Studies of Intramolecular Hydrogen Bonds: Protonation of Keto and Enol Forms of β-Diketones by Hydrogen Bromide in Dibromodifluoromethane

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N.m.r. spectroscopic studies over the range 158–258 K show that 1-phenylbutane-1,3-dione, 2-methyl-1,3-diphenylpropane-1,3-dione, and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione are mono-protonated by HBr in CBr_2F_2. In the ^1H n.m.r. spectrum of 1-phenylbutane-1,3-dione in solutions of HBr–CBr_2F_2 at 158 K, distinct signals are found at δ 14.31 and 12.51 for the hydroxy protons in the protonated enol tautomer and at −2.23 for HBr. Proton exchange with HBr leads to collapse of the peak at δ 14.31 at temperatures above 168 K, and above 208 K the peak at 12.51 and that of HBr coalesce. For solutions of 2-methyl-1,3-diphenylpropane-1,3-dione and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione in HBr–CBr_2F_2 at temperatures below 180 and 158 K respectively, distinct signals are found for HBr at δ *ca.* −2 and for the acidic protons in the protonated keto forms at 21.44 and *ca.* 14.1, respectively. The measured negative values of the isotope effect on the chemical shift [$\Delta\delta(^1H-^2H)$] of the added protons in the protonated diketones show that the proton is located between the keto groups in a very strong intramolecular hydrogen bond.

Dibromodifluoromethane containing hydrogen bromide is proving to be a useful strongly acidic solvent for studies of the protonation of weak organic bases.[1] In previous work [2] it was found that 1,1,1-trifluoropentane-2,4-dione does not undergo protonation in HBr–CBr_2F_2, but that addition of HBr across the enol double bond occurs resulting in the formation of an α-bromo alcohol. In the present work more strongly basic β-diketones have been examined in an attempt to observe protonation. It is found that the enol form of 1-phenylbutane-1,3-dione does undergo protonation and that for 2-methyl-1,3-diphenylpropane-1,3-dione and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione protonation of the keto forms is observed. Our preliminary studies with 2-methyl-1,3-diphenylpropane-1,3-dione have been published.[3] Previous investigations of the protonation of β-diketones in super-acid systems[4,5] are compared with the present observations in HBr–CBr_2F_2.

Experimental

Materials.—A commercial sample of 1-phenylbutane-1,3-dione was used and 2-methyl-1,3-diphenylpropane-1,3-dione[6] and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione[7] were prepared as described previously. Hydrogen bromide (BDH 99.8%) was purified on a vacuum line by repeated passage between traps cooled at −78 °C. Deuterium bromide was prepared by passing HBr through a trap containing 98% D_2SO_4 (Aldrich, isotopic purity 99.5 atom % D) and purified by the procedure used for HBr. Solutions for n.m.r. spectroscopy were made up by adding weighed amounts of the diketones to dibromodifluoromethane (Aldrich) and were handled in a dry box. The concentrations of the diketones were typically 0.1 mol dm^{-3} for 2-methyl-1,3-diphenylpropane-1,3-dione and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione but because of limited solubility, 1-phenylbutane-1,3-dione was studied at concentrations of *ca.* 0.02 mol dm^{-3}. Hydrogen bromide and deuterium bromide were introduced by being bubbled through the solvent. The concentrations of solutions of HBr were determined by comparison of the ^1H n.m.r. integral with that for a weighed amount of added 1,1,2,2-tetrachloroethane. The concentration of DBr was obtained from the ^2H integral compared with added CD_2Cl_2.

The partial introduction of deuterium into solutions of HBr in CBr_2F_2 was accomplished using two procedures. It has been observed previously[8] that alcohols undergo protonation and proton exchange in HBr–CBr_2F_2 but are otherwise chemically stable. Hence to achieve partial deuteriation in HBr–CBr_2F_2, CH_3OD (*ca.* 1.0 mol dm^{-3}) was added to a *ca.* 2.0 mol dm^{-3} solution of HBr in CBr_2F_2 containing the diketone. In a second procedure, deuterium was introduced by adding to the solvent a partially deuteriated sample of hydrogen bromide. ^1H and ^2H spectra were recorded for samples of the partially deuteriated solutions.

