FTIR study of chiral modifier–reactant interactions. The cinchonidine–alkenoic acid system

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Cyclic cinchonidine : acid complexes (1 : 1 and 1 : 2) of the chiral modifier cinchonidine (CD) and an alkenoic acid, tiglic acid, in dichloromethane solvent have been observed by FTIR spectroscopy. Both the OH and the quinuclidine N atom of CD are involved in the hydrogen bond with the acid molecule(s). Such dual-site modifier–reactant interactions play an important role in the enantioselective hydrogenation of alkenoic acids over CD-modified Pd catalysts. The stability of these 1 : 1 and 1 : 2 complexes has been probed by addition of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), a stronger base than CD. DBU builds ion pairs with the acid (with 1 : 1 and 1 : 2 stoichiometry) and a hydrogen bond with the OH of CD. However, despite the large difference in basicity between CD and DBU, 1 : 2 CD : acid complexes can still be detected when more than 0.5 equivalent DBU was added with respect to the acid, at which ratio the enantiomeric excess (ee) drops dramatically. Hence, the molecular structure of CD favours formation of cyclic complexes *via* a dual-site interaction, which is not possible for DBU : acid complexes, and stabilises 1 : 2 CD : acid species, which are proposed to be responsible for enantiodifferentiation.

Introduction

The molecular structure and conformation of the chiral modifier (cinchonidine or in general a *cinchona* alkaloid) play a crucial role for the enantiodifferentiation in the asymmetric hydrogenation of α-ketoesters on Pt[1] and alkenoic acids on Pd.[2] In the case of the enantioselective hydrogenation of α,β-unsaturated carboxylic acids on supported Pd catalysts both the hydroxy group and the quinuclidine N atom are necessary for achieving good enantiomeric excess (ee). The OH and the quinuclidine N of cinchonidine as well as their relative arrangement are important for the modifier–acid interaction as it has already been demonstrated by spectroscopic[2,3] and mechanistic[2,4,5] studies. Recently, it has been found that such an interaction involving both OH and quinuclidine N is fundamental also in the Pd catalysed hydrogenation of 4-hydroxy-6-methyl-2-pyrone whose OH group is of comparable acidity to acetic acid.[6]

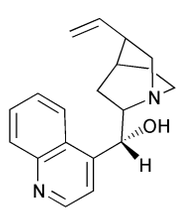
Formation of 1 : 1 and 2 : 1 acid–base complexes is usually observed in solution.[7–10] 1 : 1 complexes exhibit a $NH^+ \cdots {}^-O$ ionic interaction. In 2 : 1 complexes an additional acid molecule is hydrogen bonded to the ion pair. By FTIR spectroscopy it has been shown that 1 : 2 cinchonidine–acetic acid complexes can be found in dichloromethane solvent.[3] The stability of the complexes arises due to the particular arrangement of the OH and quinoline groups of cinchonidine. In fact, the OH of cinchonidine is involved in the bonding to the second acid molecule, which is not deprotonated by the quinuclidine N. The IR spectrum of these species is characterised by a typical signal due to the hydrogen bonded OH of cinchonidine. Moreover, these 2 : 1 complexes are structurally rather flexible so that their adsorption on a metal surface appears easier than for 1 : 1 species.

Similarly, 1 : 1 cinchonidine–4-hydroxy-6-methyl-2-pyrone complexes have also been observed by IR spectroscopy.[6] However, in this case cyclic 1 : 2 species are rather disfavoured with respect to cyclic 1 : 1 complexes.

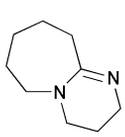
Moreover, 1 : 2 cinchonidine–alkenoic acid complexes have also been postulated to be the determinant species for enantioselectivity.[5] A drop in the ee has been observed on addition of the strong bulky base 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), which is assumed to break 1 : 2 species at concentrations exceeding 0.5 equivalent with respect to the acid. The same behaviour of ee on addition of DBU has been observed for the substituted 2-pyrone.[6]

This different relative stability of 1 : 1 and 1 : 2 complexes of cinchonidine with carboxylic acids and 4-hydroxy-6-methyl-2-pyrone can be explained by the different arrangement of the two groups involved in the bonding. In carboxylic acids the two O atoms which interact with cinchonidine are separated by only one C atom, whereas three C atoms separate the corresponding O atoms in the pyrone. This leads to a considerable 'ring stress' in cyclic 1 : 1 cinchonidine–carboxylic acid complexes, which favours formation of cyclic 1 : 2 complexes.

