FT-IR Spectrometric Study of *N*-t-Butoxycarbonylglycine *N'*,*N'*-dimethylamide and its Interaction with Proton Donors

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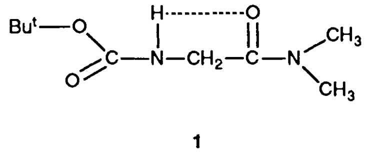
FT-IR spectra of *N*-t-butoxycarbonylglycine-*N'*,*N'*-dimethylamide and its deuteriated ND counterpart, in solution and in the solid state, have been analysed between 3800 and 400 cm^{-1}. An assignment is proposed for some important vibrations, especially for the so-called amide vibrations, by comparison with literature data on similar molecules. The frequency shifts and intensity changes of the vibrations sensitive to the physical state of this model dipeptide strongly suggest that intermolecular hydrogen bonds involving mainly the NH and C=O (amide) groups are formed in the solid state. Thermodynamic parameters (equilibrium constants and enthalpies) of the hydrogen-bond formation with phenol derivatives have been determined in carbon tetrachloride and in 1,2-dichloroethane. The complexes investigated are of medium strength. The FT-IR spectra in the $\nu_{C=O}$ region and the double perturbation of the ν_{NH} band assigned to the five-membered intramolecular NH $\cdots$ O=C hydrogen-bonded ring clearly show that complex formation occurs at both the amide and urethane carbonyl groups. About 45% of the complexes are formed on the C=O (urethane) function, almost independent of the acidity of the phenols. The unusual broadness of the OH $\cdots$ O=C complex band originates from the superposition of two complex bands. *N*-t-Butoxycarbonylglycine-*N'*,*N'*-dimethylamide can be considered as being built up from two model molecules, methyl-*N*-methylcarbamate and *N*,*N*-dimethylacetamide.

Several IR studies on the interaction between simple aliphatic amides, such as *N*,*N*-dimethylacetamide,[1,2] *N*-methylacetamide[3] or acetamide,[4] and model proton donors are available in the literature. To date, very little work has been done on hydrogen-bond systems involving dipeptides as proton acceptors and hydroxylic compounds as proton donors. The hydrogen-bonding equilibrium constants at different temperatures have been measured for the interaction between phenol and *N*-acetylsarcosine-*N'*,*N'*-dimethylamide in dichloromethane,[5] but the interaction site of this model dipeptide has not been systematically investigated.

Owing to the growing interest in the biological compounds of oligopeptides, their vibrational spectra have been investigated experimentally and by *ab initio* force fields.[6–14] Their conformations[15–23] and self-association properties in solution[24–25] have also been studied by spectroscopic methods.

In this work the FT-IR spectra of *N*-t-butoxycarbonylglycine-*N'*,*N'*-dimethylamide [BGDA (**1**)] and its deuteriated ND counterpart ($[^2H_1]$BGDA) are investigated both in solution and in the solid state and some important vibrational modes are tentatively assigned by comparison with literature data on similar molecules.



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The hydrogen-bond equilibrium constants and the enthalpy of complex formation have been measured for phenols acting as proton donors and BGDA as proton acceptor. BGDA has two principal acceptor sites available for hydrogen-bond formation, namely the carbonyl groups of the urethane (U) and of the amide (A) functions. The study of the IR spectra, mainly in the $\nu_{C=O}$ and ν_{OH} regions, allows the identification of this interaction site. It is also interesting to comment on competitive proton-acceptor sites within single functional groups, which are in the present case methyl *N*-methylcarbamate and *N*,*N*-dimethylacetamide.

Experimental

IR Spectra.—The IR spectra were recorded on an FT-IR IFS 88 (Bruker) spectrophotometer using the software AD (SCA.AFA + SCB.AFB) for the addition of the spectra. Measurements of the equilibrium constants *K* were carried out by dispersive IR spectrometry (Perkin-Elmer 883). The *K* values were determined from the absorbance of the free ν_{OH} band of the phenol derivative at concentrations ranging from 0.005–0.008 mol dm^{-3} in carbon tetrachloride and from 0.015–0.02 mol dm^{-3} in 1,2-dichloroethane (1,2-DCE). BGDA was always in excess. The enthalpies of complex formation ($-\Delta H$) were calculated from the *K* values at 298 and 323 K.

Materials.—The solvents were dried by standard methods and the phenol derivatives recrystallized from light petroleum (b.p. 60–80 °C).

