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Speciation of chromium and manganese using pneumatically assisted electrospray mass spectrometry

by

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CHAPTER 1. GENERAL INTRODUCTION

It is not an exaggeration to say that much of chemistry involves ions in solution. A technique which allows for ions to be transferred from solution into the gas phase and subsequently analyzed by mass spectrometric detection would be of importance. If structural information, representative of the solution chemistry could be gained from these gas-phase ions, this would also be important. Electrospray mass spectrometry (ES-MS) is such a technique.

Historical Perspective

Although the study of electrospray phenomena extends back many years, perhaps almost three hundred years to the work of Bose[1], the actual research on the use of electrospray as an ionization source was conducted by Dole[2,3] in the late 1960s. The purpose of Dole's research was to use ES to produce gas-phase macro ions. A mass spectrometer was not available and only ion retardation or ion mobility measurements were possible. In 1984, electrospray ionization and mass spectrometry were combined and almost simultaneously reported by Fenn[4] and Aleksandrov[5,6] in separate laboratories.

Most of the developments in ES-MS have been in organic and biological areas. ES offers a unique and relatively simple way of generating intact gas-phase ions from large solution ions and macromolecules. Of particular importance in ES of macromolecules is the phenomenon of multiple charging. By placing multiple charges on one species, the mass to charge ratio (m/z) of a molecule will be reduced. A reduced m/z is essential for analysis of extremely large (up to 200 kDa) molecules as the effective m/z range of a quadrupole based mass spectrometer is approximately 2000 Da. Inorganic ES-MS has developed more slowly than its organic/biological counterpart; nevertheless, strong work has been done and continues to be done by many researchers[7-13].

Electrospray Ionization Process

Although the use of electrospray ionization for mass spectrometry is relatively new, it and related phenomena have been investigated extensively [14-22]. Electrospray ion production requires two steps: dispersal of highly charged droplets at near atmospheric conditions, followed by droplet evaporation. An electrospray is generally produced by applying a high electric field to a small liquid flow (1 - 10 μL/min) from a tube, usually a capillary. In pneumatically assisted electrospray, a needle gas is forced around the capillary and helps facilitate droplet formation. A potential difference of 3 - 6 kV is typically applied between the capillary and counter electrode located roughly 1 cm away. The electric field results in charge accumulation on the liquid surface. The liquid flow rate, resistivity, and surface tension are important factors in droplet production. Positively or negatively charged droplets can be produced depending upon the capillary bias. Solvent choice is an important role in selecting the proper surface tension. Actual solvent composition varies but usually a aqueous/organic system is used. Ions, charged clusters, and charged droplets, depending on the extent of desolvation, may be sampled by the mass spectrometer through a small orifice.

Electrospray droplets undergo many changes as they travel from capillary tip to the mass spectrometer. Droplets are sampled into a small orifice and collide with a curtain gas, typically nitrogen heated to 60 °C. This heated curtain gas evaporates solvent from the droplets. As the solvent evaporates, the droplets shrink to the point where repulsive Coulombic forces approach the level of droplet cohesive forces (surface tension). These charged droplets undergo what is referred to as Rayleigh fission (often times called electrohydrodynamic disintegration). Rayleigh fission has been measured[23] where a charged droplet expels 15% of its excess charge but only 2% of its mass in the process. This fission can happen over and over again as highly charged droplets become smaller and smaller. The final stage of the electrospray process in which gas-phase ions are produced

from the charged droplets still remains unclear[24-26]. Two theories are described in the literature, single ion droplet theory (SIDT)[2,3,27] and ion evaporation theory (IET)[28,29]. Briefly, the SIDT is a continuation of the Rayleigh fissional process to the limit where droplets containing a single ion are produced. The IET describes ion desorption from the surface of a charged droplet. The ion is, in effect, "spit" out of this droplet which is very small (≈ 8 nm) and highly charged (≈ 80 excess charges). The ion is assumed to be solvated during the desorption step. To summarize the difference between SIDT and IET, either microdroplets or individual ion clusters are created.

Inorganic Electrospray Applications

Investigations have shown that ES-MS is a powerful tool which can probe ionic solution composition. This technique can provide elemental analysis as well as information about valence states, molecular form, and composition of solvated spheres for both cations and anions. ES-MS is a relatively soft ionization technique. Operating parameters may be altered to change ionization conditions as well as collisional conditions.

Thesis Objectives

This thesis will focus on the potential of ES-MS to reveal speciation information from solutions which contain chromium and manganese. Speciation information is needed as the toxicity and biological roles of particular elements can vary greatly depending on the chemical form. As will be described in Chapter 2, chromium can be an essential nutrient or a carcinogen to living organisms. The difference between the forms of chromium is the deciding factor in the chemistry of this element.

Thesis Organization

Chapter 2 of this thesis is a scientific manuscript that was been submitted for publication. Chapter 3 of this thesis is not a manuscipt and has not been submitted for publication. Chapter 4 of this thesis is a general conclusion which summarizes some the research presented in the previous chapters.

CHAPTER 3. SPECIATION OF MANGANESE(II) AND MANGANESE(VII) USING PNEUMATICALLY ASSISTED ELECTROSPRAY MASS SPECTROMETRY

Introduction

As previously mentioned, speciation information is needed as the toxicity and biological role of a particular element can vary greatly depending on the chemical form. Manganese is an element with biological importance. A deficiency of manganese in a living system can cause skeletal and cartilage defects, elevated serum lipids, and corneal opacity[1] . An excess of manganese can cause psychiatric disorders including memory and speech loss as well as hallucinations[2] . Manganese is used in the manufacturing of steel for rock crushers, railway points and crossings, and wagon buffers. Another industrial application of manganese is as a constituent in several alloys including ferromanganese, copper manganese, and manganin.

The importance of manganese in living systems, though known to be considerable, remains poorly explored in many areas. The manganese biochemistry which has attracted the greatest interest is that involved in O_2 release by photosynthesis. Manganese biochemistry largely results from the association of the metal with enzymes and proteins. There are many known manganese enzymes and proteins[3]. The oxidation state of the manganese within these systems varies in from Mn(II), Mn(III), and Mn(IV)[4]. The use of manganese within these enzymes and proteins varies significantly. The binding and function of manganese within these systems depends greatly upon the valence of the metal. Thus, an accurate determination of both the concentration and valence is important in understanding the role of manganese in biological systems.

Experimental

Solutions of Mn (II) in either 2% HNO_3 or 2% HCl were prepared by diluting aliquots from 1000 ppm aqueous ICP standards (Plasma Chem Corp.) with a 50% methanol/water solvent. The manganese in the HNO_3 solvent is certified to contain manganese as Mn(II). The manganese in HCl solvent was not certified. A direct discussion with the manufacturer revealed that manganese was likely present as either Mn(II) or Mn(IV). No certified Mn(IV) stock solution was available commercially.

