substantiate this claim, and future publications of work in progress will continue in this direction.

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Negative Ion Production with the Electrospray Ion Source

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Solution passed through a small capillary tube at several kilovolts relative to its surroundings is electrosprayed into a bath gas at slightly above atmospheric pressure to form a dispersion of ions that expands into vacuum through a small sonic orifice. A portion of the resulting supersonic free jet passes through a skimmer carrying ions into a quadrupole mass spectrometer. Previously reported results were obtained with positive ions formed when the capillary was at a positive potential. The present report concerns operation with the capillary at a negative potential to produce negative ions. As in the case of operation in the positive mode ions with varying degrees of solvation can be obtained from a variety of solute species including complex and nonvolatile organic molecules. No fragmentation of parent species is observed as long as electrical discharge is avoided in the gas phase. The presence of electron scavengers in the bath gas raises the potential at which discharge phenomena begin. Differences and similarities relative to operation in the positive mode are discussed.

Introduction

In a previous paper we reported our early experience with an electrospray ion (ESPI) source that showed an ability to produce positive ions in vacuo from a wide variety of species in solution.[1] The method consisted in passing a small flow of solution through a stainless steel hypodermic needle into a chamber containing a bath gas (nitrogen) at or slightly above atmospheric pressure. The needle was maintained at a positive potential of several kilovolts with respect to the chamber walls so that the surface of the emerging fluid was highly charged. The consequent coulomb repulsive forces were sufficiently large to overcome surface tension with the result that the emerging liquid was dispersed into a fine spray of positively charged droplets. As they moved under the influence of the applied field toward an orifice in the endwell of the chamber the droplets evaporated and gave rise to a gaseous dispersion of ions. Some of these ions were entrained in the bath gas that entered the orifice and emerged in the evacuated region on the downstream side as a supersonic free jet. A core portion of this jet passed through a skimmer into a more highly evacuated region containing a quadrupole mass spectrometer that analyzed the ions. This combination of electrospray and free-jet beam techniques had first been used over fifteen years ago by Dole and his colleagues in their attempt to produce beams of macroions by electrospraying a dilute solution of polymer molecules into the bath gas.[2-4] By retarding potential measurements on the final beam they obtained evidence that they had indeed been successful in producing singly charged macromolecules. They supposed that the charged droplets went through a succession of "coulombic subdivisions" as their surface area decreased by evaporation and the surface charge density consequently increased. They further assumed that in the final stages of this process many of the ultimate droplets contained only one macromolecule and one charge that remained on the molecule as the last of the solvent evaporated.

In our experiments the solute species were of much lower molecular weight, small enough to be analyzed with an available quadrupole mass filter whose upper mass limit was 400 daltons. We argued that the gas-phase solute ions we observed were more likely to have been produced by desorption from the liquid surface. Iribarne and Thomson had proposed that such ion desorption or evaporation could be expected because of the high fields resulting from increasing density of surface charge and decreasing radius of curvature as a charged droplet evaporated.[5] This mechanism seems able to account for the results that they obtained with their atmospheric pressure ion evaporation (APIE) source in some mass spectrometric studies.[6,7] It also accounts for the production of ions in the thermospray (TS) source that has been developed by Vestal and his colleagues as a means of interfacing a liquid chromatograph with a mass spectrometer.[8-10] In both APIE and TS the charged droplets are produced by atomization of an ion-containing liquid. Statistical fluctuations in the distribution of cations and anions on either side of newly formed surface result in the formation of a mixture of droplets with positive and negative charges. ESPI can be regarded as a mirror image of APIE or TS because it is based on atomization by charging rather than vice versa. Consequently, all droplets have the same sign.

Whereas our previous paper was concerned with ESPI operation at positive polarity so that only positive ions were observed, the present report summarizes our experience to date with operation at negative polarities in which the observed ions are all negative. The differences and similarities between the two cases will be set forth in what follows.