BGDA was synthesised as follows: to a solution of 1,1'-carbonyldiimidazole (3.9 g, 0.024 mol) in acetonitrile (60 cm^3) was added t-BOC-Gly (3.5 g, 0.020 mol). After the evolution of CO_2 had ceased, dimethylamine was bubbled through the resulting solution for 10 min. The acetonitrile was evaporated under reduced pressure. The remaining reaction product was then dissolved in chloroform and an excess of hexane was added. The precipitated imidazole was filtered off and the filtrate evaporated to dryness under reduced pressure. The purity of BGDA was checked by IR and NMR spectroscopy. M.p. 73 °C (lit.,[21] 75–76 °C); $\delta_H(CDCl_3)$ 1.45 (s, 9 H, t-BOC), 2.97 (2 × s, 6 H, NMe) 3.95 (d, 2 H, CH_2) and 5.53 (s, 1 H, NH).

The *N*-deuteriated dipeptide ($[^2H_1]$BGDA) was obtained by adding an excess of D_2O to a solution of BGDA in carbon tetrachloride and shaking. After a few minutes, *ca.* 100% deuteriation was achieved. The IR spectrum of $[^2H_1]$BGDA was recorded, under a dry nitrogen atmosphere, immediately after the preparation of the solution.

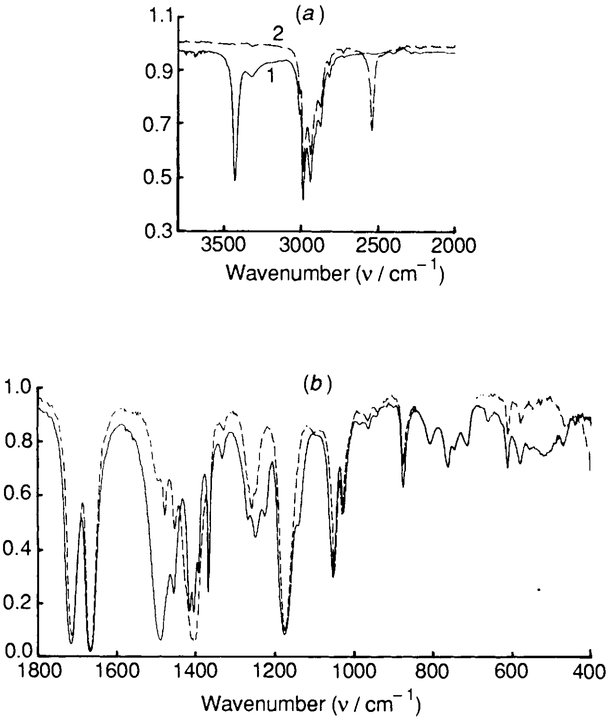


Fig. 1 FT-IR spectra: (*a*) 3800–2000 cm^{-1} region; (*b*) 1800–400 cm^{-1}. 1, BGDA (c = 0.1 mol dm^{-3}) in carbon tetrachloride (3800–850 and 700–400 cm^{-1}) and in carbon disulphide (850–700 cm^{-1}); and 2, [$^2H_1$]BGDA (c = 0.1 mol dm^{-3}) in carbon tetrachloride, d = 0.02 cm.

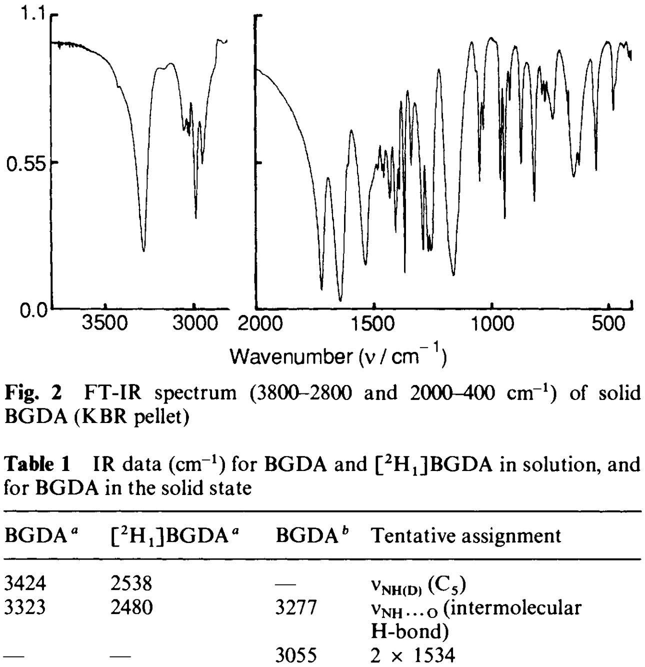


Fig. 2 FT-IR spectrum (3800–2800 and 2000–400 cm^{-1}) of solid BGDA (KBR pellet)