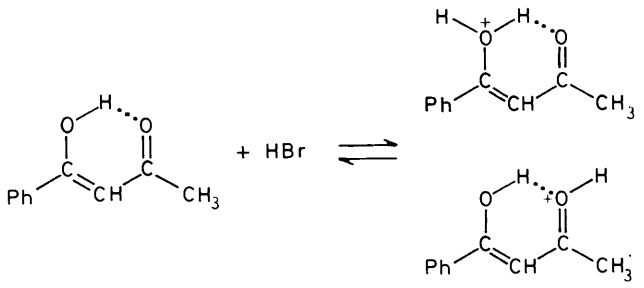
Attempts were also made to investigate the protonation of 1,3-diphenylpropane-1,3-dione in HBr–CBr_2F_2 but the solubility of the diketone was too low for n.m.r. measurements. The ^1H n.m.r. spectra of solutions of pentane-2,4-dione and 3-methylpentane-2,4-dione in HBr–CBr_2F_2 showed that complex chemical reactions had occurred in these cases and the systems were not investigated further.

N.M.R. Spectra.—^1H, ^2H, and ^{13}C Spectra were run at 250.13, 38.4, and 62.9 MHz, respectively, on a Bruker WM250 instrument fitted with a BV1000 variable temperature unit and an Aspect 3000 computer. CD_2Cl_2 was added as internal lock and ^1H and ^{13}C spectra were measured relative to added Me_4Si and ^2H spectra were referenced with respect to CD_2Cl_2 (δ 5.30). Spectra at variable temperature were run at 10 K intervals of increasing and decreasing temperatures.

Results and Discussion

1-Phenylbutane-1,3-dione (**1**).—A solution of 1-phenylbutane-1,3-dione (*ca.* 0.02 mol dm^{-3}) in CBr_2F_2 at 298 K gave a ^1H n.m.r. spectrum with peaks at δ 16.18 (s, 1 H, OH), 7.84 (m, 5 H, C_6H_5), 6.11 (s, 1 H, =CH), and 2.13 (s, 3 H, CH_3) consistent with the enol tautomer. Peaks due to the keto form were not detected. There are two possible isomeric enol forms of 1-phenylpropane-1,3-dione, but evidence in favour of the structure in the Scheme has been obtained.[9]

In the presence of 0.840 mol dm^{-3} HBr at 248 K, the OH signal in the spectrum of 1-phenylbutane-1,3-dione in CBr_2F_2 disappeared and there were shifts of the peaks due to the methine and methyl protons to δ 6.55 and 2.82 respectively,



Scheme.

giving evidence for protonation, (Scheme). The HBr peak was found at *ca.* −2.5 ppm. As the temperature of the solution was lowered, slight downfield shifts were observed in the methine and methyl peaks; and the HBr signal was observed to sharpen until at 208 K a new broad peak emerged at δ 12.5 with the HBr peak at −2.39. At even lower temperatures, the HBr signal was found to broaden, but subsequently to sharpen as a second peak appeared at δ 14.5. At 158 K the spectrum showed peaks at 14.31 and 12.51, each integrating for one proton, and peaks at 8.3–7.8 (br m, 5 H, C_6H_5), 6.7 (br s, 1 H, =CH), 2.9 (br s, 3 H, CH_3), and −2.24 (s, HBr). These spectral changes are consistent with the addition of one proton to the enol as in the Scheme and this could occur at the enol oxygen or at the keto oxygen. It seems likely that the peak first observed at δ 12.51 on lowering the temperature is due to the bridging proton between the oxygen atoms in the protonated enol. This proton is likely to exchange with the protons of HBr at a lower rate than the proton with shift 14.31.