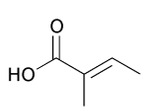
Here we report an FTIR study on the interaction of cinchonidine (CD), tiglic acid (TA) and DBU aiming at elucidating the role and the nature of the inter-molecular interactions involved in the enantioselective hydrogenation of tiglic acid on *cinchona*–modified Pd.



CD



DBU



TA

Experimental

Cinchonidine (CD, Fluka, 98%), 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU, Fluka, ≥99%) and tiglic acid (TA, Fluka, ≥97%) were used as received. Dichloromethane solvent (Baker) was stored over 5 Å molecular sieves.

FTIR spectra were recorded at room temperature on a Bruker IFS-66 spectrometer equipped with a DTGS detector

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Table 1 Characteristic IR vibrations of CD, TA, DBU, CD–TA, TA–DBU and CD–DBU species. Vibrations of 1 : 1 and 1 : 2 base–acid complexes are indicated by subscripts 1 : 1 and 1 : 2

Assignment	CD	TA	DBU	CD–TA	TA–DBU	CD–DBU
$\nu(OH)_{free}$	3598	3505				
$\nu(OH)_{CD,\ 1:2}$				3365		
ν(C=O)		1720				
ν(C=O)		1688				
ν(C=C)				1660		
$\nu(C=C)_{conj.}$		1646				
$\nu(C=N^+)$					1648	
ν(C=C)	1635					
ν(C=N)			1614			1609[a]
$\nu_{AS}(OCO)_{1:1}$				1559	1554	
$\nu_{AS}(OCO)_{1:2}$				1542	1530	
Ring stretch	1615			1615		1615
Ring stretch	1593			1593		1593
Ring stretch	1570			1570		1570
Ring stretch	1509			1509		1509
δ(C–H)			1486		1486	1486
δ(C–H)			1467		1467	1467
Ring stretch	1462			1462		1462
δ(C–H)	1454			1454		1454

[a] Value obtained by subtracting a spectrum of DBU from a spectrum of a CD : DBU solution having the same concentration of DBU.

by co-adding 200 scans at a resolution of 4 cm^{-1}. A CaF_2 cell (Portmann Instruments) of 1 mm path-length was used.

Results

The frequency of the most characteristic signals of cinchonidine (CD), tiglic acid (TA) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in the IR spectral range relevant for this work are summarised in Table 1. The frequencies of the complexes described in the following sections are also reported except for those observed in CD–TA–DBU solutions.

Cinchonidine–tiglic acid solutions

Fig. 1 shows the IR spectra of a set of solutions of CD and TA

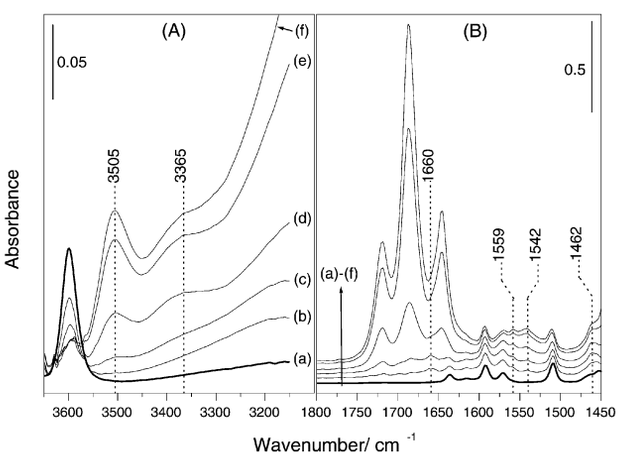

Fig. 1 FTIR spectra of CD–TA solutions at increasing TA concentration in CH_2Cl_2. C_{CD} = 0.01 M. Panel (A) shows the 3650–3150 cm^{-1} whereas panel (B) the 1800–1450 cm^{-1} spectral range. Traces (a)–(f) correspond to 0.0, 0.5, 1.0, 2.0, 4.0 and 5.0 equivalents TA.

at increasing TA concentrations. Trace (a) represents 0.01 M CD in CH_2Cl_2 solvent.

