1
Introduction and Overview

1.1
Introduction

The name ‘ion chromatography’ applies to any modern method for chromatographic separation of ions. Normally, such separations are performed on a column packed with a solid ion-exchange material, but if we define chromatography broadly as a process in which separation occurs by differences in migration, capillary electrophoresis may also be included.

Ion chromatography is considered to be an indispensable tool in a modern analytical laboratory. Complex mixtures of anions or cations can usually be separated and quantitative amounts of the individual ions measured in a relatively short time. Higher concentrations of sample ions may require some dilution of the sample before introduction into the ion-chromatographic instrument. ‘Dilute and shoot’ is the motto of many analytical chemists. However, ion chromatography is also a superb way to determine ions present at concentrations down to at least the low parts per billion ($\mu g\ L^{-1}$) range. Although the majority of ion-chromatographic applications have been concerned with inorganic and relatively small organic ions, larger organic anions and cations may be determined as well.

As in the three previous editions, our goal has been to describe the materials, principles and methods of ion chromatography in a clear, concise style. The following résumé is intended as a kind of road map to guide the reader through the contents of this book and to highlight some of the changes made in this fourth edition.

In the first chapter we recount some of the historical milestones and briefly cover the most basic principles of ion chromatography, or IC as it is often called. The various components and hardware of IC instruments are described in Chapter 2, but it is not our intention to discuss specific commercial instruments. Chapter 3 has been updated to include advances in column technology and promising new columns, such as monolithic columns. Chapter 4 on detectors has been expanded to include new material on the contactless conductivity detector (CCD) and pulsed electrochemical detectors.

Chapter 5 has been completely rewritten and now includes detailed sections on the factors that influence selectivity and efficiency. An updated and detailed treat-

Ion Chromatography, 4th Ed. James S. Fritz and Douglas T. Gjerde

ISBN: 978-3-527-32052-3

ment of anion chromatography and cation chromatography is presented in the next two chapters. Selection of appropriate columns, detectors and eluents is discussed and numerous examples of typical separations are given. Ion exclusion chromatography, Chapter 8, continues to be a popular and useful method for the separation of hydrophilic sample components, such as carboxylic acids, amines and carbohydrates.

Ion chromatography is generally defined as an analytical method in which anions or cations are separated by differences in the rate at which they pass through a column packed with either an anion- or cation-exchange particles. However, excellent separations of ionic analytes can also be obtained by ion chromatography on a standard reversed-phase HPLC column. With this technique, separation of cations or anions is achieved by using an aqueous-organic eluent together with an ion-pairing reagent. Ion-pair chromatography, covered in the new Chapter 9, is particularly advantageous for separation of organic ions.

Chapter 10 on zwitterion stationary phases is another new addition to this book. Separations are generally performed on an HPLC column coated with a zwitterion surfactant that contains both positive and negative sites. In some cases cations and anions can be separated in a single run using pure water as the eluent!

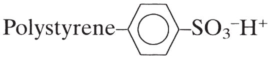
Resolution of the sample peaks obtainable in either liquid or ion chromatography is limited by two factors. One is due to mechanical pumping, which gives a curved flow profile. The second limiting factor stems from a slow rate of equilibration of solutes between the mobile and stationary phases. Use of very small ion-exchange particles can reduce but never eliminate this source of peak broadening. Capillary electrophoresis (CE), which is covered in Chapter 11, addresses both of these issues. No eluent is required for CE; sample ions are separated by differences in their electrophoretic flow rates through open capillary containing no packing material. The electrophoretic mobilities can be modified by selective interactions with electrolyte ions of the opposite charge.

Chapter 12 on Separation of DNA/RNA highlights a trend in IC toward a greater emphasis on analytical separations of bio ions. Sample pretreatment is discussed in Chapter 13. Chapter 14 on Method Development and Validation includes tips for selecting appropriate conditions for an IC analysis, and this final chapter covers chemical speciation.

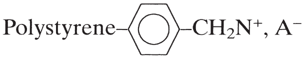
1.2
Historical Development

1.2.1
Early Ion-Exchange Separations

Modern ion chromatography is built on the solid foundation created by extensive work in classical ion-exchange chromatography. Columns containing ion-exchange resins have been used for many years to separate various cations and anions from one another. Cations are separated on a cation-exchange resin column, and anions on an anion-exchange resin column. The most used types are as follows:



Catex



Anex

For example, Na^+ and K^+ can be separated on a cation-exchange resin (Catex) column with a dilute solution of a strong acid (H^+) as the eluent (mobile phase). Introduction of the sample causes Na^+ and K^+ to be taken up in a band (zone) near the top of the column by ion exchange:

$$\text{Resin–SO}^-\text{H}^+ + \text{Na}^+, \text{K}^+ \rightleftarrows \text{Resin SO}^-\text{Na}, \text{K}^+ + \text{H}^+$$

Continued elution of the column with an acidic eluent (H^+) introduces competition of H^+, Na^+ and K^+ for the exchange sites ($-SO_3^-$), causing the Na^+ and K^+ to move down the column. K^+ is more strongly retained than Na^+, and thus the Na^+ zone moves down the column faster than the K^+ zone.

