Investigation of Cationic Hydrogen-bonded Systems by Fast Atom Bombardment Mass Spectrometry

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Fast atom bombardment mass spectrometry (FABMS) has been used to investigate the hydrogen-bonding of pyridinium and trialkylammonium ions with a range of electron donors. We have studied the effects of matrix liquid, concentration, nature of the anion, and strength of the hydrogen-bond on the observed intensity of the complex peak. The results may be easily rationalized in hydrogen-bonding terms and are in excellent agreement with those of more 'conventional' techniques such as i.r. spectroscopy.

Both spectroscopic and non-spectroscopic techniques have been used for the investigation of hydrogen-bonding.[1] In recent years, by far the most commonly used techniques have been spectroscopic in nature and include i.r., n.m.r., visible, and photoelectron spectroscopy.

The use of mass spectrometry for this purpose has received little attention. Conventional electron-impact mass spectrometry (EIMS) requires thermal volatilization of the sample, followed by ionization by means of an electron beam. The combination of these two processes effectively precludes the use of EIMS for the study of H-bonding. In contrast fast atom bombardment mass spectrometry (FABMS) is a 'soft ionization' technique[2–4] that requires no sample heating. In the FABMS experiment the sample is dissolved in a matrix liquid that is relatively involatile in the mass spectrometer source. The sample is then subjected to bombardment by 'fast atoms,' which brings about desorption and ionization of the sample. Many different matrix liquids are used but by far the most common is glycerol.[4,5]

Those familiar with the FABMS technique have long known that ions corresponding to dimers and trimers of the matrix liquid are often seen, particularly when glycerol is used as the matrix liquid. These ions, which contain clusters of molecules, are presumably held together by hydrogen-bonding. Despite this, FABMS has been used to investigate very few H-bonded systems.

Recently, the FABMS of the strongly H-bonded complex formed between imidazole and trimethyl phosphate was reported.[6] Since this preliminary report we have carried out a further study on the complexes formed between imidazole and a range of electron donors.[7]

In this study we have investigated the H-bonding of pyridinium and trialkylammonium ions with a range of electron donors. We have investigated the effects of matrix liquid, concentration, nature of the anion, strength of the hydrogen-bond, and competitive hydrogen-bonding on the intensity of the observed complex peak. The results obtained by FABMS are compared with those obtained from solution i.r. studies of the same systems.

Experimental

FAB spectra were obtained with an A.E.I. MS-30 instrument (Kratos Ltd. Manchester, U.K.) retrofitted with a saddle-field FAB gun (Ion tech, Teddington, U.K.) and a Kratos FAB source in beam 1. Argon was used as the bombarding atom, with a beam energy of 7.2 keV. A stainless steel probe tip was used in each case. All the spectra were peak-averaged from a minimum of 10 scans using a DS-55 data system. Mass conversion was carried out off-line on the basis of tris(perfluoroheptyl)-*s*-triazine calibration. FAB samples were prepared by dissolving the sample in acetonitrile (at known concentration) and were then mixed with the matrix. The acetonitrile was then pumped off in the vacuum lock of the mass spectrometer.

I.r. spectra were recorded for solutions in acetonitrile (at known concentration) using an Analect FX 6260 FT-IR instrument at 4 cm^{-1} resolution. The cell used had CaF_2 windows with 0.5 mm path length. *m*-Nitrobenzyl alcohol (NBA), pyridine, tri-n-propylamine, dimethylbenzylamine, triphenylphosphine oxide, diphenyl sulphoxide, benzophenone, and tetrabutylammonium fluoride trihydrate were obtained from B.D.H. or Aldrich (reagent grade) and were used without further purification.

Pyridium salts were prepared by dissolving pyridine (1 g, 12.6 mmol) in acetonitrile (100 ml); hydrochloric, hydrobromic, or hydroiodic acid (12.6 mmol) was then added. The acetonitrile was then removed under vacuum to leave the crystalline salt. I.r. and ^1H n.m.r. spectra were identical with those of authentic samples. The tri-n-propylammonium and dimethylbenzylammonium salts were similarly prepared.