The 3650–3150 cm^{-1} spectral region [Fig. 1(A)] shows the effect of the titration of CD on the OH stretchings of both CD [$\nu(OH)_{CD}$] and TA [$\nu(OH)_{TA}$]. The $\nu(OH)_{CD}$ at 3598 cm^{-1} is fast attenuated up to a TA concentration of 0.01 M (equivalence) and more slowly after this concentration. Two signals appear at 3505 and 3365 cm^{-1}. The former represents the ν(OH) of free TA, while the second is attributed to 1 : 2 CD–TA complexes as already discussed for acetic acid–cinchonidine solutions.[3] This signal is already detectable at an acid concentration of 0.01 M [Fig. 1, trace (c)].

The 1800–1450 cm^{-1} spectral region [Fig. 1(B)] shows on the other hand the behaviour of the carboxy (1720, monomer and 1688 cm^{-1}, dimer) and C=C (1646 cm^{-1}) bands of TA. These are hardly visible until an acid concentration of 0.01 M has been reached [trace(c)]. Moreover, weak bands at *ca.* 1660, 1559 and 1542 cm^{-1} are observed as the concentration of TA increases. The signal at 1660 cm^{-1}, the most prominent band of TA at low concentration, is found as a shoulder of the signal at 1646 cm^{-1} at high TA concentration. The signals at 1559 and 1542 cm^{-1} are assigned to the O–C–O asymmetric stretching of two distinct carboxylates. Both signals are observed already at low TA concentration [Fig. 1, trace (b)]. The signal at 1559 cm^{-1} is related to a 1 : 1 complex with CD, whereas a 1 : 2 complex is more likely to be attributed to the band at 1542 cm^{-1}.[3] This is in good agreement with the appearance of the signal at 3365 cm^{-1} at the same TA concentration [compare Fig. 1(A) and 1(B)]. Accordingly, the band at 1660 cm^{-1} is assigned to the stretching of a non-conjugated C=C of deprotonated TA, which is expected to be blue-shifted with respect to the vibration of the conjugated C=C (1646 cm^{-1}).[11]

Protonation of CD at the quinuclidine N leads to the appearance of the typical broad signal occurring in the 3200–2100 cm^{-1} spectral range associated with the N–H^+ group. The signal is overlapping with the characteristic bands of the acid at 2682, 2630 and 2559 cm^{-1} and the broad OH ··· O signal of acid dimers,[12–14] and is attributable to the delocalisation of the proton in the CD–TA ion pair due to protonation.[7,9,10] Apart from this broad band the protonation of the quinuclidine moiety has only a minor effect on both the band position and intensity of vibrational bands associated with this group. On the other hand, the C–O stretching of the OH group of the alkaloid at 1093 cm^{-1} disappears (not shown in Fig. 1) upon addition of the acid in agreement with this group participating in the formation of CD–TA complexes. Interference due to the appearance of strong signals of TA in this spectral region does not allow assignment of the position of the band associated with the C–O stretching mode of CD within the complexes.

