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## OPTIMIZATION OF THE INSTRUMENTAL PARAMETERS OF A COMBINED LIQUID CHROMATOGRAPH-MASS SPECTROMETER, COUPLED BY AN INTERFACE FOR DIRECT LIQUID INTRODUCTION

### IV\*. A NEW DESOLVATION CHAMBER FOR DROPLET FOCUSING OR TOWNSEND DISCHARGE IONIZATION

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#### SUMMARY

A new desolvation chamber has been coupled to a liquid chromatograph-mass spectrometer interface. The shape of the drift tube was designed to focus the electrically charged droplets from the diaphragm nebulizer into the chemical ionization source. A voltage applied to the desolvation chamber influenced both the total ion current and the relative abundance of the ions when constant flow-rates of acetonitrile were nebulized. A stable but unsustainable Townsend discharge occurred when the voltage on the desolvation chamber was above 140 V.

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#### INTRODUCTION

Recent work has emphasized the importance of a droplet drift zone placed between the liquid nebulizer of a direct liquid inlet (DLI) interface and the chemical ionization (CI) source block of the mass spectrometer for liquid chromatographic-mass spectrometric operations<sup>1-4</sup>. The drift zone is believed to play several roles, although explanations in different reports often appear contradictory. Liquid droplets of analyte solutions must be injected under a vacuum in order to sample non-volatile molecules to the mass spectrometer ion source<sup>5</sup>. Droplet injection is com-

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patible with liquid chromatographic requirements as it does not broaden chromatographic peaks. As a consequence, several ingenious devices, including pneumatic nebulizers<sup>6</sup>, ultrasonic nebulizers<sup>7</sup>, diaphragms<sup>4,8</sup> and heated tubes<sup>9,10</sup>, have been used to produce stable and reproducible droplet sprays under a vacuum. The phenomena and the parameters affecting the production of solute ions from these solution droplets are less clear.

Rapid desolvation of the solution aerosol may leave neutral evaporated sample molecules which are subsequently ionized in the gas phase by ion-molecule reactions with the reactive species of a plasma<sup>11</sup>. Alternatively, it has been demonstrated that preformed ions (*e.g.*, carbocations, quaternary ammonium ions, protonated molecules, ionic clusters) can cross the surface of liquid droplets charged at high potentials and be isolated in the gas phase, either intact or clustered with solvent molecules; thus solution parameters and electrical charges would appear to be more important<sup>12,13</sup>. The direct isolation of solute-derived ions from electrolytic solutions in the absence of any external ionization process confirms the validity of the second hypothesis<sup>9,10</sup>. However, it was verified experimentally that heat must be applied to the droplets prior to their introduction into the ion source, and that an optimum temperature exists for different analytes<sup>2,3</sup>; thermal conditions for a desolvation process must therefore also be considered.

Although the exact mechanisms involved in the ionization of samples in solution cannot yet be established, the above work has oriented research towards the design of simple devices that may assist the desolvation and/or the ionization of solute molecules, and are currently referred to as desolvation chambers<sup>1-4</sup>. We described one such device in previous papers<sup>1,2</sup> that proved to be very effective in the determination of series of non-volatile molecules. The shape of the inner drift tube was designed so as to accelerate the speed of the droplets and minimize possible collisions with the walls of the desolvation chamber. This device is still in use in our laboratories and will not be discussed here. However, a different model has been developed for the purpose of comparison, and utilizes a slightly different concept. Preliminary work had shown that the liquid droplets are highly positively charged during the nebulization and that contacts with the walls of the desolvation chamber should in general be avoided; thus a positive potential on the walls could repel droplets. By adopting an appropriate geometry, the droplets could be focused along the drift tube axis, or converge to a favourable location. The design of this desolvation chamber and results of a series of experiments at different voltages are reported here; applications to the determination of quaternary ammonium salts will be presented in the next paper in the series.

## EXPERIMENTAL

### *General equipment*

The DLI probe, the quadrupole mass spectrometer and the cryopump were as described previously<sup>8,14</sup>, apart from recent modifications and the new desolvation chamber, which are described below.