The hydrogen-bonded complexes were prepared by dissolving the pyridinium salt (1 g) in acetonitrile, and adding 1 mol equiv. of the electron donor to the solution. Removal of the bulk of the acetonitrile by rotary evaporation resulted in crystallization of the complex, which was then isolated and pumped dry under vacuum (0.1 Torr). ^1H N.m.r. in deuteriated dimethyl sulphoxide showed 1:1 complex formation and no water. The trialkylammonium salt complexes were similarly prepared.

Results and Discussion

Pyridinium and trialkylammonium ions are ideal candidates for the study of hydrogen-bonding by FABMS. Hydrogen-bonding between various electron donors and the N–H bond of the pyridinium or trialkylammonium ion results in the formation of a cationic complex and thus has an inherently high FABMS sensitivity. These hydrogen-bonded ions, which show only 1:1 complex formation, are clearly distinct from clusters formed by electrostatic interaction, which are ions of general formula $[\text{cation(cation/anion)}_n]^+$ (n = 1,2,3 . . . .). In the case of a saturated solution of pyridinium iodide in NBA we have been able to observe electrostatic clustering of this kind for every value of n up to 4, corresponding to m/z 908.

The choice of matrix liquid is critical in a hydrogen-bonding FABMS study. By far the most commonly used is glycerol,[4,5] but weakly hydrogen-bonded species would not be expected to be observed in such a strongly hydrogen-bonding solvent. A comparison of several matrix liquids is shown in Table 1 for the

Table 1. Effect of matrix liquid on FABMS spectrum of the H-bonded complex pyH^+ --- $Ph_3P=O$ (*m/z* 358) at a sample concentration of 0.5M, with bromide as anion

Matrix (1 µl)	% Total ion current		
	pyH^+ (*m/z* 80)	Ph_3POH^+ (*m/z* 279)	Complex$^+$ (*m/z* 358)
Glycerol	2.3	30.3	0.7
Monothioglycerol	3.7	32.2	0.8
Tetramethylene sulphone	2.5	27.5	0.4
Tetramethylene sulphone + 30% glycerol	0.0	42.9	0.7
Nujol		No sample peaks	
Nitrophenyl octyl ether	0.0	7.2	0.0
m-Nitrobenzyl alcohol	2.6	27.5	0.9
Polyethylene glycol 300	7.0	14.9	0.4
Polyphenyl ether	0.0	6.4	0.0
Solid state		No sample peaks	

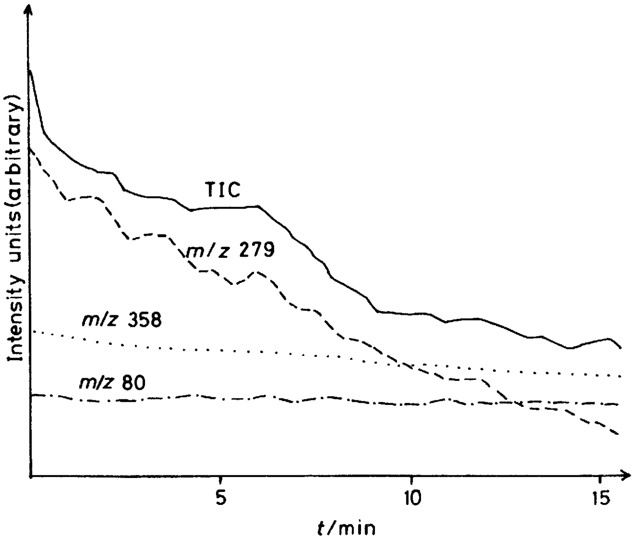

Figure 1. Cross-scan report of $Ph_3P=O$ --- pyH^+Br^- complex in NBA (0.5M)

hydrogen-bonded complex pyH^+ --- $Ph_3P=O$. The use of matrix liquids such as polyphenyl ether and Nujol, which are ideal in terms of their poor hydrogen-bonding ability, is limited by the poor solubility of the pyridium ion. This results in crystallization of the sample on the surface of the matrix and hence loss of ion current. Despite high solubility of the complexes in glycerol we were able to observe only the more strongly hydrogen-bonded species, as expected. The use of monothioglycerol, tetramethylene sulphone, and tetramethylene sulphone–glycerol mixtures as matrix liquids is limited by their short lifetimes in the mass spectrometer source.