Tiglic acid–DBU solutions

Fig. 2 shows the titration of 0.02 M TA with DBU in the 1800–1450 cm^{-1} spectral range. With increasing concentration of DBU the signals corresponding to the carboxy group of TA

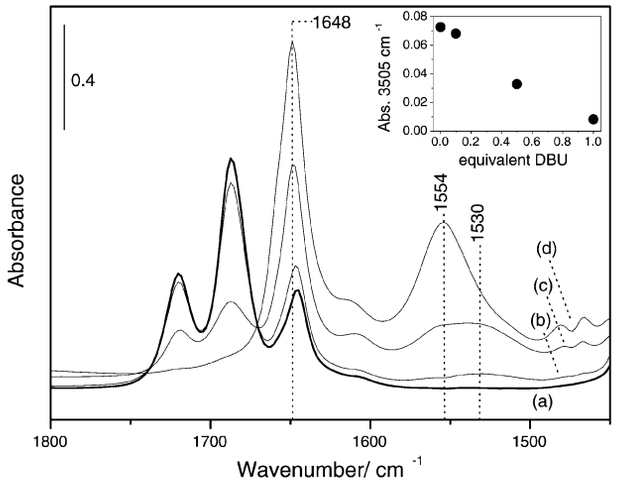

Fig. 2 FTIR spectra of TA–DBU solutions at increasing DBU concentration in CH_2Cl_2. C_{TA} = 0.02 M. Traces (a)–(d) correspond to 0.0, 0.1, 0.5 and 1.0 equivalent DBU. The inset shows the behaviour of $\nu(OH)_{TA}$ at increasing amount of DBU.

completely disappear due to deprotonation of the acid. Carboxylate bands are clearly distinguishable at about 1550 and 1530 cm^{-1}. At 0.1 equivalent DBU [trace (b)] a single signal at around 1530 cm^{-1} appears, whereas at 0.5 equivalent DBU [trace (c)] a broad feature composed of the two signals can be observed. At 1 equivalent DBU [trace (d)] the signal at 1554 cm^{-1} dominates. Formation of TA : DBU ion pairs is also supported by the disappearance of the signals of the carboxy groups of TA. In analogy to the CD–TA solutions, the signals at 1554 and 1530 cm^{-1} are assigned to 1 : 1 and 2 : 1 adducts, respectively. Hence, the spectra indicate formation of mostly 1 : 1 complexes. The strong signal growing at 1648 cm^{-1} corresponds to protonated DBU.[15] Some DBU is still free when 1 equivalent is used as the signal at about 1610 cm^{-1} suggests. This also indicates that both TA–DBU 1 : 1 and 2 : 1 species are present.

In the high frequency region, the $\nu(OH)_{TA}$ gradually disappears as DBU is added (inset of Fig. 2) in agreement with the behaviour of the signals in the 1800–1450 cm^{-1} spectral range. On the other side, a very broad signal centred at around 2500 cm^{-1} and extending from 3200 to 2100 cm^{-1} grows with increasing DBU concentration. This signal again indicates formation of an acid–base ion pair.

Cinchonidine–DBU solutions

Fig. 3 shows the IR spectra of a 0.01 M CD solution at increasing DBU concentrations. The inset of Fig. 3 shows a plot of the absorbance of $\nu(OH)_{CD}$ *versus* the equivalents of DBU. The intensity of the signal at 3598 cm^{-1} drops by about 15% as 0.5 equivalent of DBU (with respect to CD) is added. At 1 equivalent DBU about 75% of the original signal is detected. Moreover, the spectra show a broad signal extending over the 3400–2200 cm^{-1} spectral range, which is not characteristic of the spectrum of neither DBU nor CD, also shown for comparison. The band is assigned to a strong $(N)_{DBU} \cdots (HO)_{CD}$ hydrogen bond with the hydrogen atom having some proton character and being strongly polarised between the N and O atoms. In fact, since this broad band is usually observed in the case of acid–base interactions, as described for CD–TA and TA–DBU solutions, it indicates that DBU behaves as a strong hydrogen bond acceptor. In the fingerprint region the addition of the stronger base only results in the appearance of the signals of DBU. However, comparison of the strong signal at 1612 cm^{-1} [ν(C=N)] of DBU solutions and CD–DBU solutions shows that in the latter case a component at 1609 cm^{-1} can be distinguished. Although the shift with respect to the value for DBU solutions (Table 1) is of only 5 cm^{-1} this band may

