Articles

Atmospheric Pressure Chemical Ionization Source. 1. Ionization of Compounds in the Gas Phase

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A novel chemical ionization source for organic mass spectrometry is introduced. This new source uses a glow discharge in the flowing afterglow mode for the generation of excited species and ions. The direct-current gas discharge is operated in helium at atmospheric pressure; typical operating voltages and currents are around 500 V and 25 mA, respectively. The species generated by this atmospheric pressure glow discharge are mixed with ambient air to generate reagent ions (mostly ionized water clusters and NO^+), which are then used for the ionization of gaseous organic compounds. A wide variety of substances, both polar and nonpolar, can be ionized. The resulting mass spectra generally show the parent molecular ion (M^+ or MH^+) with little or no fragmentation. Proton transfer from ionized water clusters has been identified as the main ionization pathway. However, the presence of radical molecular ions (M^+) for some compounds indicates that other ionization mechanisms are also involved. The analytical capabilities of this source were evaluated with a time-of-flight mass spectrometer, and preliminary characterization shows very good stability, linearity, and sensitivity. Limits of detection in the single to tens of femtomole range are reported for selected compounds.

The development of new ionization sources for mass spectrometry (MS), which has long been a major research activity in analytical chemistry, has increased significantly in recent years. This increase is partially due to the growing use of MS as an analytical tool. Also, because of continuous improvements in mass spectrometers, the ionization source often becomes the bottleneck in MS techniques. The development of new ionization strategies usually opens the way to new fields of application; ground-breaking applications have followed the introduction of new ionization sources such as electrospray ionization (ESI) and matrix-assisted laser desorption ionization (MALDI).

Soft ionization techniques, such as chemical ionization (CI), are attractive because they preserve the structural integrity of the 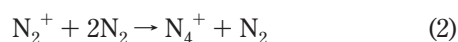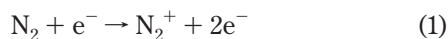molecules under study. Thus, they provide molecular mass information and yield simple spectra, particularly important in the analysis of complex mixtures. Although the limited amount of structural information that can be obtained has been traditionally a weakness of this approach, the problem can be addressed by the use of tandem MS techniques. Another significant advantage of CI over many other ionization strategies is the possibility of being operated at atmospheric pressure. Not only is sample introduction simplified by working at atmospheric pressure, it also improves the CI process. The increased number of collisions at higher pressures has two important consequences in this respect. First, the influence of diffusion is reduced, leading to longer residence times in the source, and enhancing the CI reaction efficiency.[1,2] Second, excess energy generated during the ionization reaction can be released through collisions with the buffer gas. This collisional cooling helps to lessen fragmentation. Atmospheric pressure chemical ionization (APCI) was first reported by Horning et al.[3,4] more than three decades ago. Since then, the technique has been an invaluable tool in the development of interfaces for separation procedures, such as liquid chromatography, with mass spectrometry.[5,6] Nowadays, APCI is an essential analytical tool for organic mass spectrometry.[7,8]

The mechanisms for the generation of reagent ions and the ionization pathways are similar for the most common APCI sources ([63]Ni and corona discharge). First, the buffer gas is ionized by a beam of electrons accelerated in a high electric field. Then, a series of reactions, which vary depending on the buffer gas composition, lead to the generation of the reagent ions. As nitrogen is by far the most commonly used buffer gas in APCI, the initial series of reactions is typically[3,9]
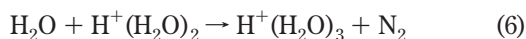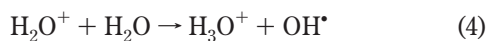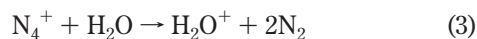
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$$N_2 + e^- \rightarrow N_2^+ + 2e^- \tag{1}$$

$$N_2^+ + 2N_2 \rightarrow N_4^+ + N_2 \tag{2}$$

Then, because of the presence of traces of water vapor,[6,9,10] ionized water clusters are generated:

$$N_4^+ + H_2O \rightarrow H_2O^+ + 2N_2 \tag{3}$$

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH^\bullet \tag{4}$$

$$H_3O^+ + H_2O + N_2 \rightarrow H^+(H_2O)_2 + N_2 \tag{5}$$

$$H_2O + H^+(H_2O)_2 \rightarrow H^+(H_2O)_3 + N_2 \tag{6}$$

Reaction 6 can proceed with successive addition of water molecules, leading to the formation of larger water clusters, H^+-$(H_2O)_n$. This reaction scheme is at the heart of any current APCI source, and it is deeply linked to the qualitative and quantitative performance of the source. Because of reactions 4−6, proton transfer becomes the main ionization pathway in APCI.[2,7,8] As a result, the ionization capabilities of the source will depend on the gas-phase acid/base behavior of the target molecules. Obviously, the number of reagent ions generated is also important, because it dictates the amount of the analyte substance that can be ionized and also the influence of other sample species on the ionization efficiency of the analyte (target species).

The most commonly used APCI source is the corona discharge (CD). In a CD, a high voltage (usually 3−5 kV) is applied to a needle electrode in nitrogen or air until currents in the single microampere range (usually 3−5 μA) are reached.[8,11] These low currents correspond to a very low degree of ionization of the buffer gas (reactions 1 and 2). CDs are widely used because of their simplicity and acceptable performance. Nevertheless, they possess several drawbacks, many of which are related to the limited number of reagent ions they generate. This limitation usually constrains the analytical performance in terms of linear range and ionization suppression caused by competitive reactions. For this reason, alternative soft ionization techniques for organic MS have been developed in recent years.