However, by using *m*-nitrobenzyl alcohol (NBA) we were able to obtain a stable and long-lasting total ion current as well as reliable peak intensities for up to 15 min. The mean value for the percentage of total ion current for the pyH^+ --- $Ph_3P=O$ complex cation in NBA at a concentration of 0.5M was found to be 0.96%, with a standard deviation of 0.3. The standard deviation on a single day with a range of samples was as low as 0.05. Cross-scan reports of the spectra showed the very stable nature of the ion current arising from the H-bonded complexes (see Figure 1). Similar matrix effects have been reported previously in FABMS studies of hydrogen-bonded complexes of imidazole.[7]

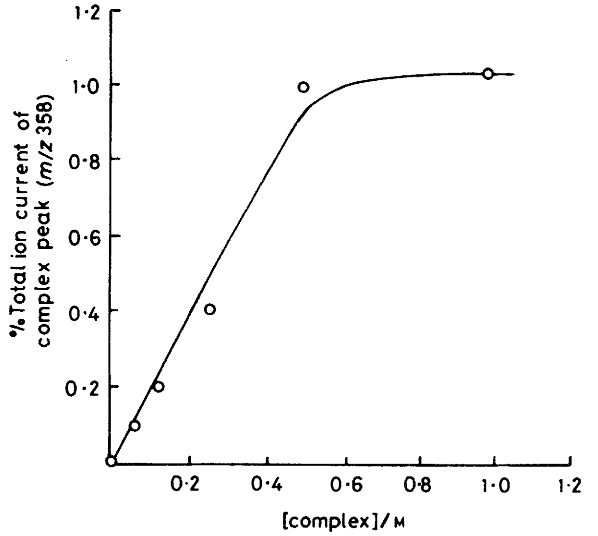

Figure 2. Intensity of $Ph_3P=O$ --- pyH^+Br^- H-bonded complex peak (*m/z* 358) as a function of concentration in NBA matrix

In a hydrogen-bonding matrix which is present in excess, such as NBA, one might expect the concentration of the hydrogen-bonded complex under study to be low. However, experiments we have performed suggest that the complex is not formed by ion–molecule reactions but is desorbed as the intact complex. The dependence of the intensity of the complex peak in terms of percentage of total ion current (TIC) upon the H-bonding ability of the matrix can be seen in Table 1. A stronger H-bonding matrix such as glycerol results in lower peak intensity for the complex, because of stronger H-bonding to the matrix in comparison with NBA. We have also found that the intensity of the pyH^+ --- $Ph_3P=O$ complex peak (in terms of percentage of TIC) is independent of the repeller voltage which is applied to the FAB probe tip. The repeller voltage might have affected the residence time of the ions in the source and hence the intensity of the complex peak, if the complex were formed in an ion–molecule reaction.[8]

In the case of $Ph_3P=O$ --- pyH^+Br^- we have also studied the intensity of the H-bonded complex peak as a function of its concentration in the matrix (see Figure 2). The percentage TIC for the complex peak increases approximately linearly with concentration up to a limit of 0.5M. After this point no further increase in intensity is observed. This concentration is assumed to correspond to monolayer formation of the complex on the matrix surface; further increases in concentration result in an increase in bulk rather than surface concentration. This interpretation is supported by the fact that at concentrations below 0.5M matrix peaks increasingly dominate the FABMS spectrum, whereas at a complex concentration of 0.5M and above the matrix peaks are almost completely suppressed. A typical spectrum of the $Ph_3P=O$ --- pyH^+Br^- complex at 0.5M is shown in Figure 3; the pyridinium ion (*m/z* 80), the quasimolecular triphenylphosphine oxide ion (*m/z* 279), and the H-bonded complex ion (*m/z* 358) can be clearly seen.