Table 1 IR data (cm^{-1}) for BGDA and [$^2H_1$]BGDA in solution, and for BGDA in the solid state

BGDA[a]	[$^2H_1$]BGDA[a]	BGDA[b]	Tentative assignment
3424	2538	—	$\nu_{NH(D)}$ (C_5)
3323	2480	3277	$\nu_{NH \ldots O}$ (intermolecular H-bond)
—	—	3055	2 × 1534
1714	1710	1720	amide I (U)
1664	1665	1641	amide I (A)
1486	*ca.* 1400	1534	amide II (A)
1268	1259	1267	ν_a CNC (A)
1247	1247	1254	CC_3 skeletal
1226	*ca.* 1030[c]	1288	amide III (A)
1175	1172	1160	$\nu_{C=O}$
611	609	623	amide IV
598	579	551 (?)	amide VI
520	<400	647	amide V (A)

[a] In solution. [b] Solid. [c] Overlapping with the band at 1026 cm^{-1}.

Results and Discussion

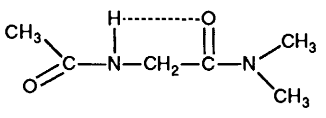
The FT-IR spectra of BGDA and [$^2H_1$]BGDA have been recorded in dilute carbon tetrachloride solution (4000–850 and 700–400 cm^{-1}) and carbon disulphide solution (850–700 cm^{-1}). These spectra are shown in Fig. 1. The FT-IR spectrum of solid BGDA is reproduced in Fig. 2.

The IR data for some important vibrations, along with their tentative assignments, are presented in Table 1.

The ν_{NH} absorption observed at 3424 cm^{-1} (ν_{ND} at 2538 cm^{-1}) is assigned to the five-membered intramolecular NH ••• O=C hydrogen-bonded ring.[15–23] The isotopic ratio of 1.349 indicates that the ν_{NH} mode is almost pure, in agreement with recent potential energy distribution calculations on a glycine dipeptide.[12] The weaker band at 3323 cm^{-1} (*ca.* 2480 in [$^2H_1$]BGDA), whose intensity increases with concentration,[26] is assigned to the $\nu_{NH \ldots O}$ vibration of intermolecular hydrogen-bonded species. The lower values of the stretching frequencies and of the isotopic ratio (1.339) indicate that the intermolecular hydrogen bonds are stronger than the intramolecular ones.

The absorptions observed at 1714 and 1664 cm^{-1} are assigned to the $\nu_{C=O}$ vibration (amide I) of the urethane (U) and amide (A) groups, by analogy with methyl *N*-methylcarbamate and *N,N*-dimethylacetamide, where the carbonyl stretching vibrations are observed at 1730[27] and 1650 cm^{-1} [28], respectively.

The absorption observed at 1486 cm^{-1} is attributed to the Amide II (δ_{NH} in-plane bending coupled with amide C–N stretching) vibration. Recent *ab initio* force-field calculations performed on *N*-acetylglycine-*N'*-methylamide [AGMA (**2**)] in the C_5 conformation have shown that the band at 1520 cm^{-1} corresponds to a coupled $\delta_{NH}(55\%) + \nu_{C-N}(28\%)$ motion.[12] The 1486 cm^{-1} absorption shifts to 1400 cm^{-1} in [$^2H_1$]BGDA and the low value of the isotopic ratio (1.06) suggests that the contribution of the δ_{NH} motion to the band observed at about 1500 cm^{-1} is lower in BGDA than in AGMA. The amide III band, originating from a coupled $\nu_{C-N} + \delta_{NH}$ motion, is assigned to the absorption observed at 1226 cm^{-1}. This band shifts to *ca.* 1030 cm^{-1} in [$^2H_1$]BGDA, and the isotopic ratio of 1.10 suggests that this vibrational mode has a high δ_{NH} character. Similar observations were made for AGMA in solid argon, where the bands observed at 1516 and 1286–1271 cm^{-1}, assigned to the amide II and amide III vibrations, were shifted to 1416 and 1017 cm^{-1} in the *N*-deuteriated derivative.[10]