Atmospheric pressure photoionization (APPI)[12,13] represents one of the most recent attempts to improve APCI techniques. APPI was conceived as a way of directly photoionizing organic compounds by using high-energy photons (typically ~10 eV). The efficiency of direct photoionization, however, is limited by attenuation of the photon flux when a large excess of organic species, such as solvent molecules, is present in the gas phase. For this reason an easily photoionizable dopant, such as acetone or toluene, is usually added. The dopant is then directly photoionized, acting then as a reagent ion.[14,15] Therefore, APPI usually becomes in effect a photochemically initiated APCI source. Some of the improvements achieved with APPI stress the relevance of enhancing the generation of reagent ions in APCI sources.

An alternative way of generating reagent ions is by using a glow discharge (GD). Like the CD, the GD is based on ionization of the buffer gas by electrons.[11] However, the operating currents of a GD are typically in the single to tens of milliamperes, several orders of magnitude higher than in a CD. This higher current means that a GD can generate a much larger number and wider variety of reagent ions.[16] After early attempts to use a GD for organic mass spectrometry by Carazzato and Bertrand[17] and Mason and Milton,[18] several alternative GD arrangements for the analysis of organic substances were introduced; they include the particle-beam GD,[19] the fast-flowing afterglow,[20] and the gas-sampling GD.[21] The recently introduced proton-transfer reactor,[22] for example, uses a direct-current GD as a primary ion source for the generation of ionized water species. Unfortunately, the GD is operated at reduced pressure in all of these sources (usually in the single Torr regime). Under these conditions, fragmentation is favored and special arrangements, such as switched[23] or pulsed[24,25] powered schemes, are required in order to obtain intact molecular ions. Furthermore, sample introduction becomes more complex when the source is at reduced pressure. Although some studies dealing with atmospheric pressure GD using radiofrequency powering have been reported,[26,27] the use of radiofrequency significantly raises the instrumental complexity. Lubman et al.,[28,29] however, developed a direct-current atmospheric pressure glow discharge (APGD) in helium for the ionization of organic compounds. Unlike its low-pressure counterparts, the APGD yielded the molecular ion under a wide range of operating conditions. Furthermore, this source combined the simplicity of direct-current powering with very good sensitivity for a wide variety of organic compounds. One disadvantage of this approach is that the sample must be introduced into the discharge chamber, which can lead to several problems. First, the presence of organic compounds can alter the processes that sustain the GD. Second, the deposition of material on the electrodes or on the discharge chamber walls can lead to short- or long-term instabilities, memory effects, and other difficulties.

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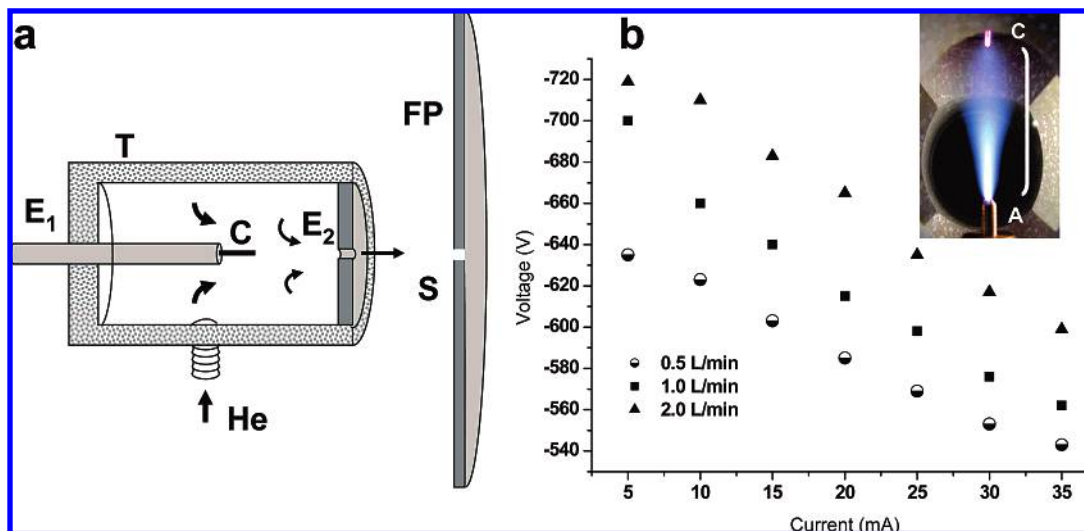(29) Zhao, J.; Zhu, J.; Lubman, D. M. *Anal. Chem.* **1992**, *64*, 1426−1433.

Figure 1. (a) Cutaway view of the flowing afterglow APGD cell: E_1, steel mount; C, tungsten cathode; T, Teflon body; E_2, anode; FP, mass spectrometer front plate; S, sample ionization region. The arrows indicate the He flow. (b) Discharge voltage as a function of cathode current of the APGD using the cell shown in part a for varying helium flow rates. The inset shows a photograph of a typical APGD with a pin cathode (C) and a rod anode (A). The gap between the electrodes in this case is 3 cm.