A Gilson (Villiers-le-Bel, France) Model 302-5S solvent delivery system and a Rheodyne (Berkeley, CA, U.S.A.) Model 7120 loop valve injector equipped with a 10- $\mu$ l loop were directly connected to a modified DLI probe, and acetonitrile was

pumped at a constant flow-rate in the range 20–50  $\mu\text{l}/\text{min}$  through the entire system, from the solvent reservoir to the vacuum space of the mass spectrometer. A thin capillary Monel tube, 0.2 mm O.D.  $\times$  0.1 mm I.D. (Le Guellec, Douarnenez, France) was connected at one end to the loop valve injector, and the other end was inserted inside the shaft of the DLI probe as far as the nickel diaphragm nebulizer. The rest of the DLI assembly was as described elsewhere<sup>8</sup>. The interface was kept at constant temperature by circulating water at 15°C, and the cryopump attached to the mass spectrometer envelope was chilled with liquid nitrogen<sup>14</sup>. Regeneration of the cryopump was effected overnight after turning off the liquid nitrogen supply and the diffusion pumps, and blowing 5 cm<sup>3</sup> (STP) min of helium through the CI source block to avoid source contamination by materials desorbed from the trap. This procedure is completely safe and reproducible.

### Desolvation chamber

The new droplet transfer line (Figs. 1–3) is permanently attached to the CI source block (6). It consists of a heated drift tube held at different voltages and temperatures, and a Macor (Corning machinable ceramic) insulator.

The drift tube (4) is a copper cylinder with an internal conically shaped tube. The apex of the cone is located inside the ion source on the trajectory of the electron beam emitted by a heated rhenium ribbon (8) (Fig. 3). Under normal LC-MS experiments, the Vespel (DuPont polyimide) nut at the end of the DLI probe is sealed tightly against the cone entrance

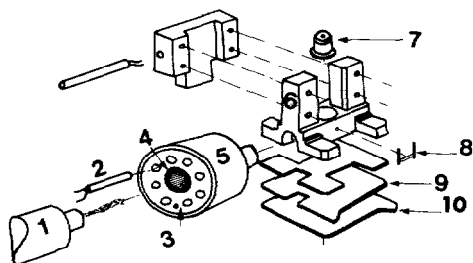


Fig 1 Exploded view of the LC-MS interface 1 = DLI probe end (Vespel) with 2- $\mu\text{m}$  nickel diaphragm, 2 = cartridge heater, 3 = copper heater housing, 4 = copper desolvation chamber, 5 = Macor insulator, 6 = ion source block, 7 = repeller assembly, 8 = rhenium filament; 9 = focusing lens, 10 = ion energy lens

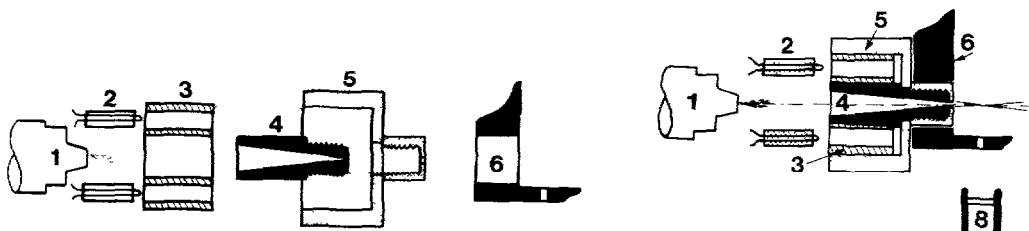


Fig 2 Section of an exploded representation of the LC-MS interface Components as in Fig 1

Fig 3 Section of the assembled interface showing the intersection of droplet flights with the electron beam from the rhenium filament Components as in Fig 1

The copper cylinder (3) that surrounds the drift tube was machined to accommodate several cartridge heaters, an iron-Constantan thermocouple and a connection to a voltage supply taken from the ion optic power supply (consequently this voltage could only be varied between  $-200$  V and  $+200$  V). A  $1\text{ m}\Omega$  ( $2\text{ W}$ ) resistor was added between the voltage supply and the copper cylinder for current limiting.

The Macor insulator (5) provides thermal and electrical insulation, so the desolvation chamber can be set at any voltage or temperature within given limits.