Apparatus and Procedures

The design and operation of an ESPI source were described

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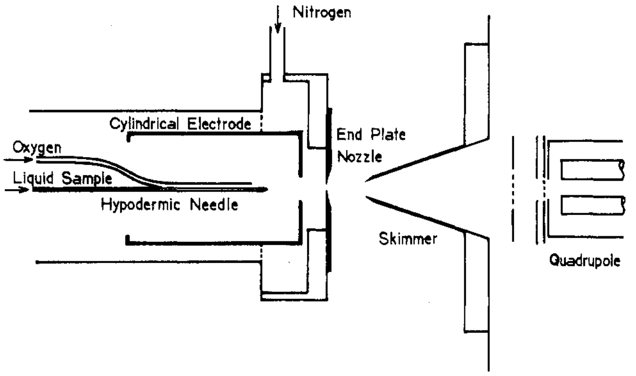

Figure 1. Electrospray ion source (ESPI) configuration for producing negative ions. Note the provision for introducing O_2 in the vicinity of the tip to inhibit discharge.

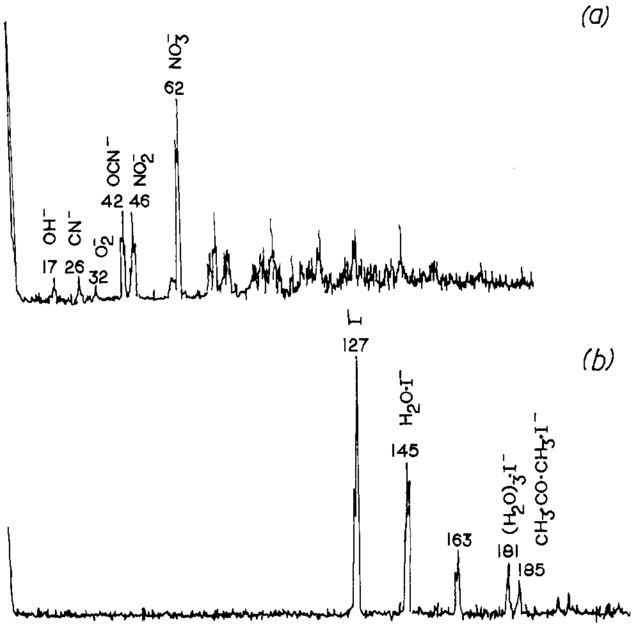

Figure 2. Negative ion mass spectrum of NaI solution. Solute mol fraction = 1.9×10^{-4} in acetone–Water (2:1). Needle voltage: (a) −6 kV; (b) −3.5 kV.

in our previous paper.[1] Some modifications were necessary to accommodate negative ions so it will be convenient to set forth essential features of the version used in this study by reference to the schematic representation in Figure 1. Sample solution from a syringe pump, driven by a lead screw at a flow rate typically between 6 and 20 μL/min, was introduced through a stainless steel hypodermic needle (B&S_2 gauge 26 s with an i.d. of 0.1 mm) into a chamber through which passed a bath gas of nitrogen at a rate of about 140 cm^3/s, a pressure of 1050 torr, and a temperature of about 330 K. In the end plate of the chamber at a distance of 15 mm from the needle tip was an orifice comprising a 0.07-mm hole photochemically etched in stainless steel shim stock 0.1 mm thick. Bath gas entering this orifice formed a supersonic free jet in a second chamber maintained at about 10^{-3} torr by a 4-in. oil diffusion pump. A skimmer with a 4-mm aperture passed a core portion of this jet into a third chamber that contained a quadrupole mass filter (QUAD 250 RGA with an Extranuclear power supply, QPS 111) and was maintained at pressures between 10^{-5} and 10^{-6} torr by two 6-in. diffusion pumps.

The liquid emerging from the needle was dispersed in a fine spray of charged droplets by an electric field produced by maintaining the needle at a negative potential typically between −2000 and −3000 V, the surrounding cylindrical electrode at −700 V, the orifice plate at −500 V, the skimmer at −40 V, and the two ion lenses between the skimmer and quadrupole at −20 and +100 V, respectively. The droplets were driven by the field gradient toward the end plate against a counter current flow of bath gas that was introduced in the annular space between the end plate and the cylindrical electrode. Consequently, the vapor from the evaporating droplets and ion clusters was swept away so that the ions reaching the end plate and entrained in the flow of dry gas through the orifice were largely, sometimes completely, desolvated. It is most important that the gas in the expanding jet be free of solvent vapor in order to avoid condensation and clustering of the ions.