In the present study, we present an alternative approach that preserves the advantages of the APGD while avoiding the drawbacks of introducing compounds into the discharge compartment. A recently developed direct-current APGD sustained in helium[30] is used in the flowing afterglow (FA) mode as a chemical ionization source: the ions and excited species generated by the APGD are transported outside the discharge chamber, where they react with atmospheric constituents. These reactions lead to the production of reagent ions, so the sample need not be introduced into the discharge chamber. The idea of using the afterglow of a gas discharge for the ionization of organic compounds was proposed several decades ago as a replacement for the flame ionization detector[31,32] and is the foundation of the helium ionization detector (HeID), a device that uses the afterglow of a helium discharge (it is not clear in which discharge regime) for ionizing organic substances.[33,34] The HeID should be an ideal ionization source, because it has the ability to ionize virtually any molecule. In reality, however, because the signal that is monitored is the total ion current, the ionization of trace impurities in the buffer gas leads to unacceptably high backgrounds and the requirement of an extremely pure helium supply becomes a serious drawback. Our approach overcomes these drawbacks by taking advantage of the ionization of impurities, which become the reagent ions for CI, and by using a detector with mass discrimination capabilities. When the He APGD source is used for the ionization of organic compounds and MS detection is employed, mass spectra similar to those obtained with conventional APCI sources are obtained. This device shows very good short- and long-term stability, good sensitivity, and several other attractive analytical features that will be described in the second part of this report. The present paper will focus on the design

and operation of the FA-APGD and on preliminary characterization of the source for the ionization of organic compounds in the gas phase.

EXPERIMENTAL SECTION

Reagents. All reagents used were analytical grade. High-purity He (99.999% ultrahigh purity helium, Airgas, Radnor, PA) was used in all experiments.

Instrumentation. A diagram of the FA-APGD source can be seen in Figure 1a. The GD cell consists of three components: two electrodes (a pin, E_1, and a plate, E_2) tightly mounted in a discharge chamber (T). Electrode E_1 is a 1.5 mm diameter tungsten pin mounted into a 5 mm diameter steel rod that can be moved to adjust the interelectrode distance. Electrode E_2 is a 10 mm diameter, 2 mm thick brass disk with a 1 mm diameter orifice in its center. For practical reasons, E_1 was used as the cathode and E_2 as the anode. Switching the glow discharge polarity did not result in significant changes, providing that the pin is always the powered electrode in order to avoid electrical breakdown between E_2 and the mass spectrometer front plate FP. In this switched-polarity configuration, similar ions, but with slightly lower intensities, were observed. Also, the discharge becomes more unstable. The body of the cell (T) is Teflon and has a suitable entrance orifice for the discharge gas (helium). This helium flow can exit only through the orifice in anode E_2.

The He gas flow was set and monitored by means of a mass flow controller (model FC-280-SAV, Tylan General, Carson, CA). The GD was operated with a direct current (dc) high-voltage power supply (model DRC-5-400R, Universal Voltronics, Mount Kisco, NY) in the current-controlled mode. Negative voltage was supplied to the cathode through a 2.5 kΩ ballast resistor placed in series. The GD anode (E_2) was connected to a low-voltage dc power supply (model 6299A, Hewlett-Packard-Harrison Division, Berkeley Heights, NJ) in order to bias the GD operating voltage. The cell was mounted on a 3-D translation stage in order to align it with the entrance orifice of the mass spectrometer.

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Ions were detected by a LECO Renaissance (LECO Corp., St. Joseph, MI) time-of-flight (TOF) inductively coupled plasma (ICP) mass spectrometer. The ICP source was disabled and moved aside, and the APGD cell was positioned facing the ion-sampling interface of the spectrometer, on axis with the ion-sampling orifice. The original conical sampling plate of the Renaissance spectrometer was replaced by an ion-sampling interface made from a flat stainless-steel plate (or front plate, FP) attached to the instrument by means of plastic screws. These screws also allow the sampling orifice to be aligned with the skimmer orifice inside the first vacuum stage. This FP was fitted with a 0.25 mm diameter sampling orifice, allowing the pressure in the first stage to remain at proper operating levels (<5 Torr) while the unit was open to atmosphere. The FP is insulated from the rest of the instrument, so its electrical potential could be independently adjusted by means of a dc power supply (model IP-17, Heath Company Inc., Benton Harbor, MI). In this way, the ion-sampling interface mimics those commonly used with APCI sources.[8,35] A 3 mm diameter copper ring electrode serving as an ion lens (IL) was placed between the skimmer and the front plate and was connected to a low-voltage dc power supply (model 6207B, Hewlett-Packard-Harrison Division, Berkeley Heights, NJ). The mass spectrometer was always operated with a 1 s integration time unless otherwise indicated.

The total ion current (TIC) was measured at the FP and in the first vacuum stage by means of a picoammeter (model 414S, Keithley Instruments Inc., Cleveland, OH). In the first stage, the TIC was measured at a copper plate, which replaced the IL and acted as a Faraday collector. The TIC at the detector was taken as the total ion signal (TIS), which is the sum of all the ion signals registered in the mass spectra.

Vapor-phase organic compounds were introduced in two different ways: (a) from an exponential dilution chamber and (b) from a gas chromatograph. In the first case, a 100 mL round-bottom glass flask was used as a cell with He continuously flowing through it as a carrier gas. The temperature of the flask and the transport line were monitored with a thermocouple and held constant at 200 °C by a heating tape connected to a variable autotransformer (Staco Energy Products Co., Dayton, OH). In the second case, a commercial gas chromatograph (model 9A, Shimadzu Corp., Kyoto, Japan) equipped with a 30 m long, 0.25 mm i.d. capillary column (phase, RTX-200, Restek Corporation, Bellefonte, PA) was used. The column temperature was set at 200 °C and the gas flow at 70 mL/min. It must be stressed that the gas chromatograph was used as a sample-introduction device, and no attempts were made to optimize a separation. A split ratio of 1:10 was employed. In both cases, sample was injected with a 5 μL syringe (Hamilton, Reno, NV).

