and a counter electrode. As the liquid is pushed through the capillary, ion migration draws the liquid to a tip that emits a fine spray of charged droplets.

1960s, two decades would pass before the technique would gain wide acceptance. In the 1980s John Fenn and coworkers revolutionized the field of mass spectrometry by making electrospray easy and practical for the analysis of large biomolecules and polymers.¹ Fenn's contributions to the body of knowledge surrounding electrospray culminated in his sharing of the 2002 Nobel prize in chemistry.

Despite the widespread popularity of ESI-mass spectrometry, questions remain regarding the mechanism by which the charged droplets evaporate to ultimately produce gas-phase ions. A more thorough understanding will certainly lead to more efficient ion sources and further unique applications.

Figure 1.2 highlights the current understanding of the "life" of an evaporating charged droplet. Initially, nascent droplets evaporate, losing solvent molecules but not charge. As a result, the surface charge density increases to a point at which the force of Coulomb repulsion at the surface overcomes the cohesive force of surface tension. The droplet releases charge and mass in a concerted "Rayleigh discharge" named after Lord Rayleigh who first predicted the event.² Smaller droplets release ions by a mechanism alternatively described by the ion evaporation model and the charge residue model. From there, nanoclusters of solvent and analyte undergo further evaporation yielding desolvated gas-phase ions.

Chapter two summarizes previous research on Rayleigh discharge phenomena in the context of understanding the mechanism of electrospray ionization. Additionally, chapter two discusses how the evaporation and discharge dynamics research presented in later chapters supplements existing research. Previous studies in the Beauchamp group

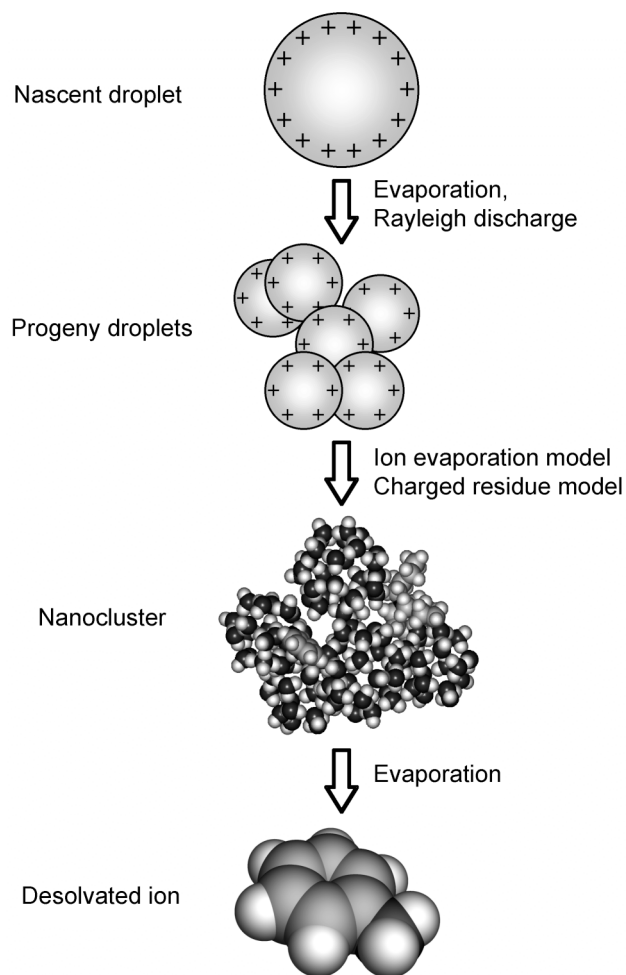


Figure 1.2. Schematic representation of the “life” of an evaporating, charged droplet.

into Rayleigh discharge phenomena focused on traditional solvents employed for electrospray ionization, specifically water, methanol, and acetonitrile.^{3,4} This work expands this research by considering nontraditional hydrocarbon solvents and specific binary solvents typically involving methanol and a lower vapor pressure constituent. In this research, solvents are electrosprayed into an ion mobility cell. Within the cell a rapidly reversing electric field allows a phase Doppler anemometer to repeatedly sample the physical characteristics of the charged droplets generated by electrospray. The instrumentation employed for these studies is virtually identical to the original designs and discussed in chapter three. Chapters four and five present the results and implications from the hydrocarbon solvents and the binary solvents, respectively.

While researching Rayleigh discharge phenomena in the literature, our attention was drawn to studies of *neutral* droplets in strong electric fields that were performed between 1917 and Malcolm Dole's original electrospray experiments. Early researchers noted that a strong electric field will cause jetting similar to that seen in electrospray ionization. In the case of a neutral droplet, two opposing jets are observed as shown in Figure 1.3. This figure represents the jetting from a small methanol droplet acquired in preliminary research in our laboratory.