As originally conceived and carried out for many years, fractions of effluent were collected from the end of the column and analyzed for Na^+ and K^+. Then a plot was made of concentration vs fraction number to construct a chromatogram. All this took a long time and made ion-exchange chromatography slow and awkward to use. However, it soon was realized that under a given set of conditions all of the Na^+ would be in a single fraction of several milliliters and all of the K^+ could be recovered in a second fraction of a certain volume. Thus, under pre-determined conditions, each ion to be separated could be collected in a single fraction and then analyzed by spectroscopy, titration, etc., to determine the amount of each sample ion.

The ability to collect a single fraction that contains all of the separated sample ion permits the use of step gradients. In this mode, conditions are adjusted so that an 'all-or-nothing' situation prevails. A sample ion either sticks onto the ion-exchange column or it passes quickly through. Conditions are selected so that only one ion type will pass through the column while the other sample ions are strongly retained and form a tight band at the top of the column. Then the eluent is changed so that a second ion is rapidly eluted, while the others remain tightly stuck. Frequently, several gradient steps can be performed to elute different sample ions at each step.

1.2.2
Cation Separations

Early studies on the separation of metal cations included separations based on affinity differences and some specific separation with complexing eluents.

Strelow and his coworkers have published extensive data relating to the selectivity of a sulfonated polystyrene cation exchanger for various cations in acidic solution [1]. The equilibria of cations in hydrochloric, nitric or sulfuric acid solutions with a cation exchanger involves complexation in some cases as well as competition between H^+ and the metal cation for the exchange sites. For example, mercury(II) and cadminium(II) form chloride complexes even in dilute solutions of hydrochloric acid. Selectivity data in perchloric acid probably give the best indication of true ion-exchange selectivity, because the perchlorate anion has almost no complexing properties with metal cations.

In general, cations with a 3+ charge are more strongly retained by a cation exchanger than cations with a 2+ charge, and ions with a 2+ charge are retained more strongly than those with a 1+ charge. Fritz and Karraker [2] were able to separate metal cations into groups according to their charge. Most divalent metal cations were eluted with a 0.1 M solution of ethylenediammonium perchlorate. Bismuth(III) and zirconium(IV) remained quantitatively o n the cation-exchange column. The use of the 2+ ethylenediammonium ion permitted a lower concentration to be used than would have been the case with an H^+ eluent.

Several inorganic acids exhibit a complexing effect for metal ions. The complexing acids include HF, HCI, HBr, HI, HSCN and H_2SO_4. The complexed metal ions are converted into neutral or anionic complexes and are rapidly eluted, while the other cations remain on the cation-exchange column.

The data for hydrochloric acid [3] indicate selective complexing between metal cations and the chloride ion. For example, cadmium(II) has a distribution coefficient of 6.5 in 0.5 M hydrochloric acid, but a $D = 101$ in 0.5 M perchloric acid.

Calcium(II), which shows no appreciable complexing, has a distribution coefficient of 147 in 0.5 M perchloric acid and 191 in 0.5 M hydrochloric acid. Strelow, Rethemeyer and Bothma [3, 4] also reported data for nitric and sulfuric acids that showed complexation in some cases. Mercury(II), bismuth(III), cadmium(II), zinc(II), and lead(II) form bromide complexes and elute in the order given in 0.1 to 0.6 M hydrobromic acid [5]. Most other metal cations remain on the column. Aluminum(III), molybdenum(VI), niobium(V), tin(IV), tantalum(V), uranium(VI), tungsten(VI) and zirconium(IV) form anion fluoride complexes and are quickly eluted from a hydrogen-form cation-exchange column with 0.1 to 0.2 M HF [6].

An eluent containing only 1% hydrogen peroxide in dilute aqueous solution will form stable anionic complexes with several metal ions. Fritz and Abbink [7] were able to separate vanadium(IV) or (V) from 25 metal cations, including the separation of vanadium(V) from 100 times as much iron(III).

Strewlow [8] used hydrogen peroxide and sulfuric acid to separate titanium(IV) from more than 20 cations by cation exchange. Fritz and Dahmer [9] separated molybdenum(VI), tungsten(VI), niobium(V) and tantalum(V) as a group from other metals by adding dilute hydrogen peroxide to the sample solution and passing it through a cation-exchange column.

Most of the eluents listed above are volatile upon heating and do not interfere with colorimetric, titrimetric or other methods for chemical determination of the metal ions separated. For the most part, group separations, rather than separation of individual metal ions, are obtained, and only a short ion-exchange column is needed. Another valuable 'all-or-nothing' group separation uses an eluent consisting of 0.1 M tartaric acid and 0.01 M nitric acid [10]. Antimony(V), molybdenum(VI), tantalum(V), tin(IV) and tungsten(VI) form tartrate complexes in this acidic medium, but lead(II) and many other metal cations are not complexed and are retained by the cation exchanger. Samples containing tin(IV) must be added to the column in the tartrate solution.

In a few cases an eluent containing an organic complexing reagent has been used successfully for the chromatographic separation of several metal ions. A notable example is the separation of individual rare earth ions with a solution of 2-hydroxylisobutyric acid as the eluent [11]. However, such separations necessitate careful equilibration of the column to maintain a desired pH. Sometimes gradient elution is used, and either the pH or the eluent concentration is changed.