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Comparison with aliphatic esters[29] allows us to assign the intense absorption at 1175 cm^{-1} to the ν_{C-O} vibration. In the 800–400 cm^{-1} region, the amide IV ($\delta_{C=O}$ in-plane bending), amide V (γ_{NH} out-of-plane bending) and amide VI ($\gamma_{C=O}$ out-of-plane bending) are expected. The absorptions observed at 611 and 598 cm^{-1} are assigned to the amide IV and VI vibrations, by analogy with AGMA.[12] The bands observed at 604, 510 and 586 cm^{-1} in *N*-acetylglycine-*N',N'*-diethylamide in an argon matrix have been ascribed to the amide IV, V and VI vibrations, respectively. Only the amide V band shows a pronounced shift on deuteriation (390 cm^{-1}).[10] In BGDA the band at 520 cm^{-1}, observed at wavenumbers lower than 400 cm^{-1} in [$^2H_1$]BGDA, is assigned to the γ_{NH} mode. These experimental results suggest that the assignment of the bands at 665 and 545 cm^{-1} in AGMA to the γ_{N1H} and γ_{N2H} vibrations[12] must probably be reversed. It must be pointed out that the modes involving the in-plane and out-of-plane motions of the carbonyl group are highly mixed in the 800–400 cm^{-1} region and that their intensities are weak. In this work, the bending vibrations of the C=O(U) and C=O(A) bonds could not be identified separately.

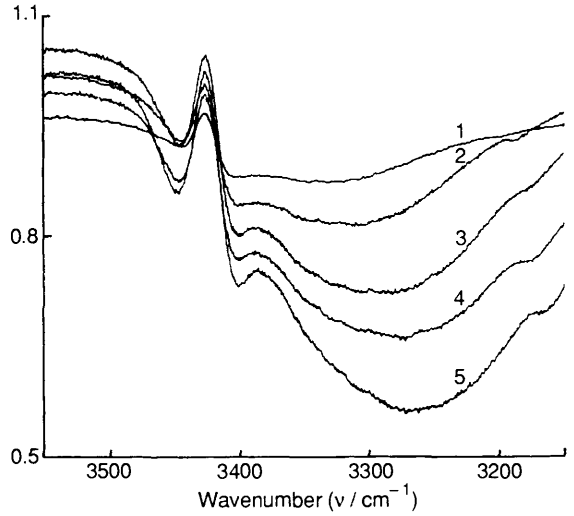


Fig. 3 FT-IR spectra, in the ν_{OH} region (3550–3150 cm^{-1}), of solutions of BGDA and phenols in carbon tetrachloride. The concentration of the phenols is 0.008 mol dm^{-3} and the concentration of BGDA ranges between 0.0085 and 0.01 mol dm^{-3}; d = 0.1 cm. 1, BGDA + phenol; 2, BGDA + 4-bromophenol; 3, BGDA + 3,4-dichlorophenol; 4, BGDA + 3,5-dichlorophenol; and 5, BGDA + 3,4,5-trichlorophenol. The spectra of BGDA at the same concentration have been subtracted.

The vibrations of the CH_3 and CH_2 groups are not very sensitive to *N*-deuteriation and the deformation vibrations can be considered as almost pure. The $\nu_{CH_3}(N)$ vibrations are observed at 3006 and 2932 cm^{-1}, and the $\nu_{CH_3}(C)$ vibrations at 2981 and 2869 cm^{-1}. The weak band at 2815 cm^{-1} is probably the first overtone of the deformation vibration δ_{CH_3} at 1414 cm^{-1}. The δ^S $N(CH_3)$ vibrations are assigned to the absorptions observed at 1480 and 1414 cm^{-1}. This last band shifts to 1409 cm^{-1} in [$^2H_1$]BGDA and is very weakly coupled with the ν_{C-N} stretch.[12] The δ_{CH_2} mode is observed at 1453 cm^{-1} (1451 cm^{-1} in [$^2H_1$]BGDA). The absorptions at 1392 and 1366 cm^{-1} are ascribed to the $\delta^s{}_{CH_3}$ vibrations of the t-butyl group. The absorptions at 1333 cm^{-1} (1330 cm^{-1} in [$^2H_1$]BGDA) probably originate from the wagging vibration of the CH_2 group.[12] The $\nu^{as}{}_{CNC}$ vibration of the $N(CH_3)_2$ group is ascribed to the band observed at 1268 cm^{-1} (1259 cm^{-1} in [$^2H_1$]BGDA), in agreement with potential energy distribution calculations on *N,N*-dimethylacetamide.[28] The bands at 1247, 816, 780 and 738 cm^{-1} probably originate from the CC_3 skeletal motion of the t-butyl group,[29,30] and the band at 874 cm^{-1} from the stretching vibration of the $(H_2)C–C$ part of the molecule.[12] The bands at 1142, 1052, 1026 and 966 cm^{-1} are assigned to the rocking vibrations of the methyl $CH_3(N)$ or Bu^t groups. The band observed at 738 cm^{-1}, also observed in *N,N*-dimethylacetamide,[28] can be assigned to the $\nu^s{}_{CNC}$ vibration of the $N(CH_3)_2$ group.