Because the bath gas was at relatively high pressure the ions were completely thermalized. Their kinetic energies as they reached free molecule flow conditions 1 or 2 from the orifice exit plane were determined essentially by the convective velocity of the gas and were only a few tenths of an electronvolt for the masses we could detect (400 daltons or less). Consequently, the ions entered the quadrupole at an energy determined essentially by the potential difference between the orifice plate and the quadrupole, typically between 400 and 500 V. For their detection at the quadrupole exit we used a Ceratron multiplier (Murata Mfg., Kyoto) whose first dynode was maintained at +2000 V. A pulse amplifier and a scalar circuit were connected by means of an isolating capacitor to the output terminal of the Ceratron that was at about +4000 V.

It turns out that for otherwise equivalent conditions a breakdown to discharge at the needle tip occurs at much lower field strengths in the case of negative polarities than in the case of the positive polarities used in our earlier study. To inhibit such breakdown we found it helpful to introduce in the vicinity of the needle tip a small flow of gas with a strong electron affinity (e.g. 30 cm^3 of O_2/s) in order to scavenge electrons and prevent their being accelerated to ionizing energies. Also helpful was the use of solution solvents with component molecules having strong electron affinities.

Results and Discussion

In the experiments of our previous paper the hypodermic needle was maintained at positive potentials so that positive ions were formed and detected. We found that in what we called the *low voltage mode*, at tip potentials below those (typically 5 kV) at which breakdown to discharge occurred, the observed positive ion species comprised cations from the solution either alone or in aggregation with one or more un-ionized solute and/or solvent molecules. As already noted, we believe the field desorption mechanism of Iribarne and Thomson adequately accounts for the appearance of these ions containing single solute species. Less tenable is the Dole scenario by which a sequence of Coulombic subdivisions of ever smaller droplets finally produces an ultimate droplet with one or more charges and containing only a single solute molecule. In most experiments the flux of solute molecules in the spray exceeds the flux of charges so that Dole's ultimate droplet would have to contain more than one solute molecule per charge.

We also noted that when tip voltages in ESPI exceeded a critical value, there was an abrupt change in the nature of the electrospray characterized by a large increase in the total current. Simultaneously, the observed ion species changed so that the predominant species comprised protons and hydrocarbon fragment ions in aggregation with neutral molecules of solvent and/or solute species. We attributed this change to the onset of a corona discharge and the variety of ion–molecule reactions that such a discharge can promote. Under these *high voltage mode* or discharge conditions the field strength at the liquid surface was sharply decreased by space charge effects and the "clean" desorption of solute cation clusters was suppressed.

Similar results were obtained in the present study in which the hypodermic needle was maintained at a negative potential. Below a characteristic voltage, whose value depended upon geometry, bath gas pressure, the amount of electron scavenger present, and solution composition, the observed species were intact anions with un-ionized solvent or solute molecules attached. At higher voltages the spectrum was much more congested and noisier, especially in the high mass region. This behavior is clearly evident in Figure