Metal cations usually form complexes with inorganic anions much more readily in organic solvents than in water. For example, the pink cobalt(II) cation requires around 4 M or 5 M aqueous hydrochloric acid to be converted to a blue cobalt(II) chloride anion. In a predominantly acetone solution, the intensely blue cobalt(II) is formed in very dilute hydrochloric acid. Thus, the scope of ion-exchange group separations is increased greatly by carrying out separations in a mixture of water and an organic solvent.

Fritz and Rettig [12] showed that zinc(II), iron(III), cobalt(II), copper(II) and manganese(II) can be separated from each other on a short cation-exchange column with eluents containing a fixed, low concentration of HCl, increasing the acetone concentration from 40% to 95% in steps. Later Strelow et al. [13] published extensive lists of metal-ion distribution coefficients in water/acetone/hydrochloric acid systems.

Korkisch and coworkers have studied the effect of ethanol, acetic acid, ethylene glycol and many other solvents upon the ion-exchange behavior of metal ions in systems containing hydrochloric and other complexing acids [14].

The selectivity of low-capacity cation columns for monovalent ions can be adjusted by the addition of an organic modifier to the eluent. Using a nitric acid eluent of pH 2.5, for example, the elution order for monovalent ions is Li^+, Na^+, NH_4^+, K^+. Simple amines elute in the order of the carbon number, after NH_4^+, with the result that $(CH_3)NH_3^+$ (methylammonium) can co-elute with potassium. In most cases, this co-elution is of little significance, because potassium and methylammonium are not often in the same sample. However, where the analysis of either of these species in the presence of the other is desired, the selectivity can be modified by the addition of 40% methanol to the eluent [15]. The methanol causes the potassium to elute later but does not affect the elution time of methylammonium.

1.2.3
Separation of Anions

Since most metal ions are cationic, it may sound strange to discuss their separation by anion-exchange chromatography. However, Kraus and Nelson, working at Oak Ridge National Laboratory in the USA, found that in aqueous hydrochloric acid solutions a number of metal ions form anionic complexes and are strongly taken up by anion-exchange resins. For most of the metal ions, a plot of the *D* value of several thousand is attained. An illustration of such plots for most of the metallic elements in the periodic table was published by Kraus and Nelson in 1956 [16].

Separations are generally achieved by adding the sample to an anion-exchange column in rather concentrated hydrochloric acid and eluting the nonsorbed metal ions with the same HCl concentration. Then the sorbed metal ions are eluted one at a time by stepwise reduction of the HCl strength of the eluent. Figure 1.1 illustrates one of the many practical separations published by Kraus and his coworkers [17].

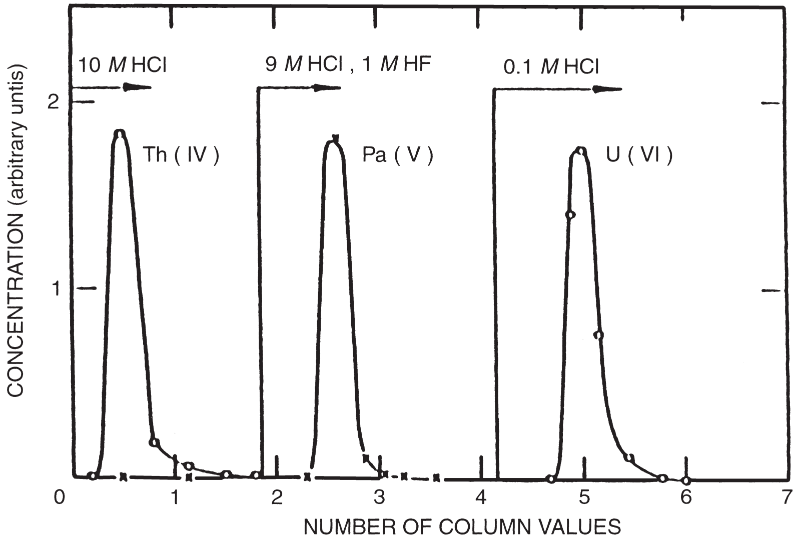


Figure 1.1 Separation of metal ions on Dowex 1 × 10 anion exchange resin. (From Ref. [18] with permission.)

In a similar manner, elements that form anionic fluoride complexes can be separated from others and from each other on an anion exchanger by eluting with eluents containing HF plus HCl [18, 19]. Extensive studies of metal ion behavior on anion-exchange columns have also been carried out with eluents containing mixed H_2SO_4/HF [20, 21].

Anion-exchange distribution coefficients for most metallic elements in sulfuric acid solution have been measured [22, 23]. Uranium(VI), thorium(IV), molybdenum(VI) and a few other elements are retained selectively by anion-exchangers from solution in approximately 6 M nitric acid [24].