The ν_{CH_3} and ν_{CH_2} vibrations are not very sensitive to the physical state of BGDA and, as can be seen from Figs. 1 and 2, almost the same frequencies are observed in dilute solution and in solid BGDA. This is in contrast with the ν_{NH} and amide I–VI vibrations (Table 1 and Fig. 2). The ν_{NH} vibration is shifted to 3277 cm^{-1} and the band at 3424 cm^{-1}, characteristic of the C_5 conformation, disappears. A new band is observed at 3050 cm^{-1}, at the high frequency side of the ν_{CH_3} vibrations. This band of medium intensity is assigned to the first overtone of the amide II vibration observed at 1534 cm^{-1} in solid BGDA. The intensity of this band, sometimes called amide B band,[31–32] increases by Fermi resonance interaction. With respect to dilute carbon tetrachloride solution, the amide I(U) band is shifted by 6 cm^{-1} to higher wavenumbers and the amide I (A) band by 23 cm^{-1} to lower wavenumbers. The amide II (A) vibration shows a marked frequency increase (+48 cm^{-1}) and the three bands observed at 1268, 1247 and 1226 cm^{-1} in dilute solution are observed at 1288, 1267 and 1254 cm^{-1} in the solid state. The broad band observed at 647 cm^{-1} ($\Delta\nu$ = +68 cm^{-1}) is assigned to the γ_{NH} vibration. The absorptions observed at 623 and 551 cm^{-1} are probably attributable to the $\delta_{C=O}$ and $\gamma_{C=O}$ vibrations, but no distinction could be made between the deformation vibrations of the two carbonyl groups, which is also the case in the solid state. The ν_{C-O} vibration also undergoes a frequency change (−15 cm^{-1}) on going from dilute solution to the solid state.

The frequency lowering of the ν_{NH} vibration, the frequency increase of the amide II, III and V bands, and the frequency lowering of the $\nu_{C=O}$ (A) band strongly suggest that intermolecular hydrogen bonds involving mainly the NH and C=O(A) groups are formed in the solid state. In dipeptides characterized by the C_5 and C_7 conformations in solution, the ν_{NH} band at 3420 cm^{-1} (C_5) disappears in the solid state and the band at 3350 cm^{-1} (C_7) is shifted to 3280 cm^{-1}.[24] The results of this work do not allow us to obtain more structural information on BGDA in the solid state. Previous work has shown that the distortion of the C_5 conformation depends on the bulkiness of the end substituents.[24,33] The δ_{CH_3} vibrations are weakly perturbed by the formation of this strong intermolecular hydrogen bond. They are observed at 1461, 1405 and 1389 cm^{-1}, showing upward shifts of *ca.* 5 cm^{-1}. The rocking vibrations of the CH_3 group are observed at 1046 and 1030 cm^{-1} (instead of 1052 and 1026 cm^{-1} in solution). Interestingly, a strong intensification of the skeletal vibration of the CC_3 group at 558 and 941 cm^{-1} can be observed. Force field calculations have shown the great insensitivity of the CH_3 and CH_2 bending modes, and of the CH_3 rock, on going from the C_5 to the C_7 conformation, characterised by a stronger intramolecular hydrogen bond.[12] This is also the case for the $(H_2)C–C$ stretch at 874 cm^{-1}.

Interaction with Phenol Derivatives.—Hydrogen-bonding equilibrium constants have been measured for phenols and BGDA in carbon tetrachloride. The thermodynamic data and the frequency shift of the ν_{OH} stretching vibration are reported in Table 2. Fig. 3 reproduces the spectra of some complexes in the ν_{OH} region. The thermodynamic parameters have also been determined in 1,2-dichloroethane, whose higher polarity makes it a much better model for real biological systems than non-polar solvents such as hexane or carbon tetrachloride.[34] Further, the present investigation on the proton acceptor ability of a dipeptide will be extended to tripeptides and polypeptides[26] whose solubility is very low in non-polar solvents. As a consequence, the comparative study of the basic properties of these model peptides is only possible in solvents of higher polarity. The logarithms of the K values are linearly related to the pK_a values of the phenol derivatives, and a least-mean-squares treatment yields eqns. (1)–(4).