The vacuum conductance of the ion source could be easily varied by changing a plug pierced by a small hole fitting to the repeller block (7). One was selected such that an inflow of  $30\text{ }\mu\text{l}/\text{min}$  of acetonitrile in the ion source at *ca.*  $100^\circ\text{C}$  produced a vapour pressure of  $0.3$  Torr as monitored by an MKS (Burlington, MA, U.S.A.) Model 221 capacitance manometer. The ionization gauges indicated the pressure to be  $1 \cdot 10^{-4}$  Torr in the source housing and  $2 \cdot 10^{-5}$  Torr in the analyser housing. Acetonitrile was obtained from Carlo Erba (Milan, Italy) and contained  $1\%$  of water; it was not further purified but was filtered through  $0.2\text{-}\mu\text{m}$  Millipore filters.

### Voltage experiments

The influence of the voltage,  $V_d$ , applied to the desolvation chamber was evaluated under the following conditions: both the desolvation chamber and the ion source were set at  $120^\circ\text{C}$  and  $30\text{ }\mu\text{l}/\text{min}$  of pure acetonitrile were nebulized. The CI source block, the repeller (7), the focusing plate (9) and the ion energy plate (10) were set at  $0$  V. Optimum focusing for the next three lenses in the Riber (Rueil-Malmaison, France) Model SQ 156 quadrupole analyser was determined and was not varied during the experiments. Mass spectra were acquired every  $1$  sec over the mass range  $20\text{--}200$  a.m.u., using a Nermag Model Sidar 5A data system for different values of  $V_d$ .

## RESULTS

The plot of the total ion current for ions in the mass range  $20\text{--}200$  a.m.u. expressed in arbitrary units *versus* the voltage applied to the desolvation chamber shows two maxima (Fig. 4).

Very weak currents were recorded for  $V_d$  values between  $-200$  V and  $+60$  V, then the current started to increase to a first maximum at *ca.*  $100$  V. The value of  $V_d$  for this maximum depends on the acetonitrile flow-rate and the source block pressure

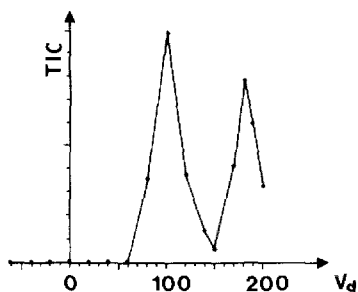


Fig. 4. Plot of the total ion current for ions in mass range  $20\text{--}200$  (arbitrary units) *versus* the potential,  $V_d$ , applied to the desolvation chamber.

and temperature. For flow-rates between 20 and 50  $\mu\text{l}/\text{min}$  and temperatures between 100 and 150°C, the maximum was at  $90 \pm 20$  V. The total ionization current for acetonitrile depended on the energy of the ionizing electrons as under conventional chemical ionization conditions with the plasma initiated by a beam of electrons. The signal was reduced to zero when the voltage difference between the filament and the ion source was 0 V, independent of the current through the rhenium ribbon.

A second regime was observed for values of  $V_d$  above 140 V. The total ion current increased again and reached a second maximum at *ca.* 180 V, then it decreased for higher  $V_d$  values. Experiments above 200 V were not pursued. The second region of the plot for  $140 < V_d < 200$  is a discharge mode. Once the discharge had been established, the voltage on the rhenium filament could be reduced to zero with no visible effect on the total ion current or the mass spectra. However, the current through the filament could not be turned off completely, otherwise the discharge disappeared. In that event, it could be re-established by increasing the current through the filament to 50  $\mu\text{A}$  and the electron voltage to *ca.* 30 V before setting this voltage back to *ca.* 0–3 V. The discharge was stable and reproducible.

The relative abundances of the ions in the mass spectrum of acetonitrile were affected when  $V_d$  was changed (Figs. 5–7). Plots of the percentage of the total additive ionization for major ions *versus*  $V_d$  were prepared (Fig. 7). The plots corresponding to ions at  $m/z = 27$  and 26 have not been included for reasons of simplification, but they follow the same pattern as the plot for  $m/z = 28$  ions.