Operating in a predominantly organic solvent greatly improves the ability of metal ions to form complexes with halide and pseudo-halide anions. Such complexes generally are taken up strongly by an anion-exchange resin. Korkisch, Fritz, Strelow and others have published extensively on anion-exchange separations in partly nonaqueous solutions. Korkisch and Hazan [25] describe a method to separate metal ions that form chloride complexes from those that do not. The method uses an eluent consisting of 90–95% methanol in 0.6 M hydrochloric acid and requires only a short anion-exchange column. The metal ions studied are either retained as a sharp band or quickly pass through the column. Thus, we have an 'all-or-nothing' situation, and excellent group separations are obtained.

Chromatographic separations of individual ions are also possible, and many have been published. An example is shown in Figure 1.2. Ion exchange in nonaqueous and mixed media has been reviewed [26].

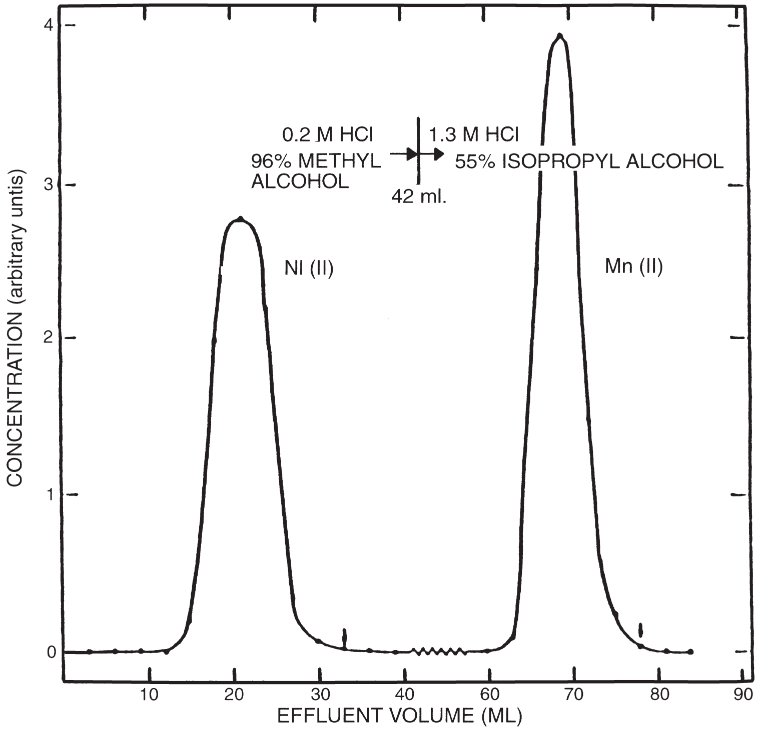


Figure 1.2 Separation of nickel(II) and manganese(II) on a 6.0 × 2.2 cm column containing Dowex 1 × 8 resin, with partly nonaqueous eluents. (From Ref. [25] with permission.)

Systems containing dimethylsulfoxide, methanol and hydrochloric acid have been studied for the anion-exchange behavior of 26 elements [27]. Numerous separations of two- to four-component mixtures of metal ions were carried out with quantitative results.

1.2.4
On-line Detection

At this stage in the development of ion-exchange chromatography, separation of cations or anions was still a slow and laborious process. It was becoming apparent that widespread use of ion-exchange chromatography as an analytical tool would require a system that gave fast separations with automatic recording of chromatograms.

In 1971 an apparatus for 'forced-flow chromatography' was described in which the eluent was pushed through the analytical column by compressed nitrogen [28]. Detection of eluted ions was by UV-Vis spectrophotometry using a 30 mm × 2 mm flow cell. Iron(III) (10–90 µg) could be separated from most other metal ions and measured quantitatively in only 6 min. Forced-flow methods were soon developed for the chromatographic separation of a number of other metal ions [29–32]. The chromatograph was modified in 1974 so that a complexing reagent such as PAR or Arsenazo could be added to the column effluent via a mixing tee [33]. This made it possible to detect virtually any metal ion that could form a highly-colored complex. A recorded chromatographic separation of all 30 rare earths was obtained in 1974 [30, 34], with this apparatus. This separation took 100 min. Five years later, Elchuk and Cassidy in Canada were able to obtain a better separation of earths in only 27 min using a similar but improved system [35].

1.2.5
The Birth of Modern Ion Chromatography

Liquid column chromatography went 'high performance' around 1970 and is now commonly referred to as HPLC. Major improvements in speed and efficiency were obtained by using columns of relatively small bore packed with small spherical particles of uniform diameter, using a pump to provide constant eluent flow, and using automatic detection of the separated sample components. However, application of this technology for the separation of ions lagged. It was mainly the lack of satisfactory detectors that held up the development of high-performance ion-exchange chromatography. This situation changed dramatically with the publication of a landmark paper in 1975 by Small et al., working at the Dow Chemical Co. [36]. As the authors put it: 'It would be desirable to employ some form of conductimetric detection as a means of monitoring ionic species in a column effluent since conductivity is a universal property of ionic species in solution and since conductance shows a simple dependence on species concentration. However, the conductivity from the species of interest is generally "swamped out" by that from the much more abundant eluting electrolyte. We have solved this detection problem by using a combination of resins which strips out or neutralizes the ions of the background electrolyte leaving only the species of interest as the major conducting species in the effluent. This has enabled us to successfully apply a conductivity cell and meter as the detector system.'