Potassium permanganate solutions were prepared by diluting a 1 N aqueous standard (Fisher) with 50% methanol/water solvent. The methanol/water solution was prepared using HPLC grade methanol (Fisher Scientific Co.) and water deionized to a resistance of 18 MΩ with a Barnsted Nanopure-II system (Newton, MA).

The pH was adjusted by adding NH_4OH (Malinckrodt) or ULTREX II ultra pure grade HCl (J.T. Baker Co.) to the aqueous solvent. Methanol/water solvent was then added to these solutions to bring the final manganese concentration to the desired level. The reported pH of solutions is not the actual pH but rather the value before the organic solvent has been added. It is difficult to determine the pH of a solution which has a mixed solvent.

For analysis, approximately 500 μL of solution was drawn into a 1 mL syringe (Hamilton Co.). Solutions were transported from syringe to ion source through a 100 μm inner diameter fused silica capillary (Polymicro Technologies Inc.) using a syringe pump (74900 series, Cole-Parmer Instrument Co.).

A Perkin-Elmer Sciex API 1 (see Figure 1, Chapter 2) mass spectrometer was used. Typical conditions are summarized in Table 1. Voltages were optimized on a daily basis to maximize the signal for the species of interest. The "best" voltages varied slightly (± 5 V) from day to day; typical values are listed in Table 1. All peak hopping data were collected using a 100 ms dwell time. All spectral scans were collected by adding 10

Table 1. Typical operating conditions

Sample flow rate	17 μL / min.
Nebulizer gas	nitrogen
Nebulizer gas pressure	40 psi
Curtain gas	nitrogen, ultra pure carrier grade
Curtain gas flow rate	80 psi
Curtain gas temperature	60 °C
Ionization needle voltage (V_{ISV})	-3200 V
Interface plate voltage (V_{IN})	-500 V
Orifice plate voltage (V_{OR})	-120 V
RF only quadrupole voltage (V_{RF})	-60 V
Mass analyzer quadrupole voltage (V_{R1})	-59 V
CEM detector voltage	+2600 V
Operating pressure of quadrupole chamber	4.0×10^{-5} torr

consecutive scans together and using a 10 ms dwell time.

Results and Discussion

It should be noted that manganese species are often difficult to identify using electrospray mass spectrometry. Manganese is monoisotopic and does not produce an isotope pattern for identification, as previously seen with chromium. The ligands attached to manganese can be of assistance in identifications if they contain a "helpful" isotope pattern. Also, the background in electrospray mass spectrometry changes constantly. Solvent may be selectively ionized depending on many factors. Some of these include pH and total ion concentration. One other factor associated with this instrument is memory.

Memory from organic acids, which are also nearly monoisotopic, have been observed in much of the speciation work. All of these factors combined can lead to misidentification of ions that do not contain manganese but are rather background or memory ions.

Mass Spectra of Mn(II) Species

Figure 1 is a mass spectrum of a 10 ppm solution of Mn(II) in HNO_3. A manganese containing species is observed at m/z = 241. This peak is attributed to $Mn(NO_3)_3^-$. The inset of Figure 1 shows the region around m/z = 160. No significant peaks are observed within this region.

It was determined during the course of this work that the pH of the solution may affect the stability of the $Mn(NO_3)_3^-$. Several 10 ppm manganese solutions were diluted from the stock standard and the pH was varied from 1 to 9. Scans were taken over a large mass range and the signal at m/z = 241 was monitored. The $Mn(NO_3)_3^-$ signal was present in all solutions. The signal intensity fluctuated slightly, most likely due to instabilities in the electrospray process. At a pH value of over 9, a brownish-black precipitate was observed. This precipitate is most likely MnO_2.

Figure 2 is a mass spectrum of a 25 ppm Mn(II) solution in HNO_3. The dominant manganese species observed are MnO_4^- (m/z = 119) and MnO_3^- (m/z = 103). Other peaks observed in this mass spectra are m/z = 113 and 125. The peak at m/z = 113 is due to TFA^- contamination (see previous Chapter 2). The peak observed at m/z = 125 is a common background peak. This peak is believed to be due to $H(NO_3)_2^-$. Solutions which contain nitrate often produce this background species. This species is also observed in non-nitrate containing solutions. When servicing the instrument, 1% HNO_3 is used to clean the components. This could be the source of nitrate for the background ion at m/z = 125.

Figure 3 is a mass spectrum of 10 ppm manganese in HCl. Under acidic conditions, Mn(II) should be the dominant form of manganese[5]. The acidic conditions and