In CCl_4

$$\log K^{298\,K} = 6.58 - 0.46\,pK_A \quad (r = 0.998) \qquad (1)$$

$$\log K^{323\,K} = 5.98 - 0.44\,pK_a \quad (r = 0.998) \qquad (2)$$

In 1,2-DCE

$$\log K^{298\,K} = 4.62 - 0.35\,pK_A \quad (r = 0.999) \qquad (3)$$

$$\log K^{323\,K} = 4.16 - 0.33\,pK_a \quad (r = 0.997) \qquad (4)$$

Comparison between the results listed in Tables 2 and 3 shows that increasing the solvent polarity has a marked

Table 2 Thermodynamic data and $\Delta\nu_{OH}$ values for the interaction between BGDA and some phenol derivatives. Solvent, CCl_4

Phenol	$K^{298\,K}$/dm^3 mol^{-1} [a]	$K^{323\,K}$/dm^3 mol^{-1} [a]	$-\Delta H$/kJ mol^{-1} [b]	$\Delta\nu_{OH}$/cm^{-1}
3,4-Dimethylphenol	61	28	25	—
4-Methoxyphenol	69	31	26	260[c]
Phenol	91	41	26	280[c]
4-Bromophenol	175	75	27	300[c]
3-Bromophenol	242	103	27	300[c]
3,4-Dichlorophenol	394	162	28	315
3,5-Dichlorophenol	604	243	29	325
3,4,5-Trichlorophenol	956	376	30	340

[a] Standard deviation = 5%. [b] Calculated from the least-mean-squares plot of log *K* *vs.* pK_a. [c] Error on the maximum = 20 cm^{-1} owing to the overlapping with the ν_{NH} and $2\nu_{C=O}$ bands.

Table 3 Thermodynamic data for the interaction between BGDA and some phenol derivatives. Solvent, 1,2-DCE

Phenols	$K^{298\,K}$/ dm^3 mol^{-1} [a]	$K^{323\,K}$/ dm^3 mol^{-1} [a]	$-\Delta H$/ kJ mol^{-1} [b]
4-Methoxyphenol	11	7	15
Phenol	13	8	16
4-Bromophenol	22	13	17
3-Bromophenol	28	16	17
3,4-Dichlorophenol	40	23	18
3,5-Dichlorophenol	56	31	19
3,4,5-Trichlorophenol	79	43	20

[a] Error on the *K* determination = 8%. [b] Calculated from the least-mean-squares plot of log K *vs.* pK_a.

Table 4 IR data (ν_{NH} and $\nu_{C=O}$ vibration) for complexes of BGDA with phenol derivatives. Solvent, CCl_4

Phenol derivative	ν_{NH}/ cm^{-1}		ν_{C-O} (U)/ cm^{-1}	ν_{C-O} (A)/ cm^{-1}
Phenol	3444	3401	1689	1650
4-Bromophenol	3446	3399	1685	1648
3,4-Dichlorophenol	3446	3398	1683	1648
3,5-Dichlorophenol	3446	3398	1683	1648
3,4,5-Trichlorophenol	3447	3398	1682	1647
Free BGDA	3424		1714	1664

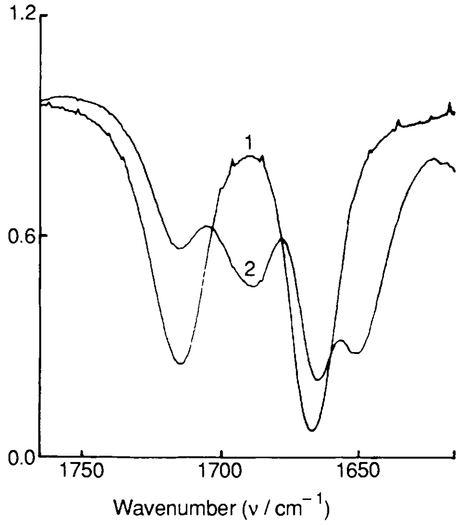


Fig. 4 FT-IR spectra in the $\nu_{C=O}$ region of: 1, BGDA (*c* = 0.008 mol dm^{-3}); and 2, BGDA (*c* = 0.05 mol dm^{-3}) and phenol (*c* = 0.05 mol dm^{-3}). Solvent, carbon tetrachloride; *d* = 0.1 cm.

influence on the formation constants, which are significantly higher in carbon tetrachloride than in 1,2-dichloroethane. Similar results have previously been reported for uracil complexes.[35]