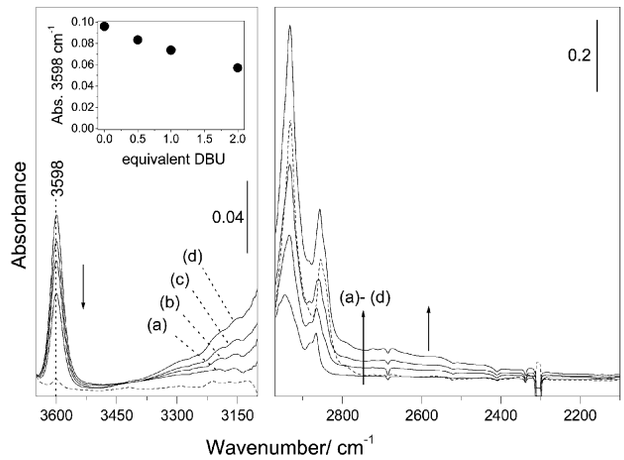

Fig. 3 FTIR spectra of CD–DBU solutions at increasing DBU concentration in CH_2Cl_2: (a) 0.0, (b) 0.5, (c) 1.0, and (d) 2.0 equivalents DBU referred to CD. The inset shows the absorbance of the IR signal at 3598 cm^{-1} [$\nu(OH)_{CD}$] for the same solutions. C_{CD} = 0.01 M. The dashed trace represents DBU 0.02 M in CH_2Cl_2. The 3100–3000 cm^{-1} spectral region is disturbed by strong signals of the solvent. The 3650–3100 cm^{-1} region is scaled by a factor of five, for clarity.

originate from hydrogen bonding involving the C=N and OH groups of DBU and CD, respectively. This agrees well with the attenuation of the signal at 3598 cm^{-1} and with the broad signal between 3400 and 2200 cm^{-1}.

Cinchonidine–tiglic acid–DBU solutions

Fig. 4 shows the IR spectra obtained by adding DBU at increas-

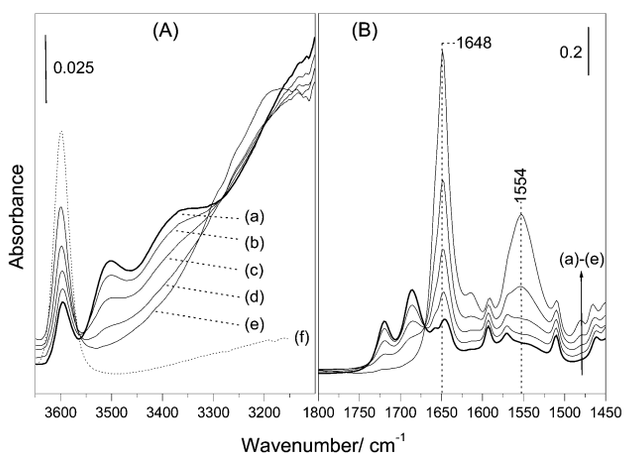

Fig. 4 FTIR spectra of CD–TA–DBU solutions at increasing DBU concentration in CH_2Cl_2. C_{CD} = 0.01 M, C_{TA} = 0.02 M. Panel (A) shows the 3650–3100 cm^{-1} whereas panel (B) the 1800–1450 cm^{-1} spectral range. Traces (a)–(e) correspond to 0.0, 0.1, 0.25, 0.5 and 1.0 equivalent DBU with respect to TA. Trace (f) represents CD 0.01 M.

ing concentration to a 1 : 2 CD–TA solution. Significant changes are observed in the spectra. In the OH stretching region [Fig. 4(A)] the intensity of the signal at 3598 cm^{-1} corresponding to free CD increases with increasing DBU concentration until one equivalent DBU (with respect to TA) has been added. Comparison with 0.01 M CD in CH_2Cl_2 [Fig. 4, trace (f)] shows that the signal does not reach the intensity observed for CD alone. Moreover, the intensity of $\nu(OH)_{CD}$ decreases again with the addition of more than 1 equivalent DBU with respect to TA (not shown). The signals at 3505 and 3365 cm^{-1} gradually disappear with the addition of DBU. This indicates that TA is deprotonated by DBU and that 1 : 2 CD–TA complexes break. However, traces (d)–(e) show that 1 : 2 CD–TA complexes are still detectable at 0.5 equivalent DBU.