A scheme for the equilibria between the matrix liquid (in this case NBA) and the $Ph_3P=O$ --- pyH^+X^- complex is shown in Figure 4. It would be expected that the hydrogen-bonding ability of the anion would affect the intensity of the complex peak. A more strongly hydrogen-bonding anion would push the equilibrium (3) further to the right, making less pyridinium ion available to hydrogen-bond to the triphenylphosphine oxide.

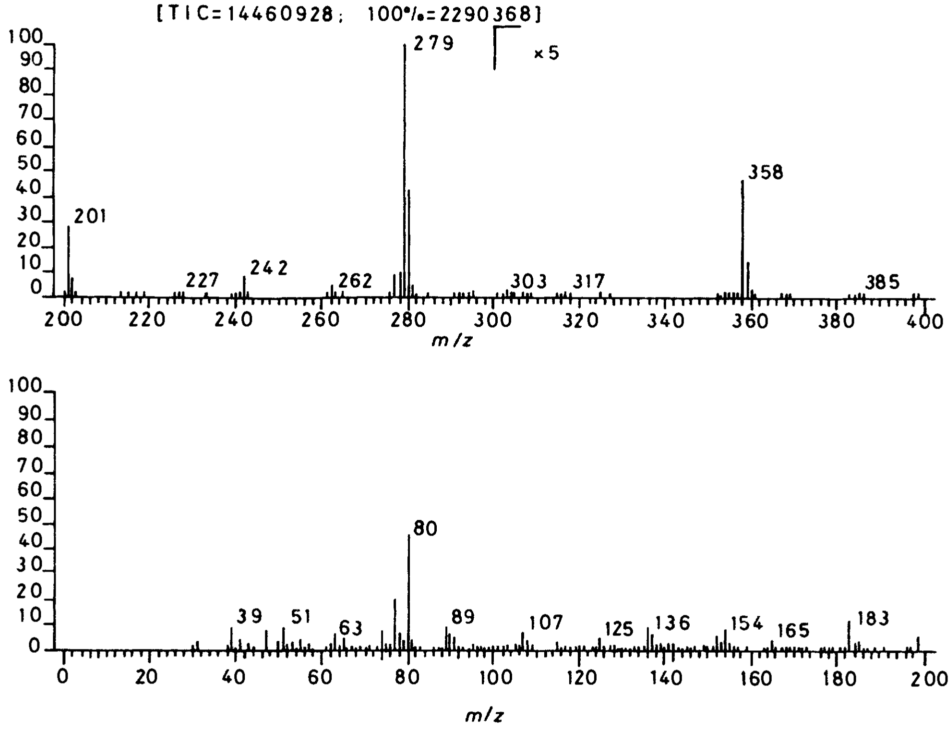

Figure 3. FABMS spectrum of the hydrogen-bonded $Ph_3P{=}O---pyH^+Br^-$ complex in NBA (1 µl) at 0.5M