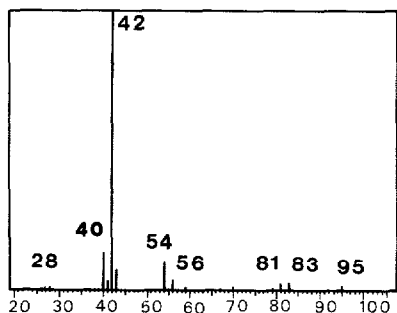


Fig. 5 Mass spectrum of acetonitrile for  $V_d = 80$  V and 70-eV electrons.

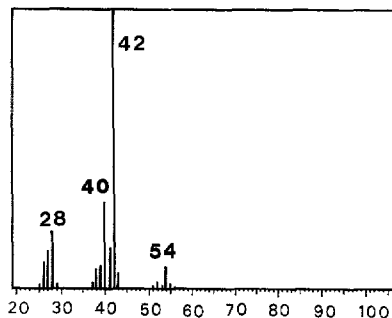


Fig. 6 Mass spectrum of acetonitrile for  $V_d = 180$  V and 3-eV electrons

The major ions appear at same  $m/z$  values previously observed by Voyksner *et al.*<sup>15</sup>, who identified ion structures using collision-induced dissociation of the parent ions in tandem mass spectrometers. The decrease in the abundance of cluster ions [ $m/z$  83 =  $\text{M}_2\text{H}^+$ ; 81 =  $(\text{M}_2\text{H} - \text{H}_2)^+$ ; 56 =  $\text{MCH}_3^+$ ; 54 =  $(\text{MCH}_3 - \text{H}_2)^+$ ; M =  $\text{CH}_3\text{CN}$ ] and protonated molecules ( $m/z$  42 =  $\text{MH}^+$ ), and the increase in the abundance of fragment ions [ $m/z$  40 =  $(\text{MH} - \text{H}_2)^+$ ; 28 =  $\text{CH}_2\text{N}^+$ ; 27 =  $\text{CHN}^+$ ; 26 =  $\text{CN}^+$ ], is consistent with the expected high energy content of the plasma in the discharge mode. The transition at  $V_d = 140$  V is self-evident.

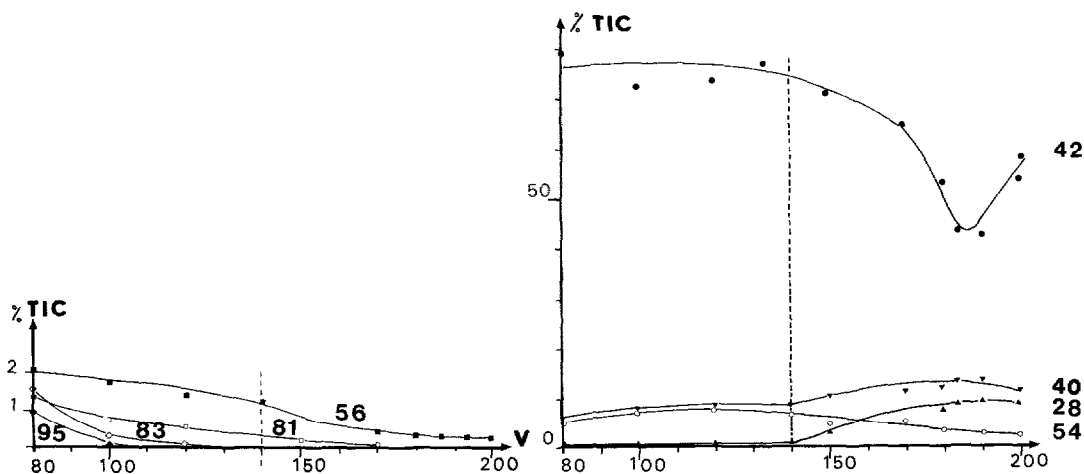


Fig 7 Plots of percentages of total additive ionization for major ions in mass spectra of acetonitrile *versus*  $V_d$

## DISCUSSION

Until now, generation of mass spectra under DLI LC-MS conditions was accomplished by bombarding the ion source with conventional electron beams from heated filaments. However, since the report by Hunt *et al.*<sup>16</sup> on a Townsend discharge ion source for CI operations and other application work that has demonstrated the success and the simplicity of this ionization method<sup>17</sup>, possible adaptation to LC-MS operations should have been investigated, as LC-MS also suffers severe problems of filament burn-outs when injecting strongly oxidizing vapours, and is the case with aqueous solutions. In fact, preliminary work on electrical discharge experiments in LC-MS had been carried out in the laboratory of Professor McLafferty at Cornell University, but had not been extended<sup>11</sup>. On the other hand, simple filament modifications that extend significantly the life-time of a rhenium filament were found<sup>1,14</sup>, which may explain the temporary lack of interest in discharge ion sources in LC-MS.