This new system, which was given the name 'ion chromatography,' enabled the analyst to quickly separate and measure quantitatively the cations or anions at low concentrations in fairly complex samples. A diagram of the system for cation analysis is shown in Figure 1.3. The upper column, called the 'separator column', was packed with polystyrene–2% DVB particles, surface-sulfonated to obtain an exchange capacity of approximately 0.02 mmol g^{-1}. The lower 'suppressor column' was packed with anion-exchange resin of high exchange capacity in the hydroxide form.

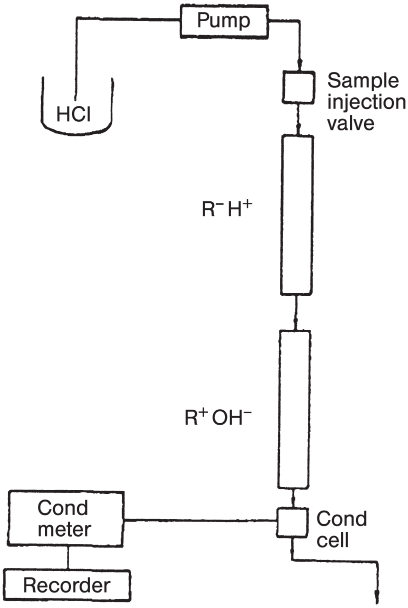


Figure 1.3 System for cation analysis by conductimetric chromatography. (From Ref. [36] with permission.)

A practical method for the separation of anions was described in the same paper [36]. This endeavor necessitated the development of a new low-capacity anion-exchange resin. It had been known for some time that cation- and anion-exchange resins have a marked tendency to clump together. Using this principle, a satisfactory anion-exchange material of low capacity was prepared by coating surface-sulfonated cation exchanger

In the original scheme for the separation of anions a mixture of sodium hydroxide and sodium phenate was used in the eluent. The suppressor column was packed with a cation-exchange resin of high capacity. The suppressor column converted the eluent ions to water plus phenol, while the sample anions A^- were converted to the highly conducting pair H^+A^-.

An instrument called the 'ion chromatograph' was offered commercially by the newly organized Dionex Co. and became an immediate success. The new technology made it possible to separate and determine both cations and most anions, but the ability to determine anions at low ppm concentrations had the greater impact. Many cations could already be determined by various spectral methods and by reasonably good chromatographic methods, but prior to the advent of ion chromatography there was no general analytical method for anions, especially at very low concentrations. Once the scientific world became aware that anions in fairly complex mixtures could be easily separated and quantified, even at low ppm concentrations, the use of ion chromatography exploded. A powerful new analytical technique had again facilitated scientific endeavors that were previously impractical.

1.2.6
Non-Suppressed-Ion Chromatography

A major disadvantage of the original Ion Chromatograph was that it required the use of a large suppressor column that contributed to peak broadening and required frequent regeneration. The eluent for anion separations had to be a base, and anions of very weak acids could not be detected because their acidic form after suppression was too weakly conducting.

In 1979 a synthetic method was described for producing anion-exchange resins of very low exchange capacity [37]. A porous polymeric resin was chloromethylated under mild conditions and then alkylated with trimethylamine to form ionic quaternary ammonium groups. The exchange capacity could be varied from 0.2 to 1.5 meq g^{-1} by controlling the time and temperature of the chloromethylation. This drastically lower exchange capacity permitted the use of much lower eluent concentrations than had previously been possible.

In 1979, Gjerde, Fritz and Schmuckler described a simple system for anion chromatography with eluents containing anions of very low conductivity such as benzoate or phthalate [38]. Anions were separated on a column containing macroporous anion-exchange particles of very low exchange capacity: 0.07, 0.04 or 0.007 mmol g^{-1}. The eluent was an aqueous solution of the sodium or potassium salt of an organic anion that had a significantly lower equivalent conductance than the anions to be separated. In this method some of the eluent anion is replaced by a sample anion of significantly higher conductance as the sample ion is eluted from the column and passes through the conductivity detector. Because of the low resin capacity, an eluent containing only ca. 10^{-4} M of an organic acid salt, such as benzoate or phthalate, could be used. The eluent conductance was so low that no suppressor column was needed, and the separated sample ions could be detected with a simple conductivity detector. Numerous anion separations were demonstrated, and in some instances detection limits below 1 ppm were obtained. This method was initially called 'single-column ion chromatography' and later 'non-suppressed-ion chromatography.' An additional paper on anion chromatography [39] was published in 1980. A chromatographic separation of halide ions is shown in Figure 1.4.

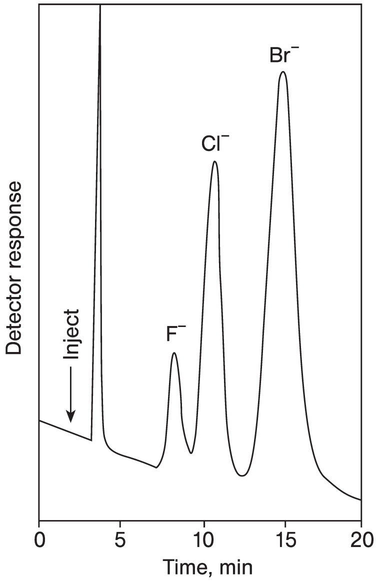


Figure 1.4 Separation of 4.8 ppm of fluoride, 5.1 ppm of chloride and 26.0 ppm of bromide on XAD-1, 0.04 mequiv g^{-1}; eluent is 0.65 mM potassium benzoate, pH 4.6. (From Ref. [39] with permission.)