We postulated that such jets might also be a source of charged droplets that would similarly evaporate and discharge to yield gas-phase ions suitable for mass analysis. Indeed, initial studies confirmed that neutral droplets in strong electric fields are a source of gas-phase ions through a process we call field-induced droplet ionization. Chapter Six presents the initial work performed on methanol droplets containing small organic salts,

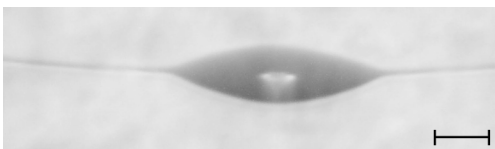


Figure 1.3. Image of a single methanol droplet subjected to a strong electric field. The field destabilizes the droplet resulting in the formation of two opposing conical jets. The bar indicates 100 μm . Adapted from Grimm and Beauchamp.⁵

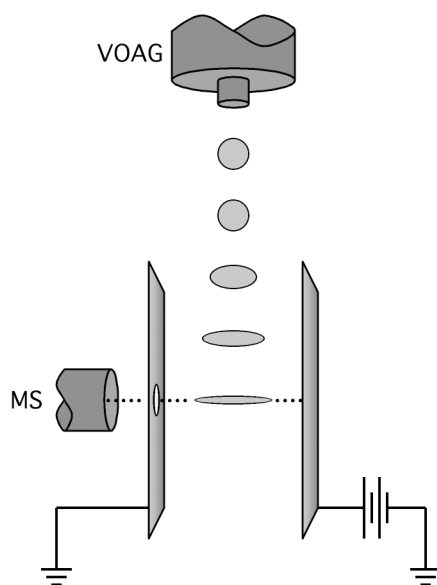


Figure 1.4. Experimental arrangement for FIDI-MS. A vibrating orifice aerosol generator (VOAG) generates a stream of droplets that pass between two parallel plate electrodes. A strong field between the electrodes causes field-induced droplet ionization and jetting of charged progeny droplets that are directed at the capillary inlet of a mass spectrometer for analysis. Adapted from Grimm and Beauchamp.⁵

organic acids, and the protein cytochrome *c*. Here, FIDI-mass spectrometry was accomplished with a relatively simple experimental arrangement shown in Figure 1.4. In this setup a stream of methanol droplets pass between two electrodes that define a region of high electric field. The field elongates the droplets, which eject jets of charged progeny droplets that are directed into the capillary inlet of a mass spectrometer. The resulting mass spectra are consistent with those acquired from a conventional electrospray ionization source.

Following the initial mass spectrometry studies, we developed an experiment to explore the parameter space associated with FIDI in an attempt to better understand and control the technique. Chapter Seven documents the use of switched electric fields for time-resolved studies of the droplet distortion, jetting, and charged progeny droplet formation associated with FIDI. Custom designed high voltage switching circuitry, a high speed flashlamp, and a digital camera-equipped microscope captured sequences of droplets such as those shown in Figure 1.5. These sequences allowed us to observe the nature of FIDI as a function of field strength, exposure duration, and the physical parameters of the droplets studied.

Understanding the dynamics of the process allowed us to develop a practical, single droplet FIDI source. Unlike the initial studies presented in Chapter Six, the single droplet source is an optimized design playing to the natural strengths of FIDI. Because the droplet can be exposed to the atmosphere for a controlled period of time before FIDI, the ability to explore heterogeneous chemistry occurring between components in the atmosphere and analytes within the droplet is a natural strength of the technique.

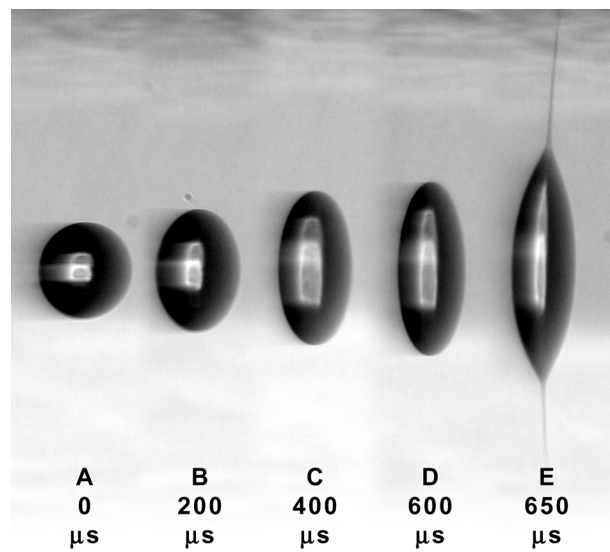


Figure 1.5. Sequence of methanol droplets exposed to a strong electric field for the time indicated in each panel. In this case, FIDI occurs after 650 μs for this field strength and droplet size.

Chapter eight explores the application of single droplet FIDI-MS applications to heterogeneous reaction chemistry between gas phase ozone and solution phase oleic acid and oleoyl-L- α -lysophosphatidic acid, or LPA (18:1). Each of these organic acids contains a carbon-carbon double bond that reacts with ozone in a heterogeneous reaction. When sampled at multiple reaction lengths, the ozone / oleic acid products show a successively increasing ratio between products and reactants indicating that FIDI-MS is a viable technique for kinetic studies of heterogeneous reactions in microdroplets. Reactions between ozone and LPA produce species that unambiguously and correctly localize the position of the double bond along the hydrocarbon chain.

Finally, the appendices present design details and circuit diagrams as an operations manual for constructing and using a single droplet FIDI source (appendix A) and a setup for switched electric field studies of neutral droplets (appendix B).

1.2. References

- (1) *Electrospray Ionization Mass Spectrometry*; Cole, R. B., Ed.; John Wiley and Sons: New York, 1997.
- (2) Rayleigh, L. *Philos. Mag.* **1882**, *14*, 184.
- (3) Smith, J. N. *Fundamental Studies of Droplet Evaporation and Discharge Dynamics in Electrospray Ionization*, California Institute of Technology, 2000.
- (4) Smith, J. N.; Flagan, R. C.; Beauchamp, J. L. *J. Phys. Chem. A* **2002**, *106*, 9957.
- (5) Grimm, R. L.; Beauchamp, J. L. *J. Phys. Chem. B* **2003**, *107*, 14161.