The results presented in this paper are very preliminary and will be completed by further work using different solvents and solutions, but some observations are already noteworthy.

The first region in the plot of the total ion current *versus* the potential on the desolvation chamber is assumed to correspond to conditions focusing the droplets. either they are repelled from the walls and are less decomposed, or they are better focused to the location where they intersect the beam of electrons from the filament. It should be pointed out that a small discharge current of *ca.* 100 nA through the 1 m $\Omega$  resistor could be measured and probably corresponds to the collection of charged liquid droplets on the walls on the desolvation chamber.

The second region corresponds to a non-self-sustained but stable Townsend discharge. Electrons from the heated rhenium filament are still required. Although both the filament and the ion source walls were at 0 V, the voltage of *ca.* 180 V on the

desolvation chamber could attract enough electrons from the filament to sustain the discharge.

When attempting to operate the interface in the anodic mode of operation (using the same nomenclature adopted by Hunt *et al.*<sup>16</sup>, *i.e.*, the CI source block being the anode and the desolvation chamber being the cathode), no discharge occurred for biasing voltages down to  $-200$  V, which is consistent with results from other experimental set-ups in which the discharge onset was at *ca.*  $-1200 \pm 200$  V<sup>16,17</sup>. In contrast, the relatively low breakdown voltage of *ca.* 140 V for the discharge in the cathodic mode of operation (the desolvation chamber being the anode and the CI source block being the cathode) should be compared with values of *ca.*  $+1200$  V observed for a Townsend discharge through reagent gases in conventional CI operations<sup>16,17</sup>. It is recalled that the mechanical disintegration of the liquid effluent through the diaphragm nebulizer into an aerosol generates highly electrically charged droplets<sup>18</sup>. Thus a possible explanation for the lower breakdown voltage in this work is the increase in the space charge resulting from the drifting of the charged droplets through the desolvation chamber; however, the reason why the anodic mode of operation is less favoured is not yet understood.

As already observed by Hunt *et al.*<sup>16</sup>, the discharge in the cathodic mode affords spectra in which the relative abundance of the low-molecular-weight ions is enhanced at the expense of the cluster ions at higher mass. The results for acetonitrile show that this is also the case for protonated molecules, however, a loss of ions because of a reduced transmission through the quadrupole analyser of high kinetic energy ions from the Townsend discharge cannot be totally excluded. If the relative abundance change results mainly from the ionization mode, then the variation of  $V_d$  appears as a very simple method for forcing the decomposition of a protonated molecule with good yields, and may serve for fingerprinting purposes, as is currently done using the alternative decomposition method of colliding charged precursors with inert gas molecule in a tight cell<sup>19</sup> or in a radiofrequency quadrupole field<sup>20</sup>.

## CONCLUSION

The new source is currently being used with the LC-MS prototype LUCIE<sup>14</sup>, and has also recently been implemented on the quadrupole mass spectrometer in the Rhône-Poulenc laboratory. Applications to the determination of quaternary ammonium salts have already been achieved.

To date, several LC-MS interfacing methods have proved to be effective in handling non-volatile molecules, *e.g.*, thermospray ionization<sup>9,10</sup>, liquid ionization<sup>21</sup>, nebulization into an atmospheric pressure ionization source<sup>12,13,22</sup> or nebulization into a CI source under a vacuum<sup>1-8,23,24</sup>. Although the experimental set-ups differ, they share in common charged liquid droplets, from spray electrification or static charging, thus indicating that a common mechanism may operate in these methods. In any case, these experimental results confirm our previous assumption that the first objective in an LC-MS experiment should not be to attempt the complete removal of the liquid solvent<sup>25</sup>.

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