Procedure. Preliminary experiments were conducted to evaluate the electrical characteristics of the FA-APGD (current vs voltage plots and voltage stability) as a function of the gas flow rate and the interelectrode gap. Next, the conditions that maximize the ion generation and transmission were determined by measuring the TIC at different points: at the FP, in the first vacuum stage, and at the detector. In each case, TIC was measured as a function of the operating parameters in an independent, one-at-a-time fashion. Then, the background mass spectra (the mass spectra

without the addition of organic compounds) were obtained under the various operating conditions. Finally, selected organic compounds were added by means of the exponential dilution chamber and, once the exponential decay of the signal was smoothed (i.e., a relatively stable signal could be registered over short periods of time), conditions were optimized for detection of the chosen organic molecules. Finally, analytical figures of merit for the compounds were evaluated by using the exponential dilution chamber. For some compounds, the figures of merit were also calculated from the GC signal profiles.

RESULTS AND DISCUSSION

Characteristics of the APGD. The characteristics of an APGD in helium were reported earlier.[30] This diffuse gas discharge can be sustained over a wide range of currents (1−150 mA is the range tested in our lab) and usually displays a negative dynamic resistance (i.e., negative slope of the voltage vs current plot). Because of the short electron mean free path at atmospheric pressure, the negative glow of the APGD is a thin (submillimeter) layer on the surface of the cathode and most of the interelectrode gap is filled with the diffuse positive column (cf. photo inset in Figure 1b). As a result, although the APGD exhibits some characteristics that are different from those of a conventional low-pressure GD, it still operates in the glow regime.

The design and operation of the cell shown in Figure 1a are slightly different from those of the APGD described in ref 30, particularly because of the different electrode geometry (pin and plate electrodes) and the strong convection of the support gas. Therefore, there might be a question whether the gas discharge used here still behaves as an APGD. First, the negative slope of the current−voltage plots (Figure 1b) is similar to those reported for the helium APGD. Although support-gas convection produces an offset of the operating voltage, it does not significantly modify the slope. Also, the operating voltage is comparable to that already reported.[30] This evidence suggests that the gas discharge used here behaves as an APGD.

The inset of Figure 1b shows a photograph of an APGD using a pin as the cathode. In this configuration, the negative glow is a thin layer that covers the surface of the pin, while the rest of the interelectrode gap is filled with the positive column. Interestingly, the area covered by the negative glow is almost independent of the current under the present operating conditions. In other words, the negative glow covers the tungsten pin but does not reach the steel rod. This arrangement provides remarkably good short- and long-term voltage stability. The discharge usually requires a few minutes for warming up, after which the RSD of the operating voltage is usually less than 1%; the stability is ordinarily limited by the power supply. No significant drift has been detected even after several hours (often more than 8 h) of continuous operation. The voltage stability is not affected by the gas flow, except at the highest gas flow tested (2 L/min), where RSD can rise to approximately 5%.

The results shown here were obtained with an interelectrode gap of 5 mm. A linear dependence between the voltage required to sustain the discharge and the electrode gap has been observed, but preliminary experiments have shown that this gap does not significantly affect the results, except for very small (less than 2 mm) or very large (more than 15 mm) gaps where voltage stability

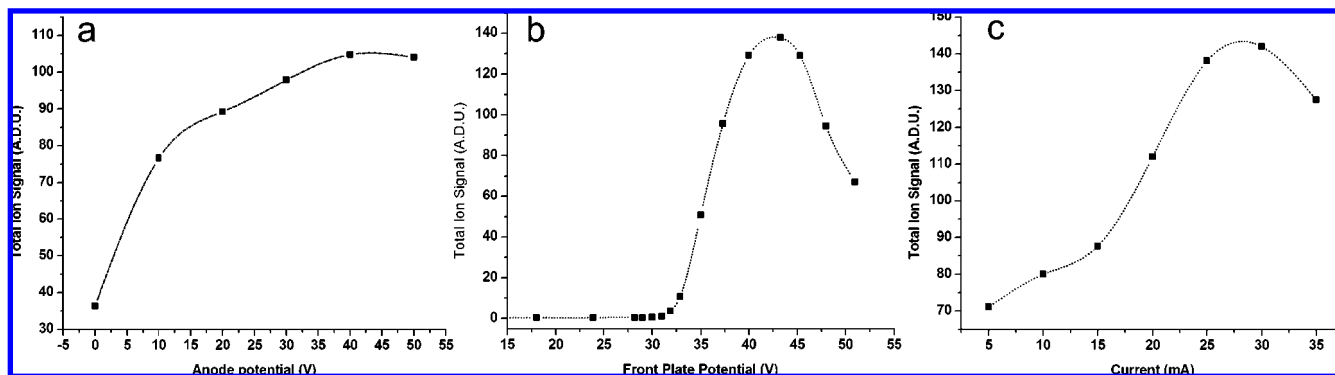(35) Bruins, A. P. *TrAC, Trends Anal. Chem.* **1994**, *13*, 37−43.

Figure 2. Optimization of the total ion signal (a) vs anode potential, (b) vs front plate potential (FPP), and (c) vs APGD operating current. Operating conditions (unless otherwise stated): gap between electrodes, 5 mm; anode potential, 45 V; FPP, 43 V; APGD current, 25 mA; He gas flow, 0.8 L/min; ion lens potential, 50 V; distance between the APGD cell and the front plate, 5 mm.

degrades, perhaps because of convection or turbulence generated inside the cell.