The observation of two distinct hydroxy signals in the spectrum of protonated 1-phenylbutane-1,3-dione contrasts with the results previously found[4] in 96% H_2SO_4 and HF–SbF_5. In 96% H_2SO_4 monoprotonation occurred as shown by the chemical shifts of the methine (δ 6.74) and methyl (δ 2.70) protons in the protonated species, but the hydroxy signals were not observable, presumably due to rapid exchange with the solvent protons. In HF–SbF_5 evidence for diprotonation was found. The dication $[MeC(OH)CH_2C(OH)Ph]^{2+}$ had singlet peaks at 3.52 (Me), 5.77 (CH_2), and a peak at δ 13.9 for one of the hydroxy protons. The other hydroxy proton was considered to be in rapid exchange with the solvent protons. Monoprotonation of the enol forms of 1,1,1-trifluoropentane-2,4-dione and 1,1,1,5,5,5-hexafluoropentane-2,4-dione has been observed[5] in HSO_3F–SbF_5–SO_2 although signals due to the two enol hydroxy protons could not be observed. Interestingly, in HBr–CBr_2F_2 these diones are not protonated: 1,1,1-trifluoropentane-2,4-dione forms 1,1,1-trifluoro-2-bromo-2-hydroxypentane-2-one and 1,1,1,5,5,5-hexafluoropentane-2,4-dione is unreactive.[2]

2-Methyl-1,3-diphenylpropane-1,3-dione (**2**) *and 2,2-Dimethyl-1,3-diphenylpropane-1,3-dione* (**3**).—The behaviour of 2-methyl-1,3-diphenylpropane-1,3-dione (**2**) and 2,2-dimethyl-1,3-diphenylpropane-1,3-dione (**3**) differs from that of 1-phenylbutane-1,3-dione (**1**). In CBr_2F_2, (**2**) is present as the keto tautomer and signals due to the enol were not detected. For (**3**), the diketone is the only possible tautomer. Consistent with these conclusions, the ^1H n.m.r. spectrum of a 0.06 mol dm^{-3} solution of (**2**) in CBr_2F_2 at 298 K gave peaks at 7.91–7.36 (m, 10 H, ArH), 5.13 (q, 1 H, CH), and 1.54 (d, 3 H, CH_3). For a 0.07 mol dm^{-3} solution of (**3**) in CBr_2F_2, peaks were observed at 7.80–7.27 (m, 10 H, ArH) and 1.61 (s, 6 H, CH_3).

In the presence of HBr at 258 K the spectrum of (**2**) was observed to change slightly with the methyl doublet and the methine quartet shifted downfield to 1.55 and 5.25, respectively, and a singlet due to HBr was found at δ −2.23. The spectrum was recorded at 10 K intervals down to 158 K. The HBr signal was found to broaden as the temperature was lowered, and the peaks at δ 1.55 and 5.25 shifted further downfield. At 183 K a new peak was observed at δ 21.5 with the HBr signal at −2.35. The methyl and methine resonances broadened and appeared at δ 2.00 (s, 3 H) and 6.14 (br m, 1 H), respectively, with the aromatic signals also broadened and occurring at 9.0–7.5 (10 H). As the temperature was lowered further, the peaks due to HBr and the acidic proton on the diketone, sharpened until at 158 K sharp singlets were observed at −2.34 and 21.44, respectively.

In the spectrum of (**3**) in the presence of HBr at 258 K the methyl singlet was observed at δ 1.64 and the HBr signal was at −2.91. As the temperature was lowered, the methyl resonance and the acid peak shifted downfield with the latter becoming broader. At 168 K a new broad peak due to the protonated diketone appeared at δ *ca.* 13.5 with the HBr resonance appearing at −2.21. At 148 K the HBr peak occurred at −1.89 and the peak due to the protonated diketone appeared at 14.1 as a broad singlet (*ca.* 120 Hz linewidth at half-height) which integrated for approximately one proton.