The non-suppressed method for anion chromatography was followed quickly in 1980 by a similar method for cations [40]. This method also introduced the concept of indirect conductivity detection. A 1×10^{-3} M solution of nitric acid was used as the eluent in conjunction with a sulfonated cation-exchange column of low exchange capacity. In this method, a baseline of relatively high conductance is established when the column is equilibrated with the acidic eluent. After introduction of a sample mixture, such as Na^+ and K^+, and continued elution with the eluent, the sample cations are gradually resolved into zones in which some of the highly conducting H^+ (equiv. conductance = 350 S cm^2 $equiv^{-1}$) is exchanged for a sample cation of much lower conductance. A sharp 'peak' of lower conductance is obtained for each sample cation.

A mixture of Li^+, Na^+, NH_4^+, K^+, Rb^+ and Cs^+ was separated in less than 10 min with a blend of 0.17 meq g^{-1} and unfunctionalized cation-exchange resins with 1.25×10^{-4} nitric acid as the eluent (Figure 1.5). Although separation of divalent cations with nitric acid was not practical, a fast separation of magnesium and calcium in tap water was obtained with a 1×10^{-3} M ethylene diammonium nitrate eluent.

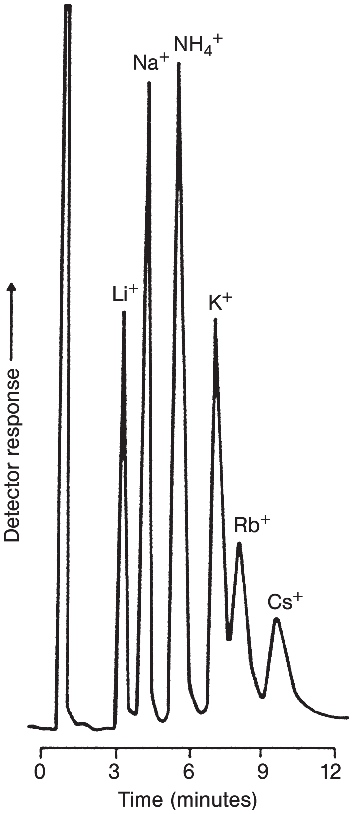


Figure 1.5 Separation of alkali metal cations on ammonium cation exchange column with a conductivity detector. Column: 350 × 2.0 mm. Packed with 0.059 mequiv g^{-1} cation exchange resin.

Development of the ion-chromatographic methods that use a conductivity detector was accompanied by a significant increase in chromatographic efficiency. The ion-exchange materials were of much smaller and more uniform size and the packing efficiency of the column was also improved. The changes that occurred were not unlike those in partition chromatography when it went from 'liquid chromatography' to 'high-performance liquid chromatography' (HPLC).

1.3
Principles of Ion Chromatographic Separation and Detection

1.3.1
Requirements for Separation

The ion-exchange resins used in modern chromatography are of smaller particle size but have a lower capacity than the older resins. Columns packed with these newer resins have more theoretical plates than the older columns. For this reason, successful separations can now be obtained even when there are only small differences in retention times of the sample ions.

The major requirements of systems used in modern ion chromatography can be summarized as follows:

1. An efficient cation- or anion-exchange column with as many theoretical plates as possible.
2. An eluent that provides reasonable differences between the retention times of the sample ions.
3. A resin-eluent system that attains equilibrium quickly so that kinetic peak broadening is eliminated or minimized.
4. Elution conditions such that retention times are in a convenient range – not too short or too long.
5. An eluent and resin that are compatible with a suitable detector.

1.3.2
Experimental Setup

Anions in analytical samples are separated on a column packed with an anion-exchange resin. Similarly, cations are separated on a column containing a cation-exchange resin. The principles for separating anions and cations are very similar. The separation of anions will be used here to illustrate the basic concepts.

A typical column used in ion chromatography might have the dimensions 150 × 4.6 mm, although columns as short as 50 mm in length or as long as 250 mm are also used. The column is carefully packed with a spherical anion-exchange resin of rather low exchange capacity and with a particle diameter of 5 or 10 μm. Most anion-exchange resins are functionalized with quaternary ammonium groups, which serve as the sites for the exchange of one anion for another.

The basic setup for IC is as follow. A pump is used to force the eluent through the system at a fixed rate, such as 1 mL min^{-1}. In the FILL mode a small sample loop (typically 10–100 μL) is filled with the analytical sample. At the same time, the eluent is pumped through the rest of the system, by-passing the sample loop. In the INJECT mode a valve is turned so that the eluent sweeps the sample from the filled sample loop into the column. A detector cell is connected to a strip-chart recorder or a data-acquisition device so that a chromatogram of the separation (signal vs time) can be plotted automatically. A conductivity or UV-visible detector is most often used in ion chromatography.