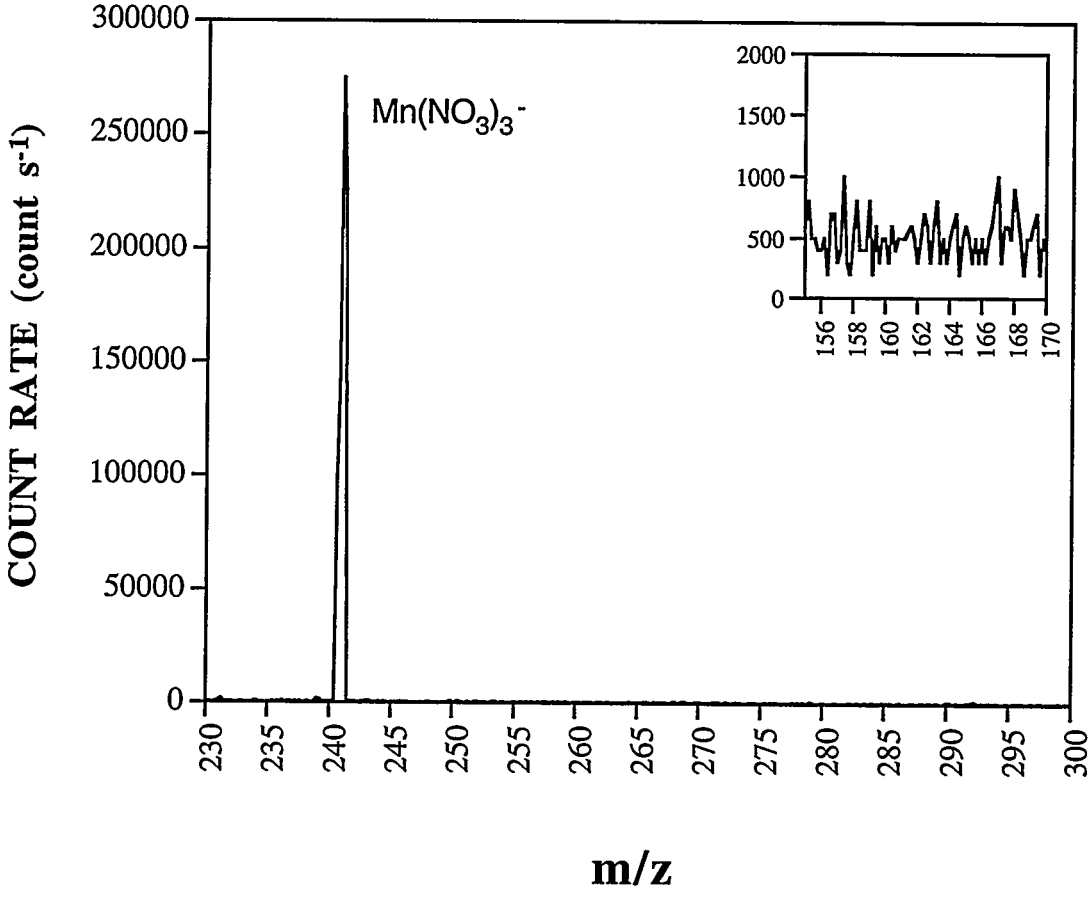

Fig. 1 Mass spectrum of a 10 ppm Mn(II) in HNO_3 solution. The inset is the region from 155 to 170 m/z

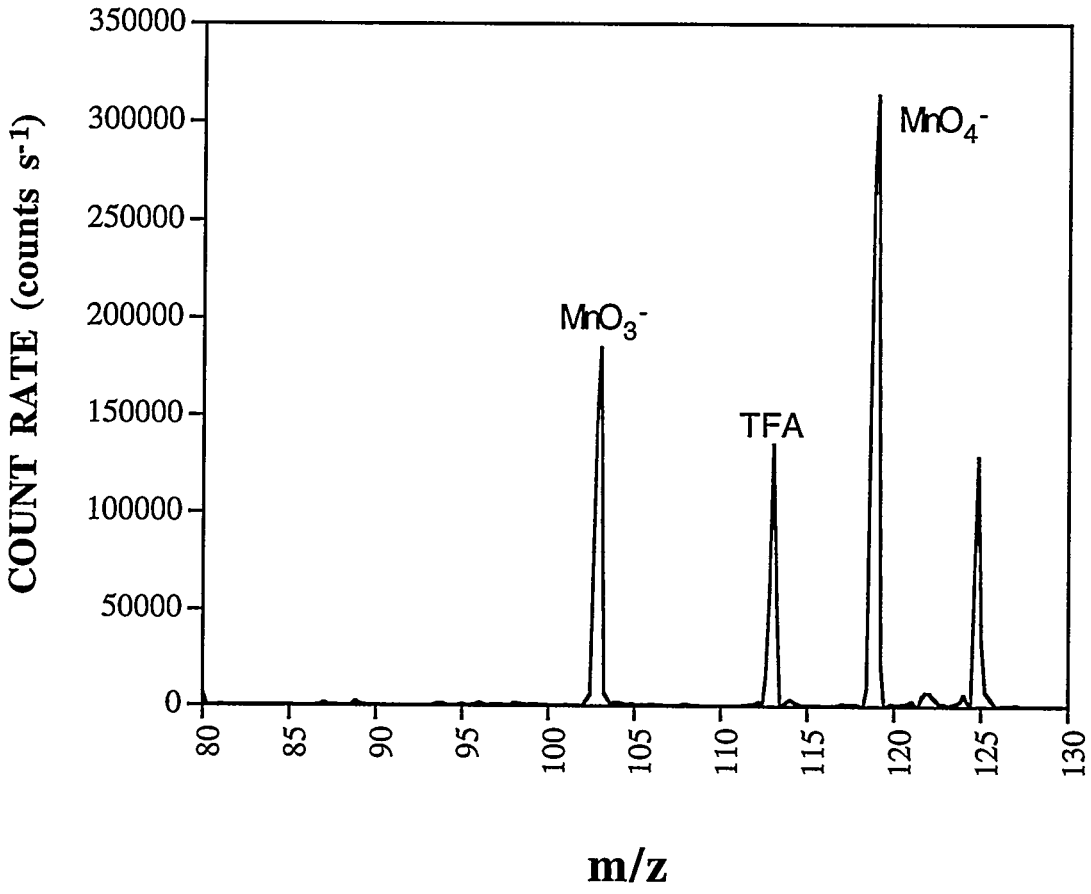

Fig. 2 Mass spectrum of a 25 ppm Mn(II) in HNO_3 solution

the results attained indicate the manganese is present as Mn(II). Two separate sets of peaks were observed which contain multiple chlorine atoms. One set of peaks observed at m/z = 285, 287, 289, 291, and 293 is believed to be $Mn_2Cl_5^-$. The isotope pattern present is in the proper ratio for a molecule with 5 chlorine atoms (24:30:26:8:1). The other set of peaks observed at m/z = 160, 162, 164, and 166 are believed to be $MnCl_3^-$. The isotope pattern present is also in the proper ratio for a molecule with 3 chlorine atoms (27:27:9:1). Several 10 ppm manganese solutions were diluted from the stock standard and pH was varied from 1 to 9. Signal was monitored from both the dominant manganese chloro complexes observed, m/z = 160 and 287. The signal intensity at m/z = 160 remained fairly constant over the pH range. The signal intensity at m/z = 287 was only present in appreciable amounts under acidic conditions. Similar to the Mn(II) in HNO_3, a brownish-black precipitate was observed at pH ≥ 9. This precipitate is suspected to be MnO_2.

A mixture which contains 10 ppm Mn(II) in HNO_3 and 10 ppm Mn(II) in HCl was prepared. A mass spectrum of this mixture is shown in Figure 4. The three major manganese species ($Mn(NO_3)_3^-$, $MnCl_3^-$, and $Mn_2Cl_5^-$) present from the two initial standards are observed. This solution is acidic, so the fact that the $Mn_2Cl_5^-$ species was observed is not surprising. The observation of both $Mn(NO_3)_3^-$ and $MnCl_3^-$ shows that the ES-MS spectrum of Mn(II) reflects both the oxidation state of Mn and the anions present in the sample.