Optimization of the Total Ion Signal (TIS). The total ion current (TIC) generated by the background ions (i.e., without the addition of any analyte) as a function of the different operating variables was evaluated. The trends observed for the TIC at the FP, in the first vacuum stage, and at the detector are generally similar. Therefore, for simplicity, the plots below will show only the TIC at the detector (i.e., the total ion signal, TIS); any substantive differences will be pointed out in the text. Because there are many interdependent variables, the results shown here are intended to illustrate major trends. The dependence of each variable was evaluated while all others were held at their optimal values. Experiments were repeated using different initial conditions; no significant differences in optimal values were found.

The effect of the APGD anode potential on the TIS can be seen in Figure 2a. As the anode potential is raised from 0 to approximately 30 V, a sharp rise in the TIS is observed. For values above 30 V, the climb is more gradual, and for anode potentials just above 40 V, the TIS reaches a plateau. These experiments were conducted with the FP potential fixed at 43 V. Consequently, the net effect of increasing the anode potential is to reduce the electrical field in the afterglow region. The optimal anode potential seems be close to the value that produces an almost field-free region. For all subsequent experiments, the anode was set at 45 V.

The effect of the front plate potential (FPP) on the TIS, shown in Figure 2b, exhibits a sharp peak in TIS over a relatively narrow range of voltages. For a FPP below 30 V, almost no ion signal is detected. When the FPP is increased to values between 30 and 40 V, a sharp rise in the ion signal occurs. The TIS reaches a maximum value at a FPP of approximately 45 V and then sharply declines as the FPP is further raised. The reason for this behavior is not yet clear, although again the optimal FPP range corresponds to establishing an almost field-free region in the afterglow. On the other hand, application of an electrical field between the sampling plate and the skimmer orifice is a common practice with APCI sources.[8,35] Typical FPP values around 10−40 V have been reported for a conventional CD.[8,36] In our case, the optimal value for the front plate was selected to be 45 V.

Figure 2c shows the effect of the APGD operating current on the TIS. The TIS rises sharply as the APGD current is increased,

until it reaches a maximum at approximately 25 mA and then drops at higher currents. Interestingly, the TIC in the first stage shows a similar pattern, whereas the TIC at the FP climbs steadily with APGD current (i.e., it does not reach a maximum value). This pattern might be the result of space-charge effects at the sampling orifice, although further work is required in order to verify this hypothesis. The operating current was set at 25 mA for subsequent experiments.

Additional variables, such as the He flow, ion lens potential, and the distance of the source from the FP, also have a marked effect on the TIS. Overall, the gas flow and the distance between the cell and the mass spectrometer have complementary effects: although the TIS declines markedly as the sampling distance becomes greater, the use of higher gas flows helps to alleviate this reduction. If the support-gas flow is sufficient (up to approximately 2 L/min), the APGD can be positioned more than 10 cm from the MS and ion signals can still be detected. At a distance of 5 mm, an optimal gas flow of 0.8 L/min was found. For the IL, an optimal voltage of 40 V (a value very close to the FPP and anode potential) was found. Under optimal operating conditions (anode potential = 43 V, FPP = 45 V, ILP = 40 V, APGD current = 25 mA, gas flow = 0.8 L/min, distance cell/FP = 5 mm), the TIC measured in the first stage was 150 nA.

Mass Spectrometry of Organic Compounds. *Background Spectra.* The flowing afterglow of the He APGD creates an extremely rich chemical environment, where a wide variety of species can be generated. Preliminary work performed in our lab has shown that changing the operating parameters of the APGD or adding different gases to the afterglow (instead of directly mixing it with air) can yield different ions, including N_2^+, O_2^+, NO^+, and Ar^+. Here we will focus on the analytical characteristics of the flowing afterglow when mixed with ambient air, a condition which mimics conventional APCI sources.

Figure 3 shows a background spectrum obtained under conditions that maximize the TIS. Under these conditions, the background spectrum is dominated by ionized water clusters, as is commonly seen with APCI sources.[6,10] The protonated water dimer, $(H_2O)_2H^+$ at $m/z = 37$, is usually the strongest signal. NO^+ and, to a lesser extent, H_2O^+ and O_2^+ are also important background species. Changes in most operating parameters (gas flow, distance to the MS FP, ion lens potential) generally produce a uniform scaling of the various ion signals. The FPP and APGD operating current, however, also affect the relative intensities of

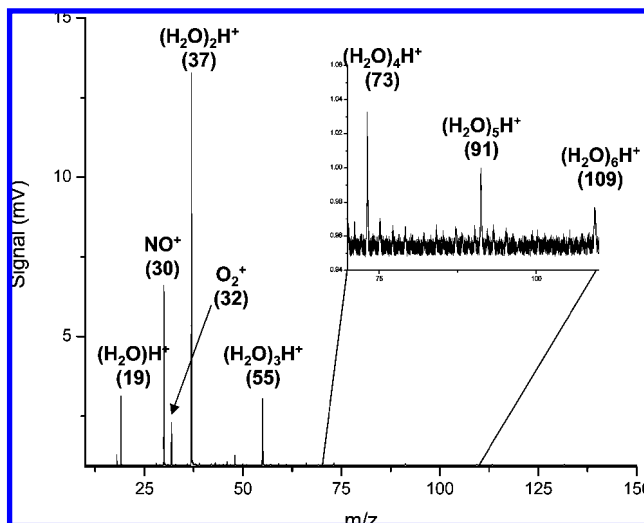(36) Kambara, H.; Kanomata, I. *Anal. Chem.* **1977**, *49*, 270−275.