The 1800–1450 cm^{-1} spectral region [Fig. 4(B)] is dominated by the strong signal at 1648 cm^{-1} assigned to protonated C=N for analogy to TA–DBU solutions. This signal increases almost linearly with DBU concentration until one equivalent has been added and increases only marginally after this point. Also, the intensity of the signals corresponding to the carboxy group of TA at 1720 and 1688 cm^{-1} drops as DBU is added and the signals completely disappear at 1 equivalent DBU. At this point all the free acid is deprotonated by DBU. However, the ν(C=N) of free DBU can be observed at 1613 cm^{-1} already before equivalence indicating that not all the added DBU is actually protonated by TA. This may suggest the presence of 2 : 1 TA–DBU adducts in solution. Also, a new signal appears at 1554 cm^{-1}. For analogy to TA–DBU solutions discussed above and for comparison with Fig. 1 and 2, this signal is attributed to a carboxylate belonging to a 1 : 1 TA–DBU complex.

In Fig. 4(B) the isosbestic point at *ca.* 1670 cm^{-1} indicates quantitative deprotonation of the carboxy group of TA and the corresponding protonation of the C=N group of DBU with formation of the ion pair.

Discussion

The results obtained for CD and TA solutions are in good agreement with what has been found for acetic acid and CD solutions.[3] Fig. 1 shows that mixtures of 1 : 1, 2 : 1 acid–base complexes, free acid and acid dimers are formed indicating that most of the *cinchona* alkaloid is complexed with the acid through both the quinuclidine N and the OH. Consistently, acid–base complexes with 2 : 1 stoichiometry are associated with the signal at 3365 cm^{-1} which represents the OH of CD hydrogen bonded to the second TA molecule. Interestingly, Fig. 3 shows that CD also associates with the stronger base DBU ($pK_{a(DBU)}$ = 23.9,[15] and $pK_{a(CD)}$ = 8.4 for the quinuclidine N[16]). A strong interaction *via* hydrogen bonding between the C=N of DBU and the OH of CD is observed in the IR spectra. This interaction appears to play some role in 1 : 2 CD–TA solutions only after 1 equivalent DBU (with respect to TA) is added since below 1 equivalent the intensity of $\nu(OH)_{CD}$ increases with increasing DBU concentration (Fig. 4).

The spectra of CD : TA : DBU solutions show that DBU breaks at some extent the 1 : 2 CD–TA species. However, CD–TA complexes can still be detected in solution even at high concentration of DBU. Two arguments support this conclusion.

When DBU is added to a CD–TA solution the increase in intensity of the signal of CD at 3598 cm^{-1} shows breaking of the hydrogen bond involving the OH of CD and indicates that CD is released from complexes with TA. The strong difference in basicity between CD and DBU also suggests that TA protonates DBU and that the quinuclidine N of CD is no longer protonated. On the other hand, the intensity of the signal at 3598 cm^{-1} never reaches the value found for a solution of neat CD at the same concentration [Fig. 4(f)]. An estimation of the amount of CD released by addition of DBU and hence the amount of CD still bonded to TA can be made from the absorbance of the signal at 3598 cm^{-1}, which has an almost perfect linear relationship with CD concentration in the range 0–0.02 M. This linear relationship also shows that CD does not self-associate significantly in this concentration range. From the deviation from linearity at higher concentration the fraction of self-associated CD can be calculated and a self-association constant determined. We find a value of $K = C_{CD2}/C_{CD}^2 = 3.1\ M^{-1}$ for CD in CH_2Cl_2, where C_{CD2} and C_{CD} represent the concentration of associated and free CD, respectively. Hence at 0.02 M the fraction of self-associated CD is approximately 10% only. Based on this calculation and from the absorbance of the 3598 cm^{-1} signal it can be estimated that approximately 20% of CD is still bonded to TA when 1 equivalent DBU (with respect to TA) is added.