Calibration Curves and Detection Limits

Calibration curves and detection limits were determined for both Mn(II) in HNO_3 and Mn(II) in HCl. In an attempt to unify solution composition, all the solutions used for the generation of the calibration curves were pH adjusted to a range of 7 - 8. Both m/z = 241 and 160 were monitored for all solutions. This was done to ensure that no manganese present initially as $Mn(NO_3)_3^-$ would change to $MnCl_3^-$ (Mn(II) in HNO_3 solution) and that

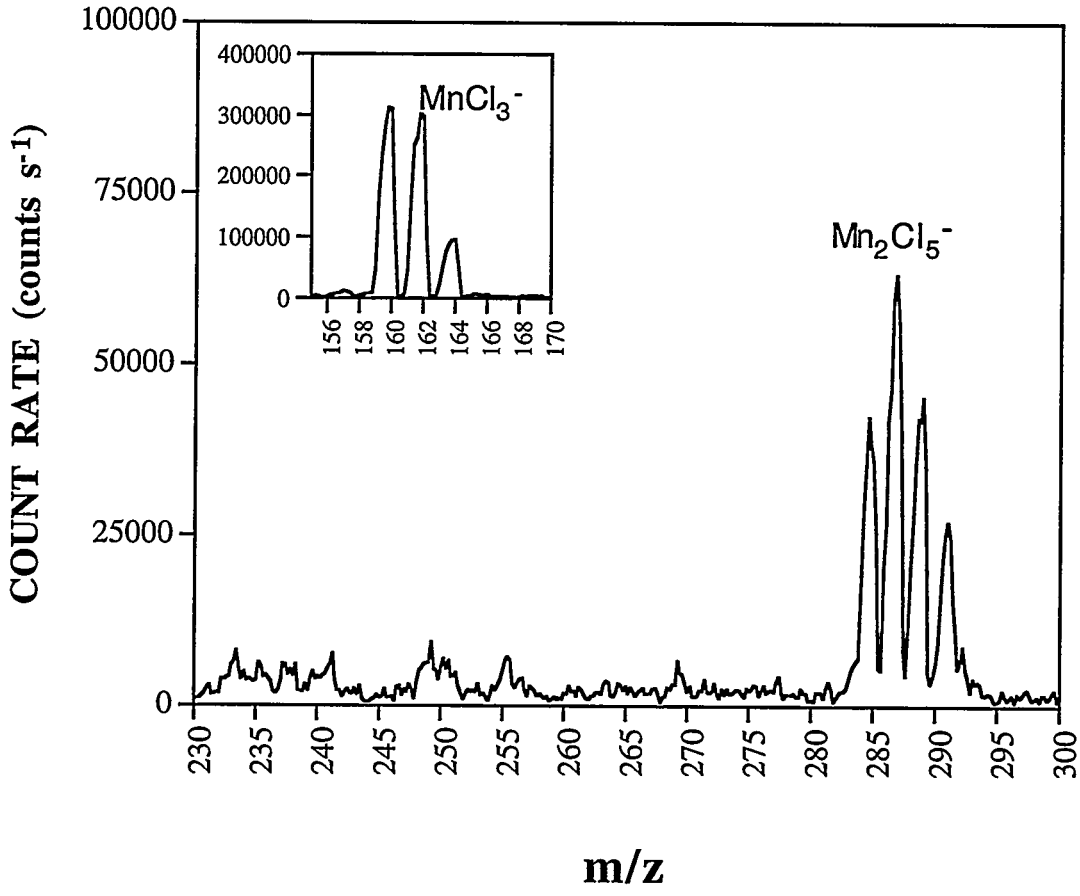

Fig. 3 Mass spectrum of a 10 ppm Mn(II) in HCl solution. The inset is the region from 155 to 170 m/z

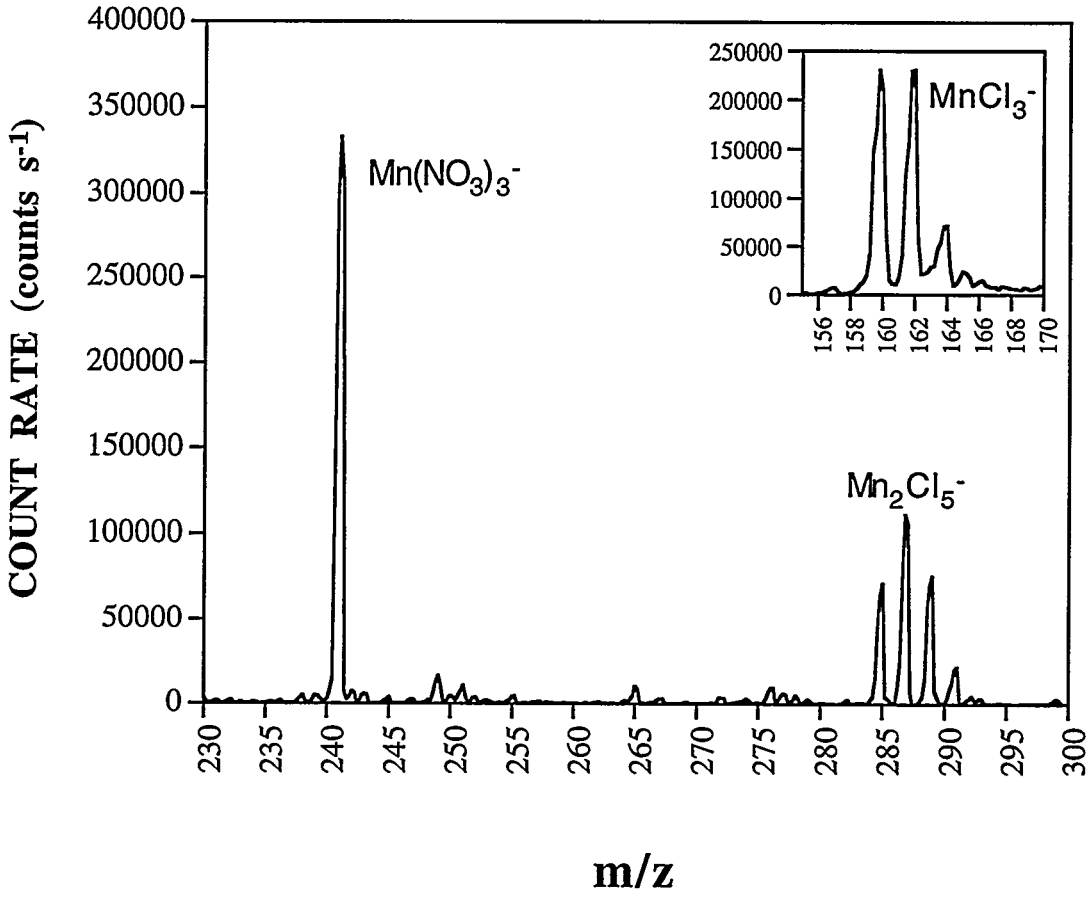

Fig. 4 Mass spectrum of a mixture containing 10 ppm Mn(II) in HNO_3 and 10 ppm Mn(II) in HCl. The inset is the region from 155 to 170 m/z

no $MnCl_3^-$ would change to $Mn(NO_3)_3^-$ (Mn(II) in HCl). No interconversions were observed in any solution.