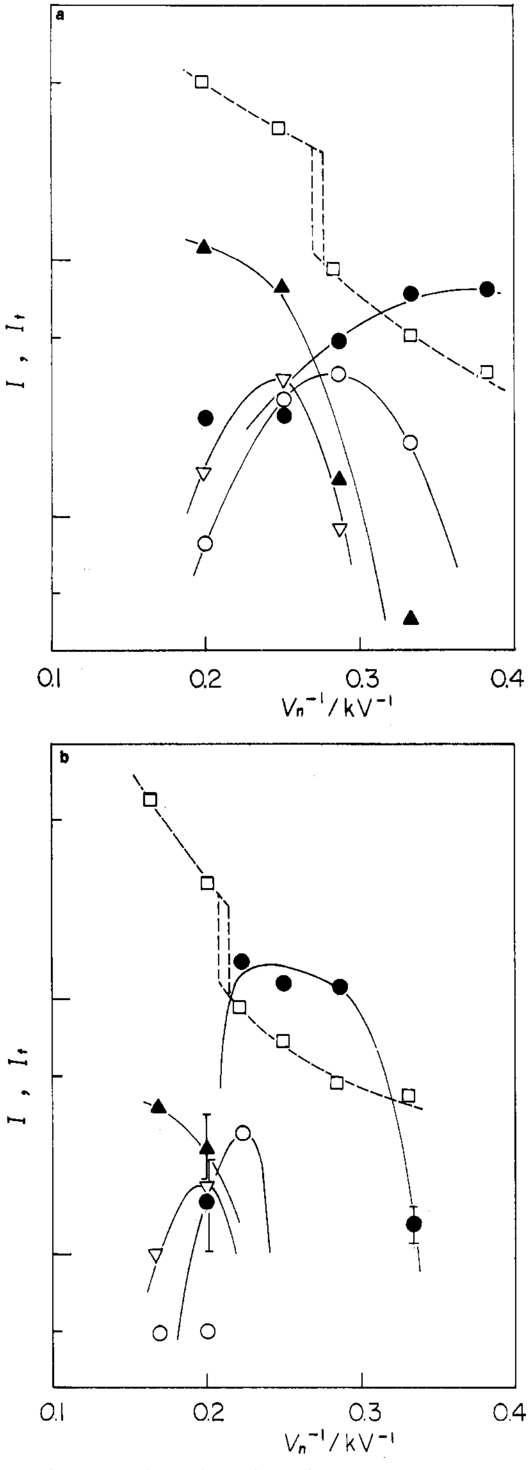

Figure 3. Current–voltage dependence for various species with (a) NaI (mole fraction = 9.0×10^{-5}) in methanol–water (2:1) and (b) NaI (mole fraction = 1.9×10^{-4}) in acetone–water (2:1): (□) total electrospray current on end plate (●) I^-; (○) $\mathrm{O_2}^-$; (▽) CN^-; (▲) $\mathrm{NO_2}^-$.

2 which displays mass spectra obtained with a dilute solution of NaI in a mixture of water and acetone. In the low voltage mode I^- and its solvated clusters are the only peaks in the spectrum. In the high voltage mode these solvated anion peaks are barely discernible and there are many fragment peaks in the low mass end of the spectrum. Figure 3 shows for NaI in two different solvents a semilog plot of relative ion currents for various species against reciprocal needle voltage. The scale factor for total spray current to the nozzle plate (open squares) is a thousand times larger than for the individual species currents that relate to what reaches the multiplier after passing through the orifice and the quadrupole. The hysteresis loop in the total electrospray current trapped by the end plate is what one might expect for breakdown and discharge in the gas because quenching of a discharge usually occurs at a lower voltage than does initiation.

The ion currents in the negative ion mode are somewhat lower than those found for positive ions under analogous conditions. It is in order to provide some actually measured values for these currents in a typical experiment. For a solution of NaI in methanol–water as in Figure 3a at a flow rate of about 10 μL/min the *total current* to the annular electrode shown in Figure 1 was 2×10^{-7} A. At subsequent stations the currents were 1.6×10^{-8} A to the end plate containing the orifice, 2×10^{-11} A through the skimmer to a collecting grid at the entrance to the quadrupole, and 2.6×10^{-15} A to the detector after the quadrupole. (The transmission of our quadrupole was very poor, about 10^{-3}.) We would stress the fact that these currents are not maximum or limiting values. Our emphasis thus far has been to see how sensitive ESPI can be for analytical purposes. Consequently, we have worked with very dilute solutions containing trace amounts of solute species. We have made no attempt to increase solute concentrations to determine how high we can go on the current scale. It is clear that the major attenuation occurs at the orifice, as might be expected. The inlet area is so small that only a tiny fraction of the ions can find their way through the hole.

The voltage–current relations in Figure 3 for each species show similar trends although the patterns differ in detail. Noteworthy is the fact that the solute cation I^- is the predominant species at voltages below breakdown. It fades rapidly at the onset of discharge after which most of the fragment ion currents first rise and then fall. The exception is $\mathrm{NO_2}^-$ which continues to rise, probably as a consequence of extensive ionization and reaction of the $\mathrm{N_2}$ and $\mathrm{O_2}$ components of the bath gas as the discharge grows in intensity and extent with increasing voltage. The other ion species, $\mathrm{O_2}^-$, CN^-, OCN^-, $\mathrm{NO_2}^-$, and $\mathrm{NO_3}^-$ show their maximum currents at different needle voltages. These species have all been found in corona discharges in air and except for $\mathrm{O_2}^-$, which is probably formed by simple attachment of electrons to $\mathrm{O_2}$ molecules, are products of ion–molecule reactions consequent to the acceleration of electrons to ionizing energies in the high field near the needle tip. The observed distribution of ion species and concentrations is the result of a complex interplay of reaction rates and their dependence on field strength, the temperature, density and composition of the bath gas, and the composition of the liquid.

