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Correlation Between Chiral Modifier Adsorption and Enantioselectivity in Hydrogenation Catalysis

Yufei Ni, Alexander D. Gordon, Florisa Tanicala, and Francisco Zaera*[a]

Abstract: By combining infrared absorption spectroscopy, performed in situ at the solid-liquid interface, with the use of a set of related compounds with targeted substitutions, the adsorption on the surface of platinum supported catalysts of 1-(1-naphthyl)-ethylamine (NEA), used as a chiral modifier in hydrogenation catalysis, was determined to occur via the amine group, not the aromatic ring as widely believed. It was established that neither naphthalene-based molecules without amine groups nor ones with tertiary amine moieties are capable of adsorbing on the metal surface to any significant extent. A direct correlation was then found between the ability of the amines to adsorb on the Pt surface and their performance as chiral modifiers, imparting enantioselectivity to the hydrogenation of α-keto esters such as ethyl pyruvate.

In order to enhance the selectivity of heterogeneous catalysts, it is imperative to develop an understanding between the nature of the active sites and their reactivity. Recent advances in spectroscopies that operate *in-situ* under catalytic conditions have greatly facilitated the identification of structure-activity correlations in processes involving gaseous reactants and products.[1-3] However, analogous research with solid-liquid interfaces remains a challenge.[4, 5] Here we discuss our results from a study on the adsorption of chiral molecules from solutions onto solid surfaces as it pertains to the bestowing of enantioselectivity to hydrogenation catalysts. In the specific system addressed, 1-(1-naphthyl)-ethylamine (NEA) is added from solution to platinum catalysts to direct the chirality of the hydrogenation of ethyl pyruvate (EtPy) to ethyl lactate (EtLac), a prototypical example of the so-called Orito reaction (Figure 1, top).[6, 7] By carrying out attenuated-total-reflection infrared absorption spectroscopy (ATR-IR) experiments *in-situ* and comparatively using a set of related compounds (Figure 1, bottom), it was found that NEA bonds to the metal through the nitrogen atom of its amine moiety, not via the aromatic ring as commonly believed.[7-16] Moreover, it was determined that only those modifiers that contain the non-tertiary amine moiety required for adsorption are capable of promoting enantioselectivity in hydrogenation catalysis.

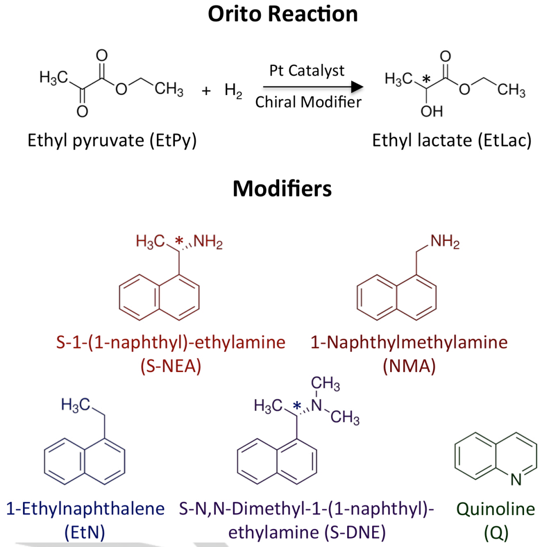

Figure 1. Orito reaction and structure of the modifiers used in this study. Chiral carbon atoms are indicated by asterisks.