Figures 5 and 6 are calibration curves for the two manganese solutions. Detection limits are shown in Table 2. These values represent the solution concentration necessary to produce a net signal equivalent to the background signal plus 3x the standard deviation of background during single ion monitoring for the dwell time used (0.1 s). The detection limits are 100 - 200 ppb (relative) or 3 - 6 pg (absolute).

Table 2. Detection Limits

Species	Relative DL (ppb)	Absolute DL (pg)
Mn(II) in HNO_3	100	3
Mn(II) in HCl	200	6

As an additional experiment, amounts of HCl were added to solutions which contained 10 ppm Mn(II) in HNO_3. HCl was added to these solutions in order to determine if the manganese chloro complexes could be observed, especially those seen from the Mn(II) in HCl solutions (set of peaks at m/z = 160, 162. 164, and 166 or set of peaks at m/z = 285, 287, 289, 291, and 293). The amount of HCl added to these solutions were enough to make the final solution concentration: 0.005%, 0.02%, 0.10%, and 1.0% (v/v) respectively. A 10 ppm Mn(II) in HCl solution would contain a final HCl concentration of 0.02% (v/v). These values for HCl addition cover the "normal" concentration of HCl as well as values higher and lower. No manganese chloro complexes were observed from any of these solutions. The dominant manganese species present continued to be $Mn(NO_3)_3^-$ (m/z = 241).