As in the case of positive mode operation the abrupt jump in total current to the end plate and the marked change in the species current patterns are accompanied by a visible change in the spray characteristics. Below the critical voltage during "quiet evaporation" of solute ions the liquid leaving the hypodermic needle is drawn by the field into a thread several diameters in length that terminates in a sharp tip from which a fine mist of droplets emerges. After the transition to the high voltage mode, characterized by a much larger total current and the appearance of fragment ions, the liquid thread disappears and the spray comprises an aggregation of small sprays from various points around the sharp lip of the hypodermic needle. It is not entirely clear to us just which of these components of the overall picture can be considered causes and which are to be regarded as effects, except of course the applied voltage which is clearly the controlling and controllable variable.

As is clear from Figure 2 solute anions, solvated to varying degrees, are the dominant species during operation in the low voltage mode. The observed extent and nature of solvation is determined by at least three factors: the initial composition of the ions as they desorb from the liquid, the amount of desolvation during drying by the bath gas on the way to the orifice, and the amount of clustering brought about by the large temperature decrease during free jet expansion. As yet we do not have enough data and insight to determine the relative importance of these factors but it does seem that the last one can be discounted because we found no evidence of solvation on any of the fragment ions during operation in the high voltage mode. They should be just as effective as clustering nuclei as would be the solute anions of the low voltage mode.

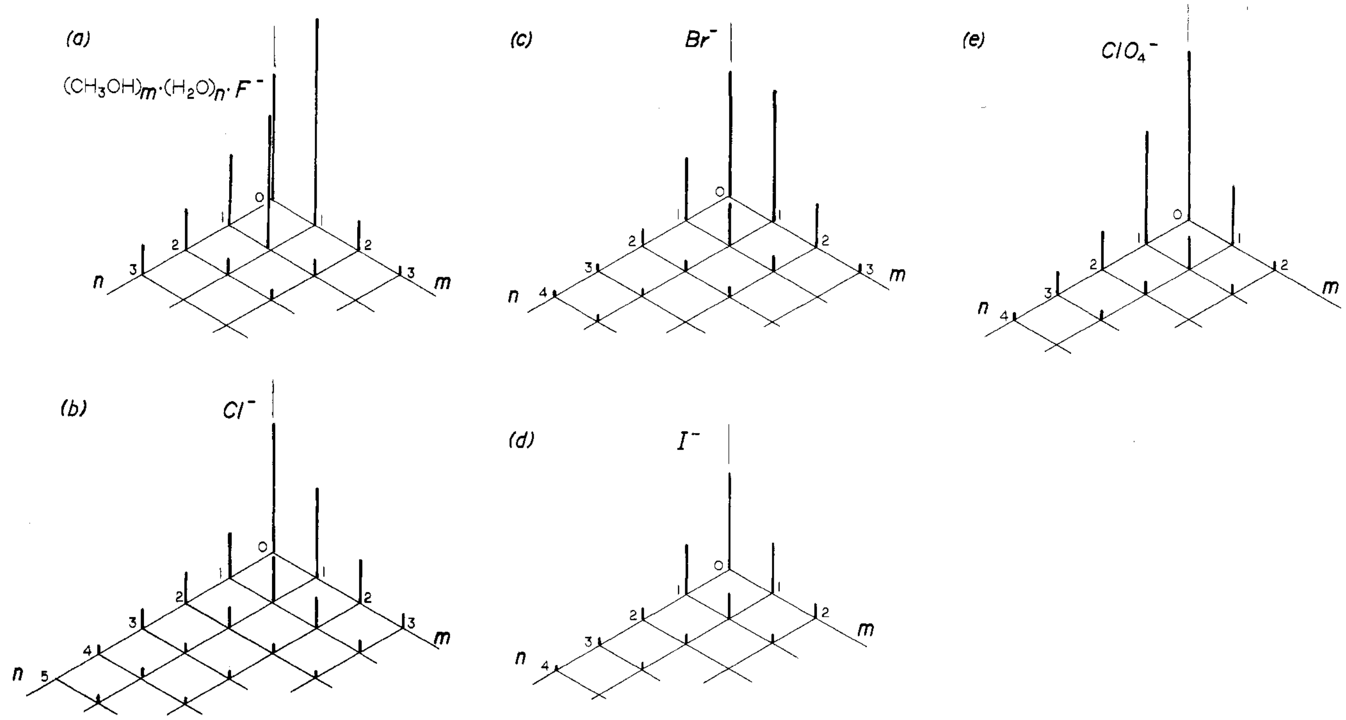

Figure 4. Distributions of cluster ion composition obtained with 90–100 ppm of solute in methanol–water (2:1) at a needle voltage of −2.75 kV. Subscripts m and n refer respectively to the number of methanol and water molecules in each cluster.