The IR spectra of the modifiers listed in Figure 1, adsorbed from 1 mM CCl_4 solutions onto a commercial 1 wt% Pt/SiO_2 catalyst, are displayed in Figure 2. Only S-NEA, 1-naphthylmethylamine (NMA), and quinoline (Q) adsorb on the platinum surface to any significant extent; no measurable uptake could be detected with either 1-ethylnaphthalene (EtN) or S-N,N,-dimethyl-1-(1-naphthyl)-ethylamine (S-DNE). Unfortunately it is difficult to quantify the signals from these IR spectra to calculate surface coverages for the adsorbed species, but it is easy to see that, on average, the intensities of the most prominent peaks in the IR traces for S-DNE and EtN are at least one order of magnitude weaker than those for NEA, NMA and quinoline (a variation not seen in the spectra of the pure compounds). What is significant about this result is that, although all of these compounds contain aromatic rings (naphthalene, except for Q), only the ones with a NH_2 moiety are capable of bonding to the Pt surface. The common wisdom has been that chiral modifiers adsorb on the metal surface via their aromatic ring,[7-16] but that does not appear to be the case here. In principle, the species detected by IR could be bonded to the acidic sites of the alumina support, but we have previously shown that the same trend is seen for adsorption on a platinum foil, where no oxide surfaces are present;[17] only the behaviour of quinoline is different between those two cases (it adsorbs on Pt/Al_2O_3 but not on the Pt foil). Blank experiments were also carried out with the support alone to rule out this possibility.

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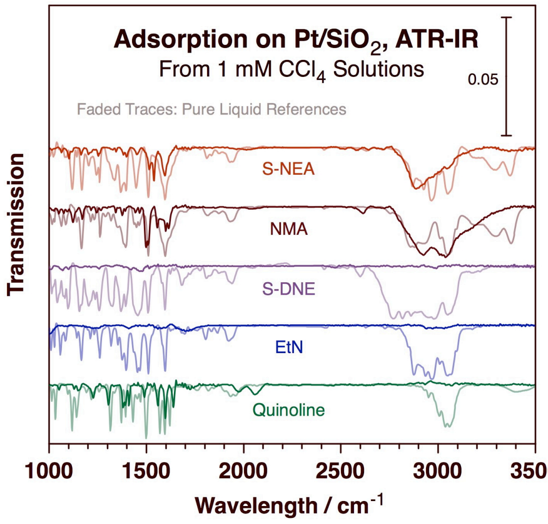

Figure 2. Attenuated total reflection infrared (ATR-IR) absorption spectra for the modifiers in Figure 1, adsorbed from 1 mM CCl_4 solutions onto a commercial 1 wt% Pt/SiO_2 catalyst. The spectra of the pure compounds are provided as faded lines for reference (the scale for those is arbitrary, as the peak intensities depend on the thickness of the films probed).

Figure 2 also shows that the spectra of the adsorbed species are quite different to those of the pure compounds. These differences are explored in more detail for the case of S-NEA in Figure 3, which displays IR absorption spectra for (from bottom to top): (1) pure NEA (acquired in transmission mode); (2 and 3) NEA adsorbed on a Pt(111) single crystal under ultrahigh vacuum (UHV, acquired in single reflection-absorption, or RAIRS, mode), after two exposures: 1.5 L (which leads to a coverage close to monolayer saturation; 1 L = 1 x 10^{-6} Torr s) and 0.5 L (representative of the low-coverage limit);[18] (4) NEA adsorbed from a 1 mM CCl_4 solution on a polished Pt foil[17, 19] (also acquired in RAIRS mode but using a different setup);[20] and (5 and 6) NEA adsorbed from 1 mM CCl_4 solutions on 1 wt% Pt/Al_2O_3 and 1 wt% Pt/SiO_2 commercial catalysts, respectively (acquired in ATR-IR mode).[21] An assignment of the peaks, based on previous studies,[18] is provided in Table 1.

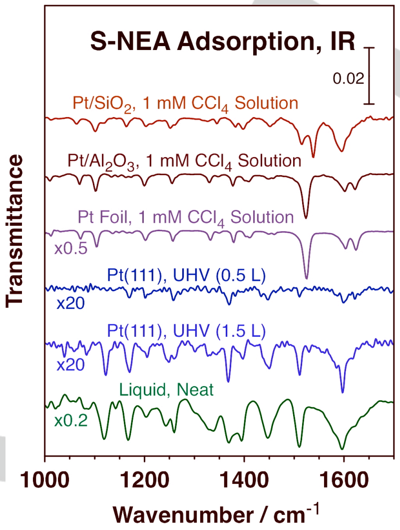

Figure 3. IR absorption spectra of NEA adsorbed on Pt surfaces under different conditions. The trace for pure NEA is provided at the bottom for reference.