The effects of protonation on the ^{13}C spectra of (**2**) and (**3**) were also investigated. In the absence of HBr a 0.07 mol dm^{-3} solution of (**2**) in CBr_2F_2 at 298 K gave peaks at δ 196.5 (C=O), 136.3, 133.4, 129.0, 128.8 (ArC), 51.5 (CH), and 14.4 (CH_3). Little change in these signals was observed in the presence of HBr (0.46 mol dm^{-3}); at 238 K the peaks occurred at 196.8 (C=O), 135.6, 133.7, 129.1, 128.9 (ArC), 50.8 (CH), and 14.5 (CH_3) and at 198 K these peaks were found at 199.0, 135.1, 134.4, 129.6, 129.5, 49.1, and 15.5. However the major significance of the ^{13}C spectrum was the absence of a peak in the region 80–100 ppm that could be attributed to a 1-bromo alcohol. In the spectrum of 1,1,1-trifluoropentane-2,4-dione with HBr in CBr_2F_2 a ^{13}C signal was found at 89.7 ppm. This was attributed[2] to 2-bromo-1-trifluoro-2-hydroxypentane-2-one formed by addition of HBr across the double bond of the enol. The ^{13}C spectrum of 2,2-dimethyl-1,3-diphenylpropane-1,3-dione (**3**) in CBr_2F_2 (0.06 mol dm^{-3}) at 298 K contained peaks at 199.7 (C=O), 136.2, 133.0, 129.6, 128.8 (ArC), 59.7 (quaternary C), and 25.5 (CH_3). In the presence of HBr (2.0 mol dm^{-3}) at 258 K, the corresponding peaks occurred at 200.4, 135.4, 133.4, 129.5, 128.9, 59.5, and 25.5. At 198 K, the chemical shifts were 201.7, 135.1, 134.3, 129.7, 129.2, 59.4, and 25.8. Again the absence of a peak in the region 80–100 ppm was taken as evidence that a 1-bromo alcohol was not formed.

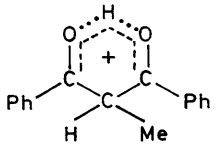
The nature of the added proton in the protonated ketones (**2**) and (**3**) was investigated in more detail by measuring the isotope effect on the chemical shift. For (**1**), the low solubility of the ketone meant that a ^2H spectrum could not be obtained. For (**2**), ^1H and ^2H spectra were recorded using different samples of the same partially deuteriated solution. When deuterium was introduced by adding MeOD at concentrations of 0.8–0.9 mol dm^{-3} to a solution of 2-methyl-1,3-diphenylpropane-1,3-dione (0.1–0.15 mol dm^{-3}) and HBr (1.5–2.0 mol dm^{-3}) in CBr_2F_2 at 158 K, the results of three separate experiments gave values for the added proton at 21.42 (^1H) and 21.70 (^2H); 21.42 (^1H) and 21.65 (^2H); 21.45 (^1H) and 21.70 (^2H). The procedure in which partially deuteriated hydrogen bromide (0.1 mol dm^{-3}) was added to 2-methyl-1,3-diphenylpropane-1,3-dione (0.1 mol dm^{-3}) in CBr_2F_2 gave δ values of 21.43 (^1H) and 21.66 (^2H). The uncertainty in the ^2H chemical shift values was ±0.15 ppm. The average value for the isotope effect on the chemical shift $[\Delta\delta(^1H–^2H)]$ for (**2**) was −0.25 ± 0.15.

The measurement of $[\Delta\delta(^1H–^2H)]$ for the added proton of 2,2-dimethyl-1,3-diphenylpropane-1,3-dione (**3**) was less satisfactory. The signal for the added proton was first resolved as a very broad peak at *ca.* 168 K. At 158 K, the peak was narrower