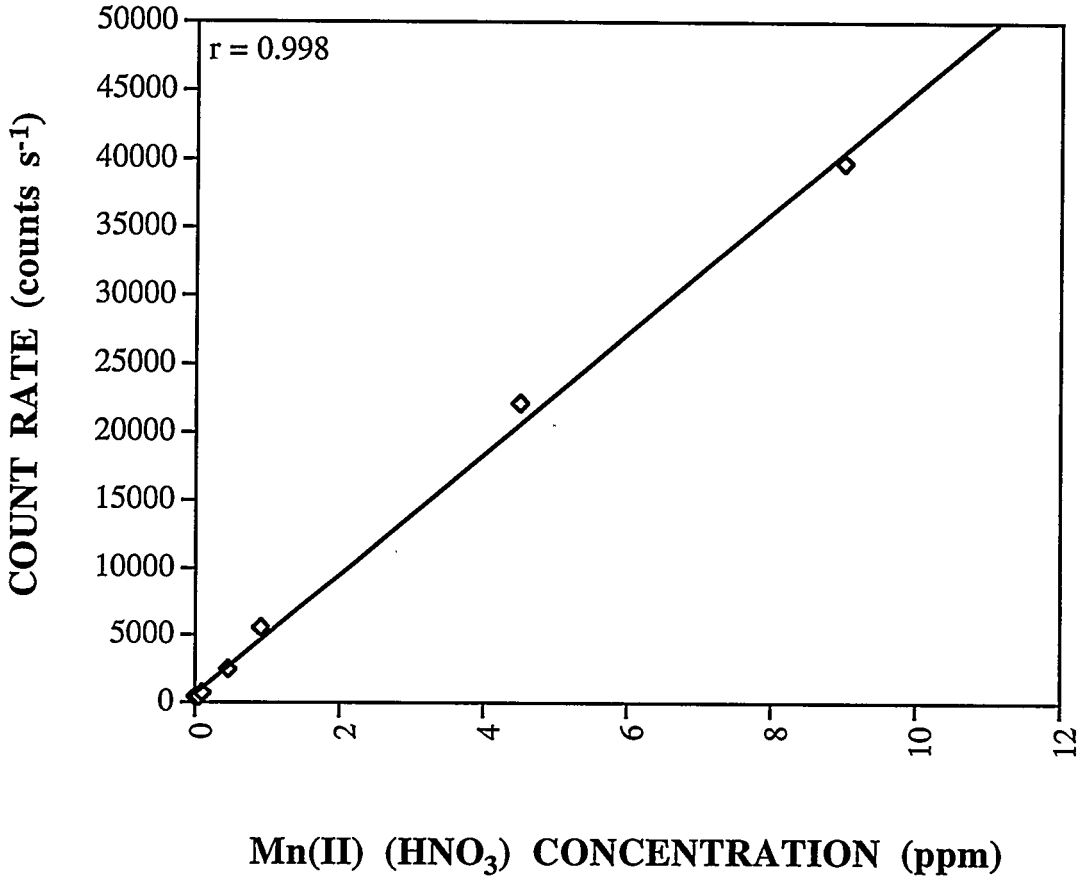

Fig. 5 Calibration curve for Mn(II) in HNO_3 solution

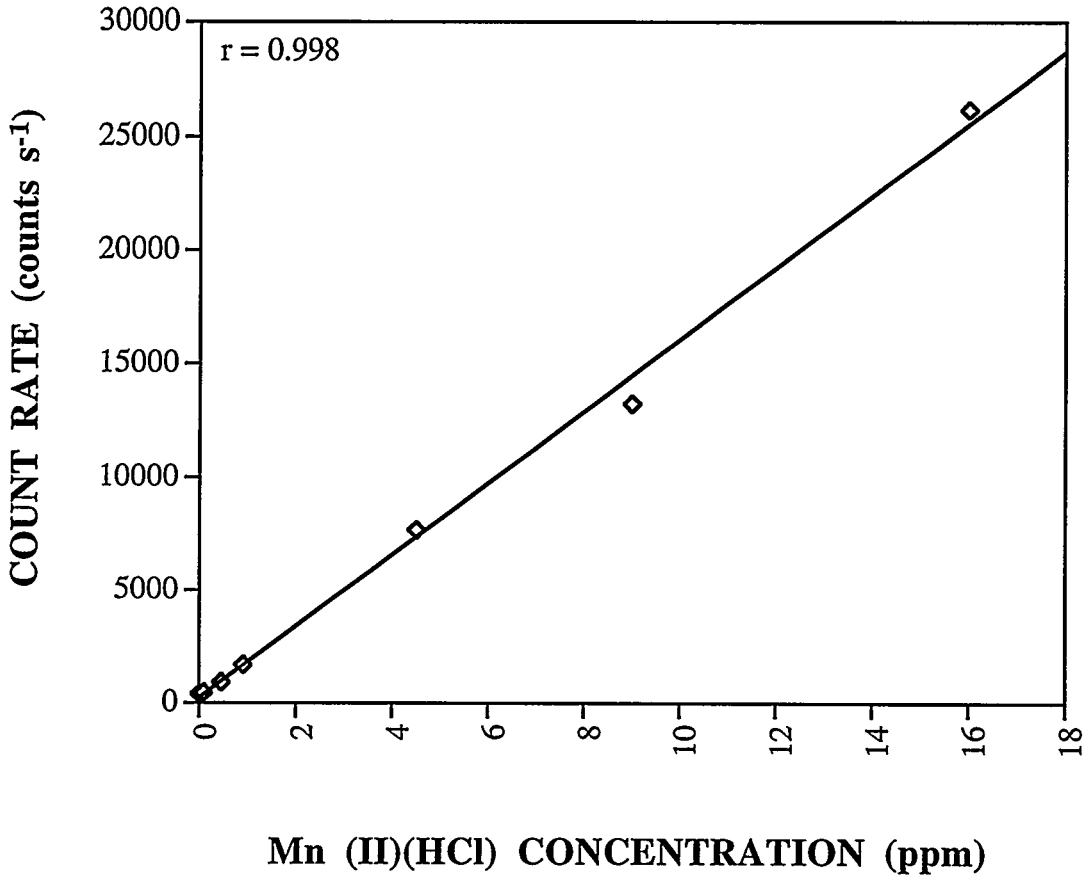

Fig. 6 Calibration curve for Mn(II) in HCl solution

Mass Spectra of Mn(VII) Species

Figure 7 is a mass spectrum of a 160 ppm $KMnO_4$ solution. Under these conditions, the dominant peaks which contain manganese are: MnO_4^- (m/z = 119), MnO_3^- (m/z = 103), and MnO_2^- (m/z = 87). The inset in Figure 7 shows the region around m/z = 241; there appears to be no appreciable amount of $Mn(NO_3)_3^-$ present is this solution. After approximately 1 hour, the normally purple solution underwent a color change to become deep brown. This is suspected to be a redox reaction in which the MnO_4^- is reduced by the MeOH/water solvent.

Selection of Collision Conditions

Figure 8, a plot of signal vs. V_{OR}, was generated from a 160 ppm Mn(VII) solution. The m/z values shown in Figure 8 are those for common manganese species previously observed (identified in caption). The main ion (MnO_4^-, m/z = 119, a) observed under soft collision conditions contains Mn as Mn(VII) and has intact oxygen ligands. As collision conditions become more energetic, the oxygens appear to be removed from the MnO_4^- resulting in the production of MnO_3^- (m/z = 103, b) and MnO_2^- (m/z = 87, c). This event is known as collision induced dissociation (CID). No appreciable signal was observed for m/z = 241 (d) which seems to indicate no manganese species present at this m/z.

Figure 9 shows a plot of signal vs. V_{OR} from a 25 ppm Mn (II) in HNO_3 solution. The dominant species observed under soft collision conditions is $Mn(NO_3)_3^-$ (m/z = 241, d). As collisional conditions become more energetic, the $Mn(NO_3)_3^-$ undergoes CID and fragments into several oxoanions (shown in caption).

Comparing Figure 8 and 9 leads to selecting soft collision conditions for the analysis of a manganese mixture. Under soft conditions ($V_{OR} \geq -85$ V), MnO_4^- is the sole manganese species observed from the $KMnO_4$ solution and $Mn(NO_3)_3^-$ is the dominant manganese species observed from the Mn(II), if NO_3^- is also present.

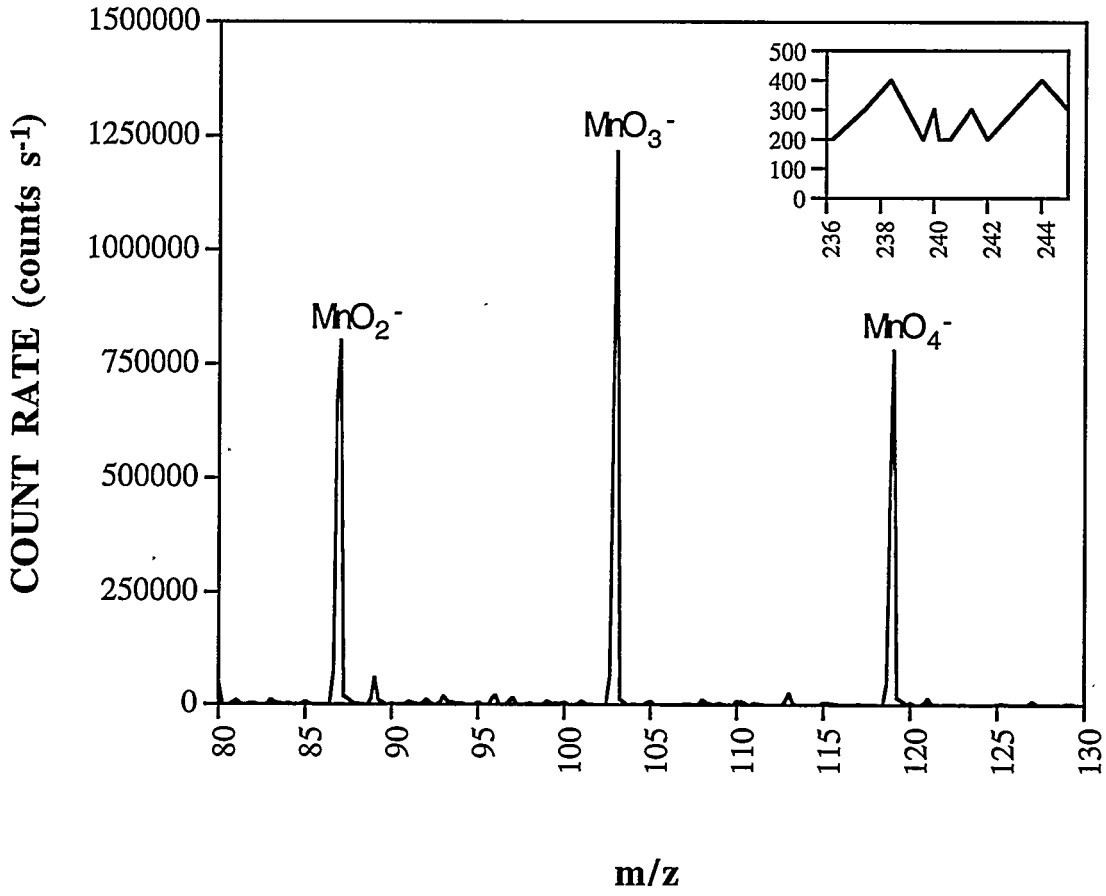

Fig. 7 Mass spectrum of a 160 ppm $KMnO_4$ solution. The inset is the region from 236 to 245 m/z