Furthermore, comparison of the signals of protonated C=N of DBU and of the carboxyl groups of TA in CD–TA–DBU solutions in the presence and absence of CD indicates that up to 1 equivalent of DBU the signal of protonated C=N is lower in intensity when CD is present than in the absence of CD. The same applies for the signals at 1720 and 1670 cm^{-1} for TA. Moreover, Fig. 4(B) shows that free DBU can still be observed when the signals of the carboxyl groups of TA have completely disappeared (all the free acid has been deprotonated).

It is rather difficult to determine the stoichiometry of the CD : TA complexes in the presence of DBU. However, the drop of the absorbance of the signal at 3365 cm^{-1} when DBU is added suggests that 1 : 2 CD–TA complexes are broken by DBU. Since at 1 equivalent DBU this signal can not be detected it is more likely that 1 : 1 CD–TA complexes exist even in presence of DBU. However, Fig. 4 indicates that at 0.5 equivalent DBU 1 : 2 CD–TA complexes are still present to some extent. Both 1 : 1 and 1 : 2 CD–TA species can be found in the presence of DBU at less than 0.5 equivalent DBU.

The rather large difference in basicity of DBU and CD cannot account for such behaviour. The results indicate that the particular atom arrangement around the OH and quinuclidine N of CD leads to a stabilisation of CD–TA complexes through a double hydrogen bond interaction, which is not feasible for DBU.

The presence of CD–TA complexes is relevant for the understanding of the mechanism of the enantioselective hydrogenation of α,β-unsaturated carboxylic acids (such as TA) over palladium catalysts modified with the *cinchona* alkaloid. Borszeky *et al.*[5] have shown that both the reaction rate and the ee do not decrease until 0.5 equivalent DBU (with respect to TA) has been added to the reaction mixture. After 0.5 equivalent DBU the decrease in ee appeared to be linear with increasing amount of DBU. The authors concluded that at DBU : TA ratios <0.5 acid dimers and 1 : 2 DBU–TA complexes are found whereas at DBU : TA ratios >0.5 1 : 1 DBU–TA complexes are mainly present. CD would be able to extract a molecule of TA from the 1 : 2 DBU–TA complexes but would not be able to break all 1 : 1 DBU–TA species. This argument was used to explain the drop in ee and reaction rate at more than 0.5 equivalent DBU. The present IR study clearly shows that when the DBU concentration is less than 0.5 equivalent with respect to TA both 1 : 1 and 1 : 2 DBU–TA species can be observed in solution [Fig. 2 and 4(B)]. At more than 0.5 equivalent DBU almost only the 1 : 1 DBU–TA complex is observed as indicated by the signal at 1554 cm^{-1} in Fig. 4(B).

The IR spectra show that CD is able to bind TA even at high DBU–TA ratio close to 1, which is the maximum amount of DBU used in the catalytic experiments.[5] 1 : 1 CD–TA complexes are stable under these conditions. Although the signal at 3365 cm^{-1} associated with 1 : 2 CD–TA complexes decreases fast already upon addition of small amounts of DBU, 1 : 2 CD–TA complexes appear to be present until 0.5 equivalent DBU [Fig. 4(A)]. The population of 1 : 2 CD–TA species completely drops to zero between 0.5 and 1 equivalent DBU. However, the presence of 1 : 2 complexes is significant in the region 0–0.5 equivalent DBU. Fig. 5 compares the absorbance of the signal at 3365 cm^{-1} [obtained by subtracting trace (e) in Fig. 4(B) from traces (a)–(d)] with the catalytic results at different TA–DBU ratios.[5] The species present in the two DBU concentration regions, above and below 0.5 equivalent, as determined by FTIR, are also indicated. For comparison with Fig. 4, the amount of CD complexed at 0.5 equivalent DBU can be estimated as 35%. Since CD is released by DBU from CD–TA complexes and the intensity of the OH of CD increases with DBU concentration this amount of complexed CD is assumed to be involved in the CD–TA species. The hydrogen bonding between CD and DBU at less than 0.5 equivalent DBU appears not to be significant when TA is present. This behaviour is