Figure 3. Background mass spectrum. The numbers in the peak labels indicate the *m/z* value.

the peaks. In general, elevating the FPP produces a "declustering" effect (i.e., larger clusters tend to break into smaller units). For example, water trimer is the main ion at low FPP, while the monomer is the base peak at high FPP. This effect has also been observed in APCI sources and was first used as a way of declustering ions by Kambara and Kanomata.[36] Under the influence of the electrical field, the ions gain kinetic energy, which is then converted through collisions into vibrational energy and results in declustering. It should be remembered that expansion of the ion beam in the first stage produces a cooling effect, which promotes condensation reactions. The additional kinetic energy provided by the electrical field helps to overcome this effect by means of collision-induced dissociation.[8] Regarding the APGD current, the signals grow uniformly until the optimal current (approximately 25 mA) is reached. Beyond this value, most of the ion signals drop sharply, with the exception of NO^+, whose relative abundance becomes greater as the current is raised.

The ions shown in the spectrum of Figure 3 can serve as reagents for the CI of other species. The mechanism by which these ions are generated in the FA-APGD might be similar to that in a CD. There is no reason to doubt, for example, that the formation of water clusters (reactions 2−6) occurs in the same way as in conventional APCI. In any case, the generation of N_2^+ is an essential step that distinguishes both approaches. In a CD, N_2 is ionized by electron impact. In the He APGD this should not occur to a significant extent, because any electrons that leave the discharge compartment do not have enough energy to ionize N_2. Instead, the He APGD provides alternative ways to efficiently generate N_2^+ and H_2O^+. The APGD is also an intense source of helium metastable species[37] which, from an analytical perspective, have two extremely attractive attributes: high energy and long lifetime. The energy of the helium metastables (He*) is approximately 20 eV, high enough to ionize virtually any molecule; the nonradiative lifetime is on the order of several seconds.[38] Thus, He* is a powerful chemical reservoir of the energy withdrawn from the electrical field in the APGD. Penning ionization can

subsequently occur when a neutral molecule collides with the He metastable species. Two such Penning processes have particularly large cross sections:[39,40]

$$He^* + N_2 \rightarrow He + N_2^+ + e^- \qquad (8)$$

$$He^* + H_2O \rightarrow He + H_2O^+ + e^- \qquad (9)$$
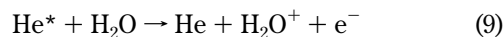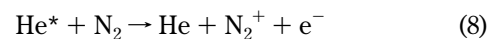
The high efficiency of these reactions has been stressed in the literature. Indeed, the efficiency of reaction 8 is high enough to use N_2 as a means of detecting and quantifying He*.[41,42] Clearly, He* will not survive long in a nitrogen-rich environment (such as open air) and will quickly generate an equivalent amount of N_2^+. The same is true for water molecules, although the partial pressure of water in air (∼5 Torr at 20% relative humidity) is much lower than that of N_2. Accordingly, the importance of reactions 8 and 9 is that their reaction products can be incorporated into the scheme of reactions 2−6, leading to the generation of reagent ions.

The background spectra also show some other minor species, such as larger water clusters ($n = 4$, 5, and 6), not clear at the amplification setting of Figure 3. Also, unidentified peaks appear at several *m/z*, particularly in the low mass (<120 u) range. Some of these peaks, as has been reported by Kambara et al.,[10] correspond to clusters with atmospheric constituents; others can be attributed to the ionization of traces of organic solvents present in the lab, as will be discussed below. Still other peaks, not yet identified, might be related to the ionization of contaminants in the mass spectrometer first stage (for example, traces of pump oil). Efforts to eliminate these background peaks have not yet been successful. Their presence, however, is relevant because in many cases they constitute the main source of background fluctuations, i.e., they influence the detection limit. This does not seems to be an inherent limitation of the ionization strategy but a drawback of the present ion sampling and detection scheme.

Ionization of Organic Compounds: Qualitative Aspects. The FA-APGD is capable of efficiently ionizing organic compounds. Our first evidence of this efficiency was the detection of background ions whose masses correspond to common organic solvents (acetone, methanol). Later, it was confirmed that these peaks arose from traces of organic vapors that were present in the laboratory air. The sources of these compounds were containers that were in use many meters from the MS instrument.

In order to perform a more systematic study, several organic vapors were added to the afterglow by using the exponential dilution chamber. With a relatively low gas flow through the chamber (∼20 mL/min) it is possible to reach, several minutes after the injection, a signal that drops very slowly as a function of time. In this way, the signal from a chosen substance persists long enough to allow recording of a mass spectrum. Also, effects due to concentration (such as dimerization) can be checked by examining the mass spectrum at different times.