A more complete and comprehensible picture of solvation patterns is given in the three-dimensional plots of Figure 4. It is to be remembered that all the ions, whether formed in the low voltage or high voltage mode, spend essentially the same amount of time (several milliseconds) in bath gas at 1000 torr on their way to the orifice. Thus, they should be at or near thermal and compositional equilibrium with the bath gas as they start the free-jet expansion. They show the number and identities of the solvating species for various core anions including the four common halides and perchlorate desorbed from 2:1 methanol–water solutions of the sodium salts. There is a provocative trend showing an increasing preference for H_2O relative to methanol as the number of electrons in the core ion increases. Less pronounced is an apparent increase in the relative amount of unsolvated core ion with increasing size (number of electrons) of the latter. The reason or reasons for these trends are not clear to us. We note once again that many things can happen between the desorption step and arrival of an ion at the mass analyzer. We cannot yet determine to what extent the final ion composition is determined as it leaves the liquid and to what extent subsequent evaporation–condensation processes in the gas phase may be governing. We are inclined to believe that the latter may be more important, that the distribution we see represents the results of arrested vaporization of clusters that were at one time in or near equilibrium with gas-phase vapor rather early in their journey from the needle to the orifice. It is to be remembered that these ions are in a bath gas at above atmospheric pressure where the collision frequency per particle approaches 10^{10}/s so that their state should adjust very rapidly to the dictates of the ambient gas with respect to both composition and temperature unless, of course, there are energy barriers to be surmounted. It seems almost certain that with rare exceptions the ions must be in the ground state electronically, even in case of fragment ions found during operation in the high voltage mode when they might have initially been formed in highly excited states.

It is of interest to see what happens when the solute species are more complex. Figure 5 shows a mass spectrum obtained with tetracyanoquinodimethane (TCNQ), a symmetric molecule with a strong electron affinity (2.8 eV) that in solution forms stable monomer and dimer anions by electron transfer from other species. The sample solution was prepared by dissolving TCNQ in a small amount of acetonitrile that was then diluted with acetone or methanol–water as the major solvent species. The predominant peak is the monomeric anion M^-. We could not see any dimer ion M_2^- if it were present because its mass is beyond the effective range of our quadrupole. With other solvents, or when the sample was old and had been exposed to air, the spectra were only slightly different. The significant peaks other than M^- in all cases included $(M + 32)^-$ or $(M{\cdot}O_2)^-$, $(M - 10)^-$ or $(M - CN + O)^-$, and $(M - 5)^-$ or $(M{\cdot}(M - CN + O))^{2-}$. The tentative assignments shown in the term immediately following the indicated ion mass are at once reasonable yet speculative. Clearly, there is a lot of interesting solution chemistry involving this species that could be fruitfully

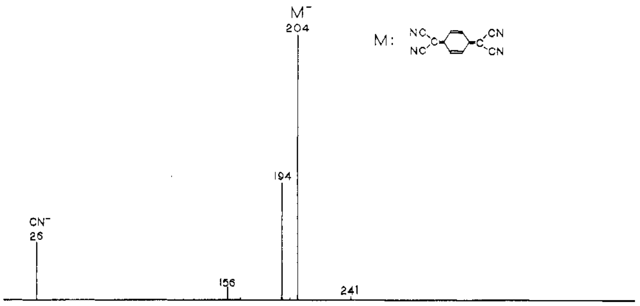

Figure 5. ESPI mass spectrum of tetracyanoquinodimethane at a mole fraction of 1.4 × 10^{-5} in acetone–acetonitrile (98:2) and a needle voltage of −4 kV.