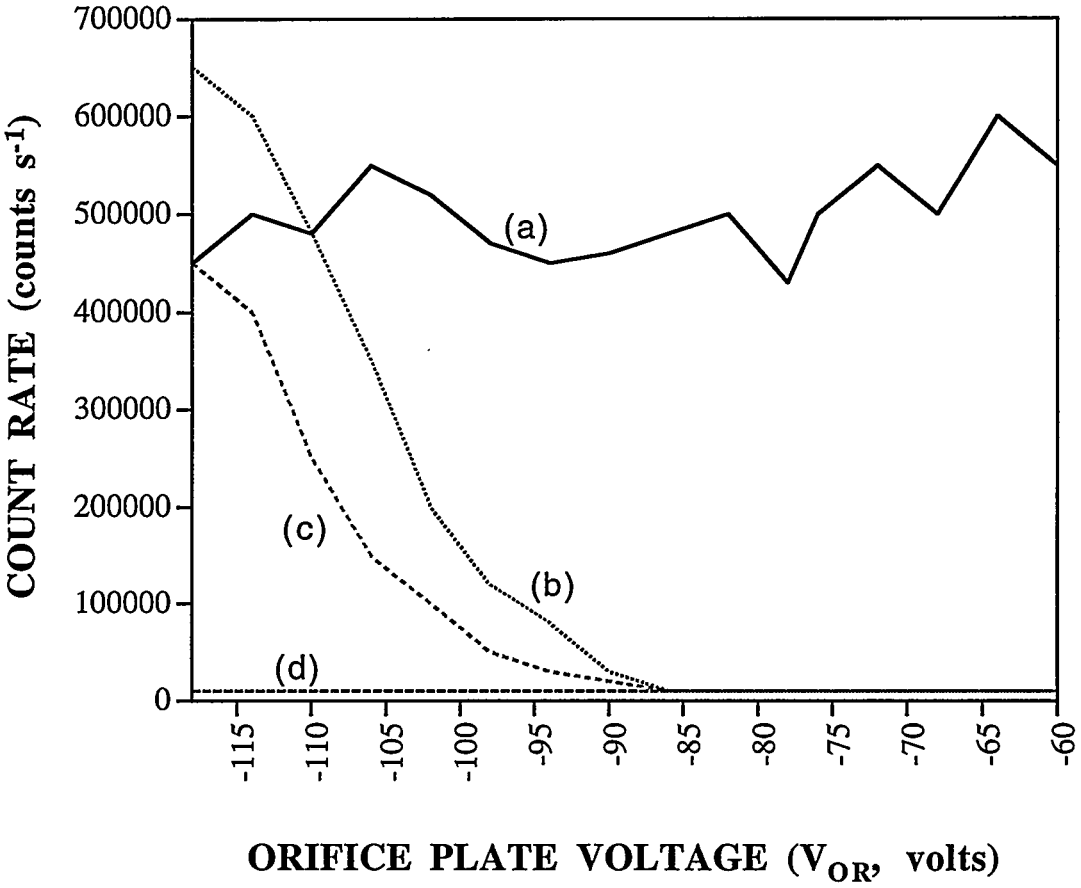

Fig. 8 A plot of signals from the major Mn species, a) MnO_4^-, m/z=119, b) MnO_3^-, m/z=103, c) MnO_2^-, m/z=87, d) $Mn(NO_3)_3^-$, m/z=241, observed from a 160 ppm $KMnO_4$ solution while varying the voltage on the orifice plate

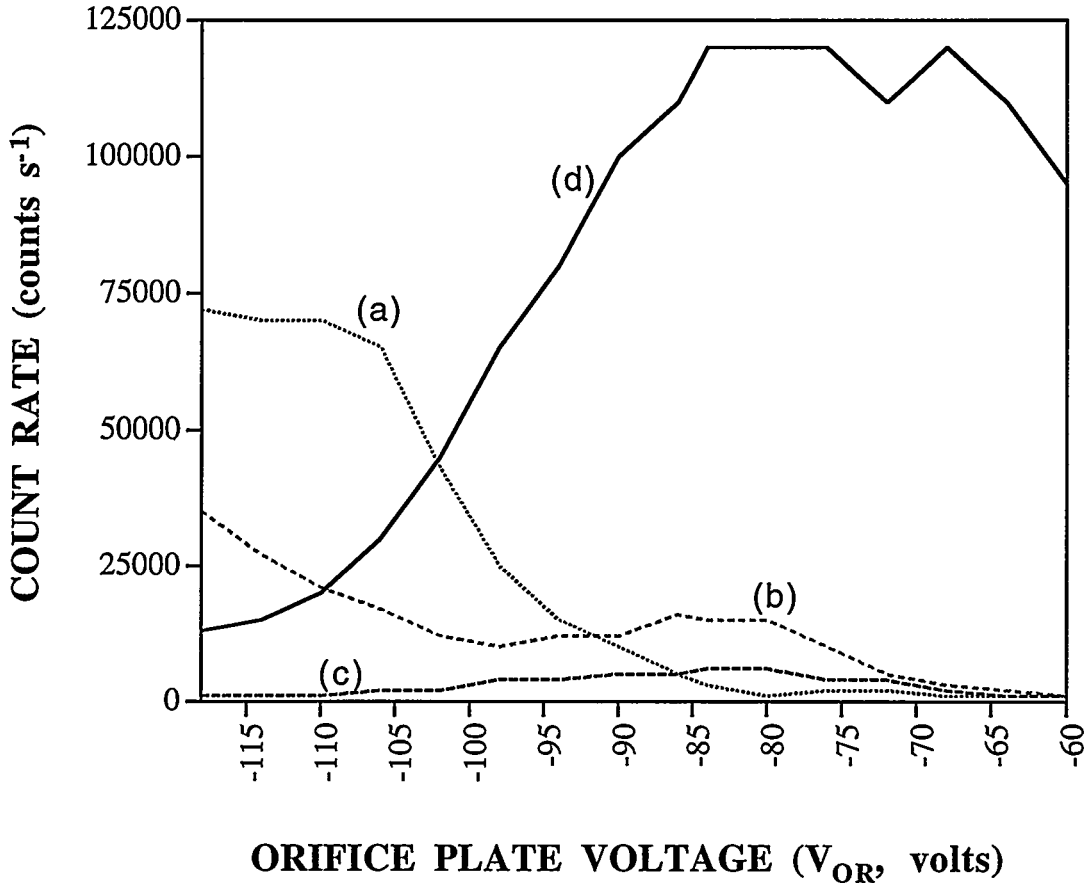

Fig. 9 A plot of signals from the major Mn species, a) MnO_4^-, m/z=119, b) MnO_3^-, m/z=103, c) MnO_2^-, m/z=87, d) $Mn(NO_3)_3^-$, m/z=241, observed from a 25 ppm Mn(II) in HNO_3 solution while varying the voltage on the orifice plate