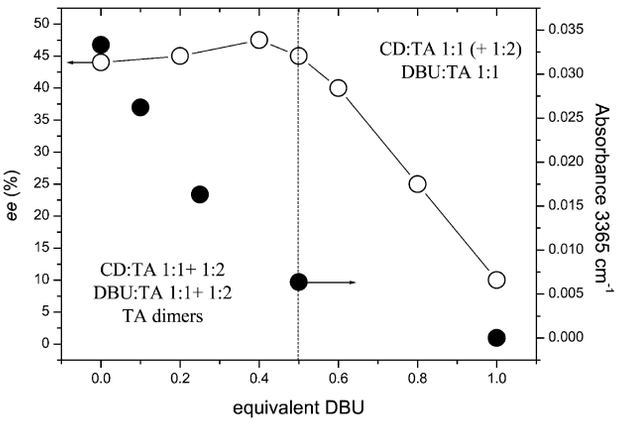

Fig. 5 Comparison between catalytic results (expressed in % ee, ref. 5) and the IR absorbance of the signal at 3365 cm^{-1} (CD–TA 1 : 2) as function of DBU equivalents. Absorbances were obtained by subtracting trace (e) from the traces (a)–(d) of Fig. 4.

probably due to the stronger acid–base interactions involved in the formation of both CD–TA and TA–DBU adducts.

On the other hand, the decrease in intensity of the OH signal of CD in CD–TA–DBU solutions at more than 1 equivalent DBU (not shown in Fig. 5) indicates that at high DBU concentration the interaction between CD and DBU becomes also important. The formation of CD–TA–DBU species can also not be excluded because of the acid–base-like interaction between CD and DBU. However, the concentration range of DBU is already exceeding the range where enantiodifferentiation is still observed. Hence, direct CD–DBU interaction does not appear to be relevant for understanding the effect of DBU on the reaction mechanism.

Comparison between spectroscopic and catalytic measurements supports the proposed mechanism of the asymmetric hydrogenation of alkenoic acids.[2,5] The abundance of CD–acid complexes having 1 : 2 stoichiometry is probably determining the catalytic behaviour of the *cinchona*-modified Pd catalyst. However, although the adsorption mode of cinchonidine on the Pd surface under reaction conditions appears to be more likely through the π-system of the quinoline moiety,[17] the adsorption in presence of the acid is still a crucial factor which needs to be clarified. No spectroscopic evidence for preferred adsorption of the 1 : 2 complexes over the 1 : 1 complexes on Pd is available to date. As suggested for CD–acetic acid adducts,[3] 1 : 2 CD–TA appears to be a species, which can easily be accommodated on the metal surface due to its relative structural flexibility.

Since the same spectroscopic results have also been obtained with (*E*)-2-methyl-2-pentenoic acid, which has also been hydrogenated on CD-modified Pd/Al_2O_3 with over 50% ee,[18] the CD–acid interaction proposed in the reaction mechanism seems to be a general feature for carboxylic acids.

Conclusions

The FTIR studies support previous catalytic experiments which suggested that 1 : 2 cinchonidine : acid complexes may play a crucial role in the enantioselective hydrogenation of carboxylic acids over cinchonidine modified supported Pt catalysts. In particular, the effect of addition of a second strong base (DBU) to the reaction solution has been studied. Our results confirm that cinchonidine is able to form cyclic 1 : 2 complexes with the carboxylic acid even in the presence of 0.5 equivalent DBU with respect to the acid. Both the interactions through the OH and the quinuclidine N of the alkaloid appear to be important factors for complex formation as shown by IR spectroscopy. This indicates that the structure of cinchonidine and in particular the relative arrangement of OH and quinuclidine N plays a fundamental role in its functioning as a modifier. On the other hand, despite its strong basicity, DBU cannot form cyclic complexes with the acid.

Acknowledgements

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