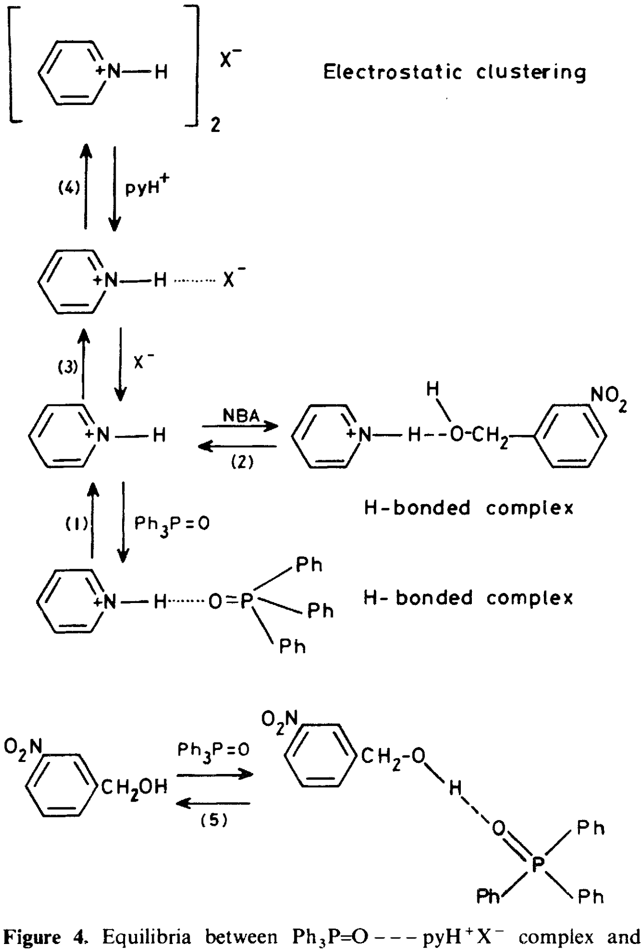

Figure 4. Equilibria between $Ph_3P{=}O---pyH^+X^-$ complex and NBA where X = F, Cl, Br, or I

Because of the net charge of zero in the pyH^+---X^- complex and the inability of FAB to ionize the pyH^+---X^- complex by removal of an electron, we were unable to observe this complex. But the percentage of TIC carried by the $pyH^+---Ph_3P{=}O$ hydrogen-bonded complex was seen to vary as predicted (see Table 2). The solution i.r. spectra of the $Ph_3P{=}O---pyH^+X^-$ complexes at 0.5M also showed an increased peak area and broader absorption due to P=O stretching when X = Br than when X = Cl.

Two other electron donors (diphenyl sulphoxide and benzophenone) were compared with triphenylphosphine oxide in terms of their ability to hydrogen-bond to the pyridium ion. Comparing the intensity of the H-bonded complex peak with that of the free pyridinium ion showed that the order of H-bonding strength is $Ph_3P{=}O > Ph_2S{=}O > Ph_2C{=}O$ as expected. We have previously observed the same trend in the hydrogen-bonding of the same electron donors with imidazole by FABMS.[7] On mixing triphenylphosphine oxide, diphenyl sulphoxide, and pyridinium bromide (all at 0.5M) in NBA, we were able to observe H-bonding only between triphenylphosphine oxide and the pyridinium ion by FABMS, providing further confirmation of the trend.

We have also synthesized and studied the H-bonded complexes formed between tri-n-propylammonium bromide or dimethylbenzylammonium bromide and triphenylphosphine oxide, by both i.r. and FABMS. The i.r. solution spectra of the complexes are similar in terms of their H-bonding characteristics. The H-bonding interaction appears to be stronger than that observed between the pyridinium ion and triphenylphosphine oxide. In the case of the ammonium complexes the N–H stretching vibration occurred at lower frequency than in the pyridinium ion complexes (2 420 cm^{-1}; *cf.* 2 540 cm^{-1}, respectively). The P=O stretching vibration of $Ph_3P{=}O$ was also seen to be broader in the ammonium complexes than in the pyridinium complex.

The H-bonding interactions in $Pr_3NH^+---Ph_3P{=}O$ and $Me_2PhCH_2NH^+---Ph_3P{=}O$ were also seen to be of similar

Table 2. Effect of anion on the intensity of the pyH$^+$ --- Ph$_3$P=O (*m*/*z* 358) H-bonded complex peak in NBA at 0.5M

	m/*z* 358	
Anion	% TIC	% Base peak (*m*/*z* 279)
Cl$^-$	0.2	1.0
Br$^-$	0.9	4.5
I$^-$	1.3	4.8