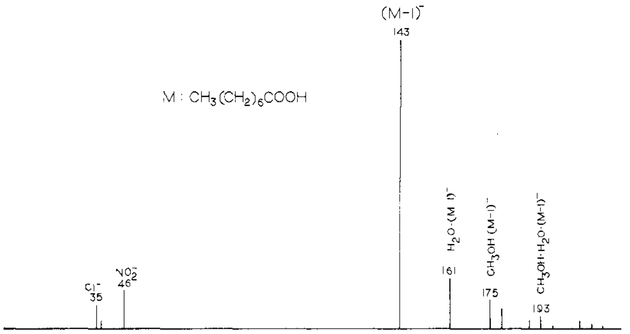

Figure 6. ESPI mass spectrum of octanoic acid at a mole fraction of 2.0 × 10^{-5} in methanol–water (2:1) and a needle voltage of −2.75 kV.

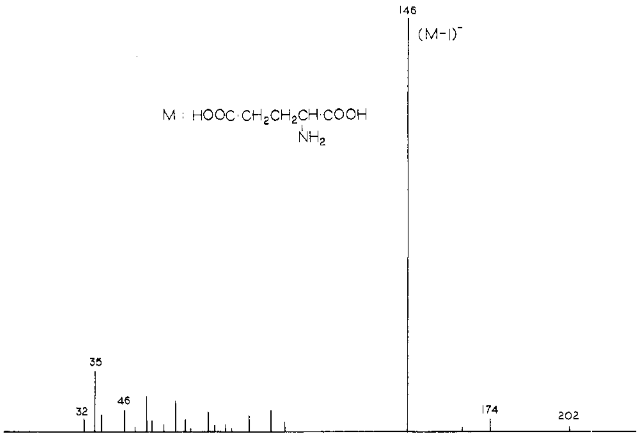

Figure 7. ESPI mass spectrum of monosodium glutamate at a mole fraction of 1.4×10^{-5} in methanol-water (2:1) and a needle voltage of -3.0 kV.

investigated by means of ESPI methods.

Carboxylic acids dissociate in aqueous solutions to give stable anions. Figure 6 shows a mass spectrum obtained with octanoic acid. The primary peak is the anion from the parent species. The other peaks in the high mass part of the spectrum can mostly be related to solvated parent anions. The only peaks in the low mass range seem to correspond to impurities. The applied voltage was relatively low and there was no evidense of discharge that would produce NO_2^- from the oxygen and nitrogen present in the bath gas. Peaks corresponding to fragment ions that would be abundant for this molecule during ionization by most other means are once again strikingly absent.

Another interesting class of species comprises the amino acids that generally display zwitterion characteristics. In solution they can be present as cations, anions, or neutral molecules depending on their isoelectric points and the pH of the solution. Glutamic acid and arginine with isoelectric points respectively of 3.08 and 10.78 represent two extremes. As shown in Figure 7 the mass spectrum obtained with monosodium glutamate in methanol-water solution shows a strong peak corresponding to $(M - 1)^-$. Using this same solution in the positive ion mode we found no peak corresponding to the cation. With arginine, on the other hand, we obtained in positive polarity operation strong peaks corresponding to the protonated molecular ion but no anion could be found in the negative mode. Alanine, whose isoelectric point of 6.11 is midway between arginine and glutamic acid, showed strong peaks for $(M + 1)^+$ in the positive mode and $(M - 1)^-$ in the negative mode. For this species the cation peak current increased when the pH was decreased in positive mode operation but increasing the pH in negative mode operation did not increase the current due to molecular anions.

Concluding Remarks

This brief glimpse of ESPI behavior in the negative polarity mode does not pretend to be either an extensive or an intensive account of the kinds of negative ions that can be produced or of the mechanism of their production. Our purpose will have been achieved if other investigators become intrigued with some of the many possibilities that we believe ESPI in the negative mode opens up rewarding research. It seems clear that the identity and relative amounts of ions in the observed spectra reflect the chemistry and physics of the initial solution. Their interpretation will pose challenging problems but the spectra contain much information so that the risk-reward ratio seems small enough to justify an effort. Even before such interpretation problems are solved ESPI shows great promise as an ad hoc source of complex ions in vacuo for study by the various kinds of spectroscopies that have been found useful in molecular beam research. One very attractive asset is the fact that the ions will almost certainly be in the ground state electronically and can also be cooled to low rotational and vibrational temperatures during free-jet expansion. For example, we plan to pursue what we think are very exciting opportunities for studying the photodetachment of electrons bound to complex molecules. Many other possibilities will doubtless occur to investigators interested in the chemistry and physics of negative ions.

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