In general, strong signals for the molecular ions are detected and little fragmentation is observed for most of the organic

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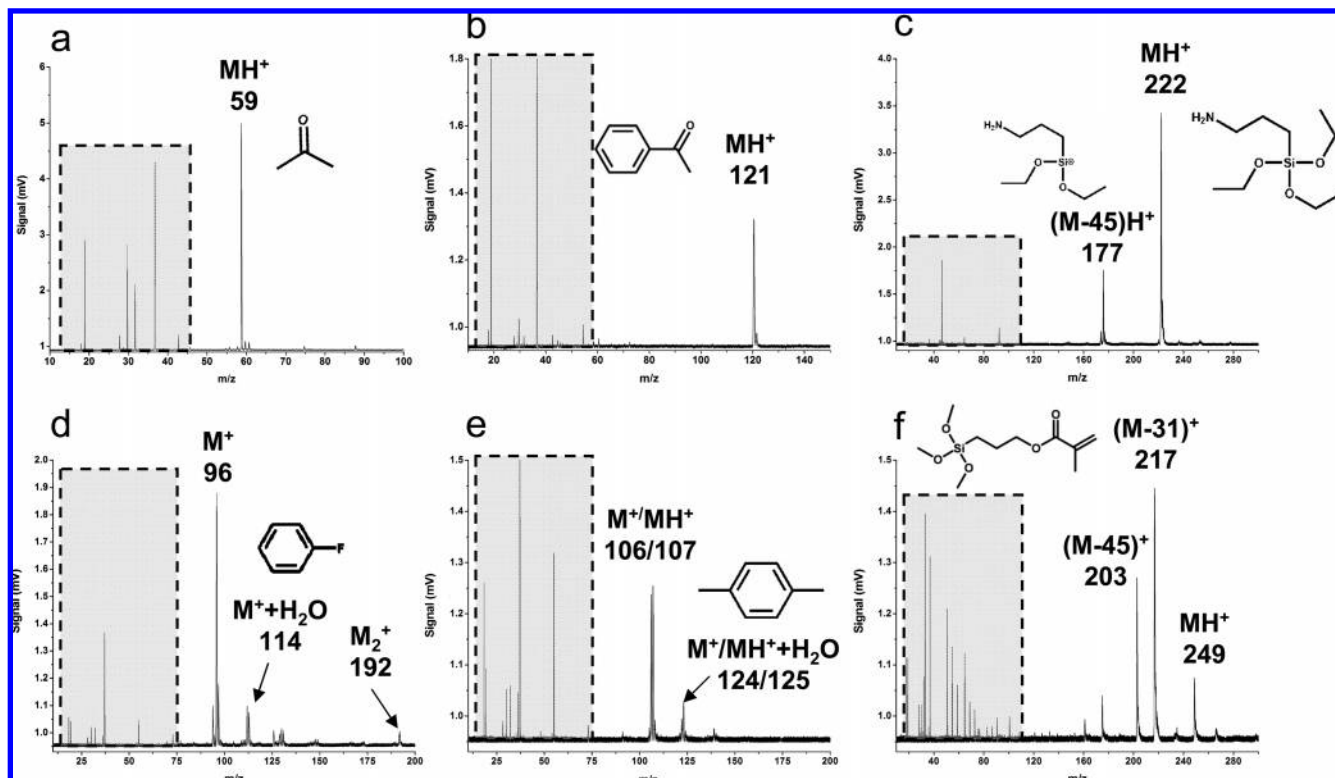
Figure 4. Typical mass spectra of some organic compounds: (a) acetone, (b) acetophenone, (c) aminopropyltriethoxysilane, (d) fluorobenzene, (e) *p*-xylene, and (f) 3-trimethoxysilylpropyl methacrylate. Peaks contained within the dashed boxes are from background signals not associated with the analyte.
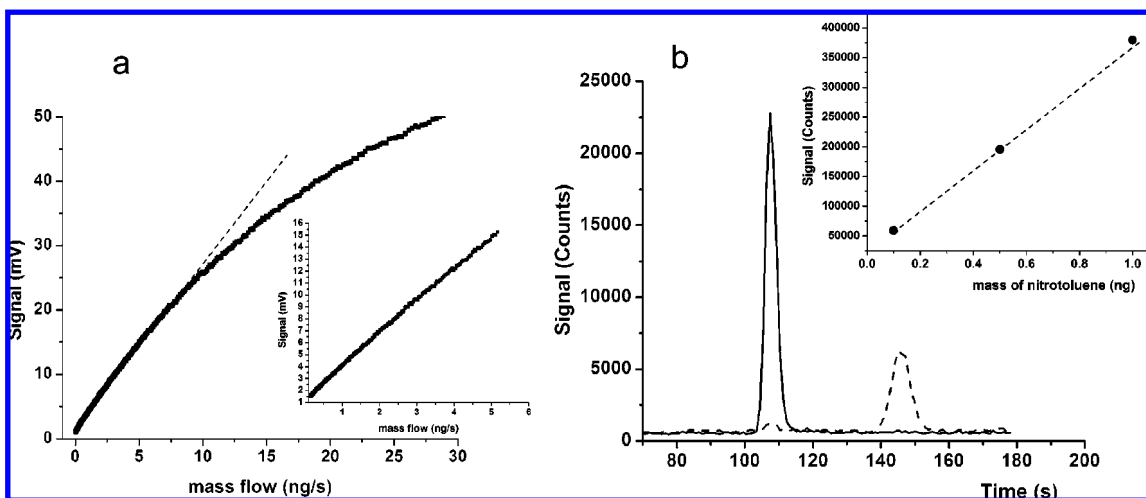

Figure 5. Quantitative determination of organic compounds: (a) calibration plot obtained from an exponential dilution experiment. The plot shows a deviation from linearity at mass flow rates larger than approximately 10 ng/s. The inset plot shows a detail of the lower portion of the curve in the range 0.03−5 ng/s. (b) Transient peaks corresponding to (i) 50 pg of acetophenone (solid line) and (ii) 50 pg of nitrotoluene (dashed line). The inset plot shows a typical calibration plot for nitrotoluene using the peak area.