The eluent used in anion chromatography contains an eluent anion, E^-. Usually Na^+ or H^+ will be the cation associated with E^- The eluent anion must be compatible with the detection method used. For conductivity, the anion E^- should have either a significantly lower conductivity than the sample ions or be capable of being converted to a non-ionic form by a chemical suppression system. When spectrophotometric detection is employed, E^- will often be chosen for its ability to absorb strongly in the UV or visible spectral region. The concentration of E^- in the eluent will depend on the properties of the ion exchanger used and on the types of anions to be separated. Factors involved in the selection of a suitable eluent are discussed later.

1.3.3
Performing a Separation

To perform a separation, the eluent is first pumped through the system until equilibrium is reached, as evidenced by a stable baseline. The time needed for this may vary from a couple of minutes to an hour or longer, depending on the type of resin and the eluent used. During this step the ion-exchange sites will be converted to the E^- form: Resin–N^+R_3 E^-. There may also be a second equilibrium in which some E^- is adsorbed on the resin surface but not at specific ion-exchange sites. In such cases the adsorption is likely to occur as an ion pair, such as E^-Na^+ or E^-H^+.

An analytical sample can be injected into the system as soon as a steady baseline has been obtained. A sample containing anions A_1^- , A_2^-, A_3^-,...., A_1^- undergoes ion exchange with the exchange sites near the top of the chromatography column.

$$A_1^- \text{ (etc.)} + \text{Res } E^- \rightleftarrows \text{Res–}A_1^- \text{ (etc.)} + E^-$$

If the total anion concentration of the sample happens to be exactly the same as that of the eluent being pumped through the system, the total ion concentration in the solution at the top of the column will remain unchanged. However, if the total ion concentration of the sample is greater than that of the eluent, the concentration of E^- will increase in the solution at the top of the column because of the exchange reaction shown above. This zone of higher E^- concentration will create a ripple effect as the zone passes down the column and through the detector. This will show up as the first peak in the chromatogram, which is called the injection peak.

A sample of lower total ionic concentration than that of the eluent will create a zone of lower E^- concentration that will ultimately show up as a negative injection peak. The magnitude of the injection peak (either positive or negative) can be used to estimate the total ionic concentration of the sample compared with that of the eluent. Sometimes the total ionic concentration of the sample is adjusted to match that of the eluent in order to eliminate or reduce the size of the injection peak.

Behind the zone in the column due to sample injection, the total anion concentration in the column solution again becomes constant and is equal to the E^- concentration in the eluent. However, continuous ion exchange will occur as the various sample anions compete with E^- for the exchange sites on the resin. As eluent containing E^- continues to be pumped through the column, the sample anions will be pushed down the column. The separation is based on differences in the ion-exchange equilibrium of the various sample anions with the eluent anion, E^-. Thus, if sample ion A_1^- has a lower affinity for the resin than ion A_2^-, then A_1^- will move at a faster rate through the column than A_2^-.

1.3.4
Migration of Sample Ions

The general principles for separation are perhaps best illustrated by a specific example. Suppose that chloride and bromide are to be separated on an anion-exchange column. The sample contains 8×10^{-4} M sodium chloride and 8×10^{-4} M sodium bromide, and the mobile phase (eluent) contains 10×10^{-4} M sodium hydroxide.

In the column equilibration step, the column packed with solid anion-exchange particles (designated as Res-Cl^-) is washed continuously with the NaOH eluent to convert the ion exchanger completely to the $-OH^-$ form.

$$\text{Res-Cl}^- + \text{OH}^- \rightleftarrows \text{Res-OH}^- + \text{Cl}^-$$

At the end of this equilibration step, the chloride has been entirely washed away and the liquid phase in the column contains 10×10^{-4} M Na^+OH^-.

In the sample injection step a small volume of sample is injected into the ion-exchange column. An ion-exchange equilibrium occurs in a fairly narrow zone near the top of the column.

$$\text{Res-OH}^- + \text{Cl}^- \rightleftarrows \text{Res-Cl}^- + \text{OH}^-$$

$$\text{Res-OH}^- + \text{Br}^- \rightleftarrows \text{Res- Br}^- + \text{OH}^-$$

Within this zone, the solid phase consists of a mixture of Res-Cl^- , Res-Br^- and ResOH^-. The liquid phase in this zone is a mixture of OH^-, Cl^- and Br^- plus its accompanying Na^+. The total anionic concentration is governed by that of the injected sample, which is 16×10^{-4} M (see Figure 1.6A).