The data of Tables 2 and 3 also show that the complexes investigated are of medium strength, the $-\Delta H$ values ranging from 15–30 kJ mol^{-1}. BGDA has two basic sites available for hydrogen-bond formation, namely the oxygen atoms of the U and A carbonyl functions. As shown in Fig. 4, the decrease in the intensity of the two bands at 1714(U) and 1664(A) cm^{-1} clearly shows that both carbonyl groups are involved in hydrogen-bond formation with a hydroxyl proton donor. The $\Delta\nu_{C=O}$ values depend slightly on the acidity of the phenols (Table 4). The relative concentration of C=O(U) and C=O(A) complexes estimated from the intensity decrease of both carbonyl bands does not depend markedly upon the acidity of the phenols. About 45% of the complexes are formed on the C=O(U) function, even with more acidic phenols such as pentachlorophenol (pK_a = 5) or 2,6-dichloro-4-nitrophenol (pK_a = 3.25). Curiously, picric acid (pK_a = 0.30) does not interact with BGDA, and this is clearly shown by the fact that the two C=O bands do not decrease in intensity in the presence of this strong proton donor. This can be explained by the fact that the intermolecular C=O • • • HO interaction cannot compete with the strong NO_2 • • • HO intramolecular hydrogen bond. It must be pointed out here that picric acid forms very strong ion-pair complexes with many N(sp^2) or N(sp^3) bases.[36]

On complex formation, the ν_{NH} band of BGDA shows a broadening to the high and low frequency side of the free band. The FT-IR difference spectra (Fig. 3) show that two ν_{NH} bands are induced by complex formation. The high frequency band is shifted by *ca.* 20 cm^{-1} with respect to free BGDA and this shift to higher frequencies suggests that the intramolecular (C_5) hydrogen bond is broken when the interaction with phenol occurs at the C=O(A) function. Wavenumbers between 3440 and 3450 cm^{-1} have been reported for the ν_{NH} vibrations of free NH bonds in dipeptides.[8]

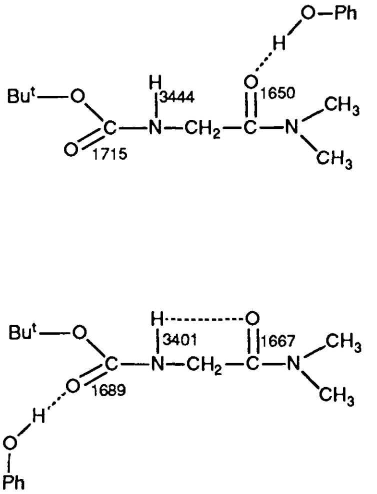
The second ν_{NH} band is shifted by *ca.* 25 cm^{-1} with respect to free BGDA. This frequency lowering is explained by a decrease in the electronic density at the N(H) atom when the hydrogen bond is formed on the C=O(U) group. Similar perturbations are observed in complexes involving *N*-methylacetamide, where the hydrogen bond is undoubtedly formed on the carbonyl function.[3,26] Owing to the increased acidic character of the NH bond, the C_5 conformation is probably retained in the U complex. The assignments of the ν_{NH} and $\nu_{C=O}$ vibrations for the phenol complex can be summarized as shown in Scheme 1.

Complex formation brings about a perturbation of other vibrational modes of BGDA; this is illustrated in Fig. 5 for the interaction with 3,4,5-trichlorophenol. The amide II band at 1489 cm^{-1} is shifted to 1501 cm^{-1} and this confirms the high ν_{C-N} character of this vibration. Owing to overlapping with phenol

Table 5 Formal concentrations, complex concentrations and K values from spectra 1–4

Spectrum	F_A/mol dm^{-3}	F_B/mol dm^{-3}	C_{AB}/mol dm^{-3}	K/dm^3 mol^{-1}	c_{tot}/mol dm^{-3}
1	7.6×10^{-3}	1.9×10^{-2}	5.5×10^{-3}	180[a]	—
2	7.8×10^{-3}	1.10×10^{-2}	7.5×10^{-3}	2000[b]	—
3	—	—	—	—	1.3×10^{-2}
4	1.95×10^{-2}	2.3×10^{-2}	1.6×10^{-2}	600	—

[a] Ref. 38. [b] Extrapolated from the log K *vs.* pK_a correlation given in ref. 2.



Scheme 1

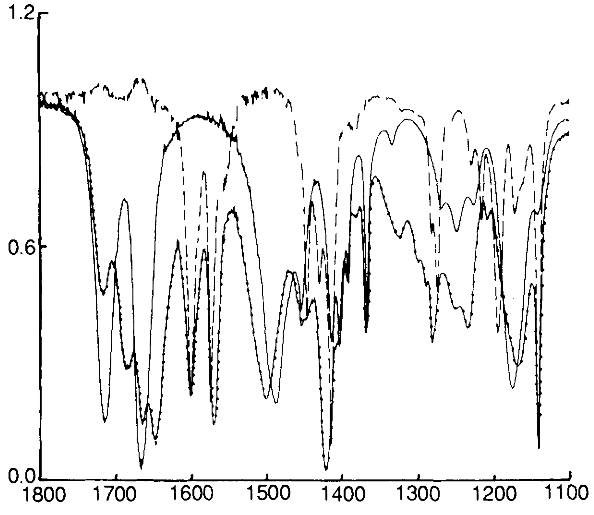


Fig. 5 FT-IR spectra (1800–1100 cm^{-1}) of 3,4,5-trichlorophenol (– – – –) (c = 0.16 mol dm^{-3}); BGDA (——) (c = 0.10 mol dm^{-3}) and BGDA + 3,4,5-trichlorophenol (· · · ·) at the same concentrations. Solvent, carbon tetrachloride; d = 0.01 cm.