compounds studied, so the mass spectra are usually very simple (see Figure 4). However, the larger the molecule, the greater the likelihood of fragmentation. When such fragmentation occurs, the pattern is relatively simple and easy to predict (cf. Figure 4f,c). Protonated molecular ions (MH⁺) are usually observed for polar compounds (Figure 4a,b), while nonprotonated molecular ions are observed in the case of nonpolar compounds (Figure 4e). This behavior reveals that ionization pathways other than proton transfer are involved. Charge transfer (from H_2O^+ or NO^+) might be playing a significant role.[6] In some cases, particularly at high

concentrations, compounds such as benzene and aniline show both M⁺ and MH⁺. Aliphatic compounds tend to yield a higher degree of fragmentation and a more complex spectrum than do aromatics, with $(M - 1)^+$ as one of the strongest peaks. This pattern might be due to ion−molecule reactions, as has been observed in APCI sources.[2] These observations all argue that this new source behaves like an APCI source.

Other spectral features, such as association between compounds (dimerization) and clustering (with water) are sometimes observed. Dimerization is not a serious problem, as it is observed

only at relatively high concentrations as seen with fluorobenzene in Figure 4d; however, clustering (especially with water) is more common, as seen with fluorobenzene and *p*-xylene (Figure 4d,e). It is often claimed that clustering is the result of cooling of the ion beam. However, as stated by Kebarle et al.,[43] the main ionization pathway here (proton transfer) is in fact a water displacement reaction. For a given organic substance (M), the proton-transfer process can be written as

$$M + (H_2O)_nH^+ \rightarrow M(H_2O)_{n-1}H^+ + H_2O \qquad (10)$$
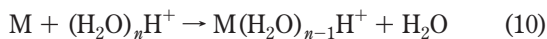
Therefore, the ions are likely formed in a solvated gaseous form, and desolvation is an additional (and necessary) step. As a matter of fact, it has been reported that the stability of the solvated ion plays a crucial role in the performance of an APCI source.[44] For this reason, improvements in the declustering of ions are often related to the ion sampling interface more than to the characteristics of the ionization source.

It is important to stress the role of temperature in APCI performance. Kebarle et al.[1,43] have studied the thermodynamic and kinetic factors that affect the efficiency of reaction 10. They have shown that a higher temperature enhances the ionization of several compounds that otherwise show poor performance.[45] It has been reported that, for some substances, the sensitivity can be increased by several orders of magnitude by heating the buffer gas. Also, raising the temperature alleviates the effect of cooling produced during the expansion in the first stage. Usually, an APCI source is heated to 250 °C so that the temperature of the gas remains high even after the expansion.[8,35] In this respect, the APGD offers a significant advantage because no external heating is required. In a GD, a significant amount of energy is transferred from the electrical field to the buffer gas through collisions with electrons. This process increases the kinetic energy of atoms or molecules in the buffer gas. Temperatures between 800 and 1000 K[30] have been found for an APGD in helium operated at 20 mA. Although the APGD used in this study operates with smaller gaps and with a considerable gas flow, it would still be expected that the afterglow is well above room temperature. Preliminary experiments using a thermocouple suggest that the temperature of the afterglow is at least 200 °C. Clearly, this value is just an approximation, and future work is needed for a more accurate evaluation by spectroscopic techniques.

Ionization of Organic Compounds: Quantitative Aspects. Quantitative performance was evaluated by using linearized exponential dilution curves and from peak profiles from the gas chromatograph. Some of these results can be seen in Figure 5. In general, a linear response was obtained up to a mass flow rate of 10 ng/s. Above this value, a deviation from linearity is observed. The upper end of the calibration plot was not further explored due to

Table 1. Figures of Merit for Some Selected Organic Substances

	sensitivity (counts/fmol/s)	LOD (fmol/s)
acetone	10.9	9.5
acetophenone	1.95	60
nitrotoluene	40.2	2
benzene	9.85	70

problems of contamination and long washout times of the sample introduction systems. The good stability of the source is demonstrated through the linearized exponential dilution profiles shown in Figure 5a. With the use of the chromatographic peaks, a preliminary idea of the sensitivity of the technique was obtained. In these experiments, the gas chromatograph was used simply as a sample introduction device and no attempts to optimize a separation were made. Signals corresponding to the injection of 50 pg (on column) of acetophenone and nitrotoluene can be seen in Figure 5b. Figures of merit for the determination of representative organic compounds are collected in Table 1. Limits of detection (LOD) are usually in the single to tens of femtomoles/second, and sensitivities (working-curve slopes) are on the order of single to tens of counts per femtomole/second. It should be stressed that the compounds listed in Table 1 belong to groups of substances that do not show particularly good sensitivity in conventional APCI.[44,45]

These results show that the helium APGD is very attractive as an ionization source for organic compounds. This new source shows considerable promise in the field of organic mass spectrometry. Analytical characterization, particularly quantitative aspects, still requires further work. However, the ion detection scheme needs to be improved before a more detailed characterization can be performed. Aspects such as the ion transmission efficiency, the mass range, the spectral resolution, and the background need to be addressed. The mass spectrometer used here was designed for a very different ion source (ICP). Furthermore, further work is necessary in order to reduce the baseline noise level, which is at present limited by chemical noise. Despite these limitations, the performance of the APGD encourages further work. Additionally, the source exhibits attractive analytical features, such as the possibility of performing direct analysis of solid substances, which will be discussed in a subsequent report.

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