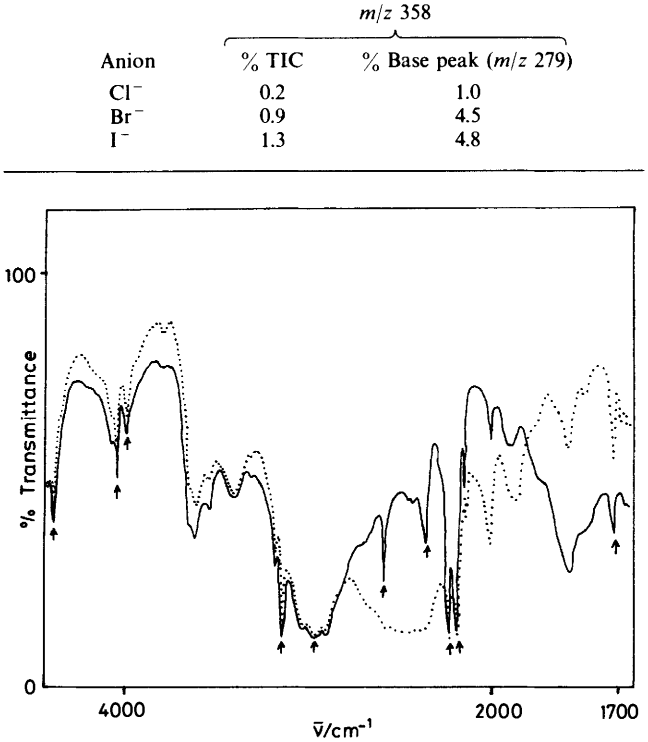

Figure 5. I.r. spectra of pyH$^+$Br$^-$ --- Ph$_3$P=O dissolved in CH$_3$CN (0.5M) (dotted line) and doped with CsF (solid line); CH$_3$CN bands marked ↑

strength in their FABMS spectra and stronger than the interaction in pyH$^+$ --- Ph$_3$P=O, as predicted from the i.r. study. Calculating the ratios of the peak intensities of H-bonded complexes to that of an internal standard (tetramethylammonium iodide) for Pr$_3$NH$^+$ --- Ph$_3$P=O, Me$_2$PhCH$_2$NH$^+$ --- Ph$_3$P=O, and pyH$^+$ --- Ph$_3$P=O gave the ratios 1.4:1.4:0.8, respectively.

Figure 4 shows that after doping the pyH$^+$ --- Ph$_3$P=O complex with a very powerful H-bonding anion (such as fluoride) one would expect a marked reduction in the intensity of the complex in the FABMS spectrum. Preferential H-bonding of fluoride to the pyridinium ion [equation (3)] makes less pyridinium ion available to the triphenylphosphine oxide. Doping the pyH$^+$Br$^-$ --- Ph$_3$P=O sample (at 0.5M) with 0.2, 0.4, and 0.6 mol equiv. of tetrabutylammonium fluoride trihydrate resulted in a decrease in the intensity of the pyH$^+$ --- Ph$_3$P=O complex in the FABMS spectrum; 0.6 mol equiv. was sufficient for complete destruction of the complex. In contrast, doping the pyH$^+$Br$^-$ --- Ph$_3$P=O complex with the weaker H-bonding bromide ion (by addition of tetrabutylammonium bromide), also at 0.6 mol equiv., resulted in a weaker but still observable peak for the pyH$^+$ --- Ph$_3$P=O complex. The Pr$_3$NH$^+$Br$^-$ --- Ph$_3$P=O and Me$_2$PhCH$_2$NH$^+$Br$^-$/Ph$_3$P=O H-bonded complexes, which were shown to be stronger than the pyH$^+$Br$^-$ --- Ph$_3$P=O complex, were also not destroyed by doping with 0.6 mol equiv. of tetrabutylammonium fluoride trihydrate, but were again significantly weakened in intensity. Doping the complex with an excess of dry CsF also resulted in complete destruction of the pyH$^+$Br$^-$ --- Ph$_3$P=O complex. The change in the H-bonding interactions on doping with CsF is also clearly seen in the solution i.r. spectrum of the complex (Figure 5).

In conclusion, we believe that FABMS may be used for the investigation of hydrogen-bonded species, even though the range of systems that may be studied is limited. However, the study of hydrogen-bonding to pre-formed ions which are especially susceptible to FABMS is simple. The results obtained may be easily rationalized in terms of relative H-bonding strengths and are in excellent agreement with those of more 'conventional' techniques such as i.r. spectroscopy. Information on relative H-bond strengths may be rapidly and easily obtained.

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