bands, the amide III vibration could not be observed. The ν_{C-O} mode shifts to lower frequencies, from 1174 to 1168 cm^{-1}, and this is perhaps due to competition between the delocalization of the free electron pair(s) of the nitrogen atom and the oxygen atom of the methoxy group to the carbonyl oxygen. Some changes in the vibrations of the phenols are also induced by complex formation. The ν_{8b} ring mode shifts from 1575 to 1570 cm^{-1}. Interestingly, the ν_{8b} frequency decrease of *p*-cresol, taken as a model for tyrosine, can be considered to be an indicator of hydrogen-bond strength. Frequency shifts of 5–7 cm^{-1} should correspond to $-\Delta H$ values between 18 and 23 kJ mol^{-1},[37] which correspond to the $-\Delta H$ values for the CH_3 or CH_3O phenol derivatives found in this work. Further, the δ_{OH} modes coupled with ring vibrations, observed at 1195 and 1275 cm^{-1} in the free phenol derivative, are shifted to 1234 and 1325 cm^{-1}. Similar perturbations have been observed for amide complexes.[2] Owing to overlap with the $\delta_{C=O}$ and $\gamma_{C=O}$ absorptions of BGDA, the ν_6 and ν_{16} vibrations of the aromatic ring could not be studied.

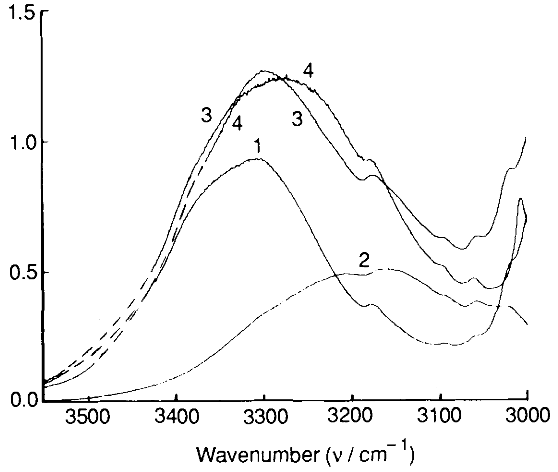


Fig. 6 FT-IR spectra, in the ν_{OH} region, of complexes between 3,5-dichlorophenol and: 1, MNMC; 2, DMA; 3, sum of spectra 1 and 2; and 4, BGDA. Solvent, carbon tetrachloride; d = 0.4 cm.

The results of this work clearly show that in the complexes between phenol derivatives and the dipeptide investigated, the two carbonyl functions are involved in hydrogen-bond formation. As can be seen from Fig. 6, the ν_{OH} band is broader than in complexes formed between the same hydroxylic proton donors and monocarbonyl bases, such as aliphatic esters, amides, ketones or carbamates. The experimental spectra show, however, one $\nu_{OH\cdots O}$ complex band. BGDA can be considered as being built up of two model molecules, namely methyl *N*-methylcarbamate (MNMC) and *N*,*N*-dimethylacetamide (DMA). Fig. 6 shows the experimental spectra in the ν_{OH} region of the complex between 3,5-dichlorophenol and MNMC (spectrum 1) and DMA (spectrum 2). The maxima of the ν_{OH} absorptions are observed at 3310 and 3160 cm^{-1}, respectively. Spectrum 3, the sum of spectra 1 and 2, shows a maximum near 3295 cm^{-1}. Finally, the experimental spectrum of the BGDA complex reproduced in spectrum 4 shows a maximum at 3275 cm^{-1}. From these spectroscopic data, it can be concluded that the unusual broadness of the ν_{OH} band in BGDA complexes originates from the superposition of two complex bands. Interestingly, in order to have the same intensity in spectra 3 and 4, different formal concentrations of proton donor (F_A) and proton acceptor (F_B) have been used. From the K values the concentrations of the complex (C_{AB}) have been computed. These concentrations are given in Table 5.

It can thus be concluded that the K values for the BGDA complexes, which represent the mean contribution of two different kinds of interaction, cannot be deduced from a simple additivity rule. This will be discussed in more detail in future work.

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