(linewidth *ca.* 60 Hz) and was found at δ 13.7. At 148 K, the peak was observed at δ 14.1 and had broadened (linewidth *ca.* 200 Hz). At these low temperatures the broadening probably arises from the increased viscosity of the solvent which is close to its m.p. (133 K). Since chemical exchange with HBr was occurring at these temperatures, the lines were broad and the chemical shift of the added proton on the diketone was dependent on temperature. In a set of experiments in the presence of partially deuteriated hydrogen bromide, it was found that the ^1H peak was most clearly observed at 163 K with δ 14.1 ± 0.1 and linewidth 70 Hz. For the same solution at 163 K the ^2H spectrum showed the added deuteron in the diketone at δ *ca.* 14.8 ± 0.3 ppm and with a similar linewidth. Little significance can be attached to the derived value of −0.7 ± 0.4 for $[\Delta\delta(^1H-^2H)]$ because exchange of the protonated ketone with HBr was not frozen and different rates of exchange for DBr and HBr could lead to an anomalous result for $[\Delta\delta(^1H-^2H)]$. However it can be concluded that deuteriation leads to a downfield shift of the acidic protons in the conjugate acids formed from (**2**) and (**3**).

Intramolecular Hydrogen Bonds in the Protonated Diketones.—The chemical shift of the enol proton in 1-phenylbutane-1,3-dione (16.18 ppm) is typical of that expected for an intramolecularly hydrogen-bonded enol proton. On protonation, (Scheme), the shift of the hydrogen-bonded proton changes to δ 12.5.

The proton which has been added to 2-methyl-1,3-diphenylpropane-1,3-dione in the presence of HBr is found at δ 21.44 in the ^1H n.m.r. spectrum and this extreme value indicates an unusually strongly deshielded environment with the proton located between the carbonyl oxygens as in (**4**). Other examples of strongly deshielded protons include that encapsulated within a cobalt carbonyl complex[10] with δ 23.2 and the hydroxy proton in a steroid with δ 21.8 in the presence of a paramagnetic shift reagent.[11] The chemical shift of the proton in (**4**) is the most



(**4**)

extreme that has been observed for an intramolecular hydrogen-bonded proton. However values of 21.0 and 20.5 have been observed[12] for the protons in the monoanions of phthalic acid and maleic acid. In protonated diaminonaphthalenes the value δ *ca.* 19.5 has been recorded[13] and in an intermolecular trifluoroacetate–trifluoroacetic acid complex, the chemical shift of the hydrogen-bonded proton was 19.0.[14]

There is no clear correlation of the chemical shift for a hydrogen-bonded proton with the strength of the hydrogen bond nor with the shape of the potential well. The sign of the isotope effect $[\Delta\delta(^1H-^2H)]$, however, is thought[12,15] to be indicative of the shape of the potential function of a hydrogen-bonded proton. For the hydrogen bonds in bifluoride ion[12,16] (δ 16.3), phthalate and maleate monoanions,[12] the $[\Delta\delta(^1H-^2H)]$ values of −0.30, −0.15, and −0.03 are found, respectively, and these negative values are interpreted in terms of single-minimum potentials characterising very strong hydrogen bonds. The value $[\Delta\delta(^1H-^2H)]$ +0.66 found for protonated diaminonaphthalenes is explained by a weaker hydrogen bond with a double-minimum potential function.[12] Thus the negative values of the isotope effect on the chemical shift of the hydrogen-bonded proton in the conjugate acids of (**2**) and (**3**) show that the bonds are also very strong with single minimum potentials.

For (**2**) in CF_2Br_2 in the absence of HBr the diketone tautomer probably exists in a non-planar *cis*-conformation similar to that found in the solid state.[6] The extra stability which the enol tautomer can achieve by intramolecular hydrogen bonding is not sufficient to overcome the steric factors arising in the planar conformation. However on protonation of the diketone tautomer the hydrogen bond with the proton between the carbonyl oxygens is sufficiently strong to drive the molecule into a planar conformation.

For (**3**) in CF_2Br_2 there can be no keto–enol tautomerism. In the protonated form the chemical shift of the added proton δ 14.1 is similar to that expected for a non-hydrogen-bonding OH group although the negative value of $[\Delta\delta(^1H-^2H)]$ shows there to be a very strong hydrogen bond. The conclusion is that the intramolecular hydrogen bond in this case results in an even shorter O • • • O distance which explains the increased shielding of the proton compared with that in the protonated form of (**2**).

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