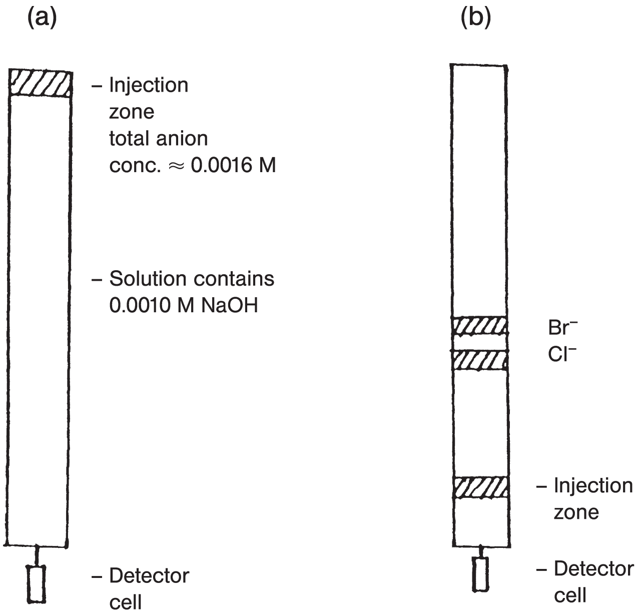


Figure 1.6 Anion exchange column: A, after sample injection; B, after some elution with 0.001 M NaOH.

In the elution step, pumping 10×10^{-4} M NaOH eluent through the column results in multiple ion-exchange equilibria along the column in which the sample ions (Cl^- and Br^-) and eluent ion (OH^-) compete for ion-exchange sites next to the Q^+ groups. The net result is that both Cl^- and Br^- move down the column (Figure 1.6B). Because bromide has a greater affinity for the Q^+ sites than chloride has, the bromide moves at a slower rate. Because of their differences in rate of movement, bromide and chloride are gradually resolved into separate zones or bands.

The solid phase in each of these zones contains some OH^- as well as the sample ion, Cl^- or Br^-. Likewise, the liquid phase contains some OH^- as well as Cl^- or Br^-. The *total* anionic concentration ($Cl^- + OH^-$ or $Br^- + OH^-$) is equal to that of the eluent (0.0010 M) in each zone.

Continued elution with Na^+OH^- causes the sample ions to leave the column and pass through a small detector cell. If a conductivity detector is used, the conductance of all of the anions, plus that of the cations (Na^+ in this example) will contribute to the total conductance. If the total ionic concentration remains constant, how can a signal be obtained when a sample anion zone passes through the detector? The answer is that the equivalent conductance of chloride (76 ohm^{-1} cm^2 $equiv^{-1}$) and bromide (78) is much lower than that of OH^- (198). The net result is a decrease in the conductance measured when the chloride and bromide zones pass through the detector.

In this example, the total ionic concentration of the initial sample zone was higher than that of the eluent. This zone of higher ionic concentration will be displaced by continued pumping of eluent through the column until it passes through the detector. This will cause an increase in conductance and a peak in the recorded chromatogram called an injection peak. If the total ionic concentration of the injected sample is lower than that of the eluent, an injection peak of lower conductance will be observed. The injection peak can be eliminated by balancing the conduction of the injected sample with that of the eluent. Strasburg et al. studied injection peaks in some detail [41].

In suppressed-anion chromatography, the effluent from the ion-exchange column comes into contact with a cation-exchange device (Catex-H^+) just before the liquid stream passes into the detector. This causes the following reactions to occur.

Eluent:	$Na^+OH^- + \text{Catex-}H^+$	$\rightarrow$	$\text{Catex-}Na^+ + H_2O$
Chloride:	$Na^+Cl^- + \text{Catex-}H^+$	$\rightarrow$	$\text{Catex-}Na^+ + H^+Cl^-$
Bromide:	$Na^+Br^- + \text{Catex-}H^+$	$\rightarrow$	$\text{Catex-}Na^+ + H^+Br^-$

The background conductance of the eluent entering the detector is thus very low because virtually all ions have been removed by the suppressor unit. However, when a sample zone passes through the detector, the conductance is high due to the conductance of the chloride or bromide and the even higher conductance of the H^+ associated with the anion.

1.3.5
Detection

This effect can be used to practical advantage for the indirect detection of sample anions. For example, anions with little or no absorbance in the UV spectral region can still be detected spectrophotometrically by choosing a strongly absorbing eluent anion, E^-. An anion with a benzene ring (phthalate, *p*-hydroxybenzoate, etc.) would be a suitable choice. In this case, the baseline would be established at the high absorbance due to E^-. Peaks of non-absorbing sample anions would be in the negative direction owing to a lower concentration of E^- within the sample anion zones.

Direct detection of anions is also possible, providing a detector is available that responds to some property of the sample ions. For example, anions that absorb in the UV spectral region can be detected spectrophotometrically. In this case, an eluent anion is selected that does not absorb (or absorbs very little).

1.3.6
Basis for Separation

The basis for separation in ion chromatography lies in differences in the exchange equilibrium between the various sample ions and the eluent ion. A more quantitative treatment of the effect of ion-exchange equilibrium on chromatographic separations is given later. Suppose the differences in the ion-exchange equilibrium are very small. This is the case for several of the transition metal cations (Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, etc.) and for the trivalent lanthanides. Separation of the individual ions within these groups is very difficult when it is based only on the small differences in affinities of the ions for the resin sites. Much better results are obtained by using an eluent that complexes the sample ions to different extents. An equilibrium is set up between the sample cations, C^{2+}, and the complexing ligand, L^-, in which species such as C^{2+}, CL^+, CL_2 and CL_3^- are formed. The rate of movement through the cation-exchange column is inversely proportional to α, the fraction of the element that is present as the free cation, C^{2+}.

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