Mass Spectrum of Mixture

Figure 10 is a mass spectrum of a mixture of 25 ppm Mn(II) in HNO_3 and 160 ppm $KMnO_4$. Three manganese species were observed, MnO_2^- (m/z = 87), MnO_3^- (m/z = 103), and MnO_4^- (m/z = 119). No discernible manganese species were observed at m/z = 241 ($Mn(NO_3)_3^-$). The initial solution color when prepared had a light purple/pink tint. Within minutes, before the solution could be analyzed, an obvious reaction had taken place. A brown precipitate, likely to be MnO_2, had formed. Apparently the solution had undergone a redox reaction. The following set of reactions may explain the redox reaction observed:

(1)	$MnO_4^- + 4\,H^+ + 3\,e^- = MnO_2(s) + 2\,H_2O$	$E^o = +1.695$ V
(2)	$Mn^{2+} + 2\,H_2O = MnO_2(s) + 4\,H^+ + 2\,e^-$	$E^o = -1.23$ V
(3)	$2\,MnO_4^- + 3\,Mn^{2+} + 2\,H_2O = 5\,MnO_2(s) + 4\,H^+$	$E^o = +0.465$ V

This could possibly explain the absence of the $Mn(NO_3)_3^-$ (m/z = 241) peak in the mass spectra of the mixture. No unique, stable peak remains for Mn(II) in this mixture. Also, the solution obviously no longer contains the original speciation information.

Conclusions

This study shows that ES-MS can distinguish Mn(II) from Mn(VII). These species will not occur together in a mixture, however. Steps could be taken to avoid forming the precipitate from the mixture prepared from Mn(II) in HNO_3 and $KMnO_4$; adjusting the pH or using a complexing agent may work for this situation. The fact remains that artificial means to stabilize systems such as these lose their "real" life applications. Samples obtained from nature will not be treated with these artificial methods and will have already undergone redox reactions. The speciation information will already have been lost in such a sample before it can be obtained. The initial focus of this work was to develop a method to determine manganese in different valences. This was not successful in this work because of the chemical nature of manganese itself. As others have seen, the chemistry of

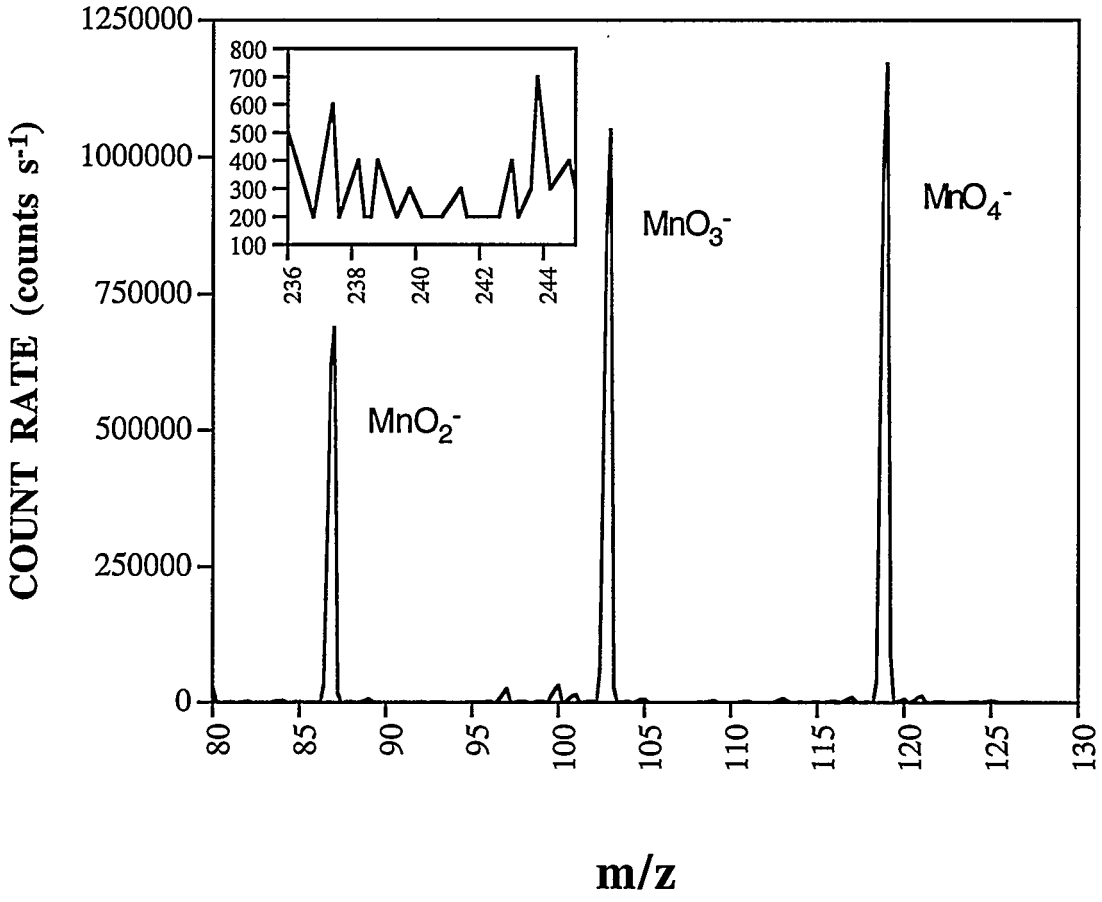

Fig. 10 Mass spectrum of a mixture containing 160 ppm $KMnO_4$ and 25 ppm Mn(II) in HNO_3 solution. The inset is the region from 236 to 245 m/z

manganese is such that complexes are readily altered as the solution composition is changed[6].

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CHAPTER 4. GENERAL CONCLUSIONS

This thesis has shown that it is possible to use pneumatically assisted electrospray mass spectrometry to obtain speciation information for solutions of mixtures. It was possible to qualify and quantify a mixture of Cr(III) and Cr(VI). This work could become a model for distinguishing other cations and oxoanions of the same element under the same spray conditions.

This thesis has also shown a real problem in speciation experiments. When species are sampled, great care should be taken to avoid changing the species present in the initial sample. In some cases, such changes are inevitable because of the reactivity of the species involved. Sampling and sample preparation work done to a sample can alter the speciation information and lead to inaccurate measurements. It is very important to understand the chemistry taking place in a sample in order to minimize these problems.

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