The data show that NEA adsorbed from the gas phase (UHV) is mostly undisturbed, as the IR peaks are almost all seen at the same frequencies as in the spectrum of the pure compound.[18] There are some differences in peak relative intensities between the data for the low (0.5 L) and high (1.5 L) coverages, reflecting a change in adsorption geometry, but all of the peak frequencies are well matched between those two traces. The traces for NEA adsorbed from the liquid solutions, on the other hand, display significant changes in both peak positions and peak relative intensities, a fact that highlights the importance of characterizing the adsorption of these chiral modifiers in situ at the solid-liquid interface to better emulate the reaction conditions.[22]

Table 1. Assignment of IR peaks for adsorbed NEA. All values are in cm^{-1}. Relative intensities are given in parenthesis.[a]

Mode[b]	Liquid	Pt(111)	Pt Foil	Pt/Al_2O_3	Pt/SiO_2
$\delta_{oop}(CH)_{ring}$			1103 (s)	1101 (s)	1101 (m)
$\delta_{ip}(CH)_{ring}$	1119 (vs)	1121 (s)			1119 (sh)
$\delta_{oop}(CH)_{ring}$	1167 (vs)	1169 (s)			1163 (m)
$\delta_{ip}(CH)_{ring}$	1204 (m)	1204 (m)	1201 (m)	1200 (m)	1203 (m) 1217 (sh)
$\delta_{ip}(CH)_{ring}$	1240 (s) 1260 (s)	1260 (m)	1257 (m)	1256 (m)	1252 (w) 1263 (sh)
$\delta(CH)_{amine}$	1327 (sh) 1339 (m)	1327 (w) 1342 (m)	1333 (m)	1331 (m)	1325 (w) 1344 (m)
$\delta_s(CH_3)_{amine}$	1367 (s)	1369 (vs)	1379 (m)	1377 (m)	1381 (m)
$\nu_{ip}(CC)_{ring,\ s}$	1395 (s)	1396 (m)	1401 (sh) 1412 (m)	1400 (sh) 1408 (m)	1398 (m)
$\delta_a(CH_3)_{amine}$	1445 (vs)	1446 (s)	1448 (w) 1460 (w)	1447 (w) 1458 (w)	1450 (m) 1461 (sh)
$\nu_{ip}(CC)_{ring,\ l}$	1510 (vs)	1511 (vs)	1526 (vs)	1524 (vs)	1514 (s) 1539 (vs)
$\nu_{ip}(CC)_{ring,\ s}$	1595 (vs)	1597 (vs)	1602 (s) 1624 (s)	1601 (s), 1622 (s)	1595 (vs) 1610 (sh)

[a] vs = very strong; s = strong; m = medium; w = weak; sh = shoulder.

[b] δ = deformation; ν = stretching; ip = in plane; oop = out of plane, s = symmetric; a = asymmetric.

First, it is clear that, in all the spectra for NEA adsorbed from solution, the dominant peak is that around 1500 cm^{-1}, corresponding to an in-plane deformation of the aromatic ring along the long molecular axis. In addition, the corresponding peaks due to the in-plane ring deformation along the short axis, those around 1600 cm^{-1}, display lower relative intensities than in the neat liquid or when adsorbed under UHV. The blue shifts of both peaks suggest an additional interaction with the solvent (or a chemical transformation, see below), and the peak split seen

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in some cases indicates intermolecular interactions, as also observed with racemic mixtures.[18, 19]

Second, the peak from the asymmetric deformation of the methyl moiety (1445-1460 cm^{-1}) of the ethylamine group is less intense, in relative terms, than the corresponding symmetric (umbrella) mode at ~1380 cm^{-1}. In addition, the deformation mode of the C–H bond next to the amine group is clearly visible in the spectra of the species adsorbed from solution, at ~1330 cm^{-1}. All together, it is this region of the spectra, which corresponds mostly to vibrations within the ethyl moiety, that shows the most differences in peak position between the species adsorbed from solution and those dosed under UHV. All of this is consistent with a model where NEA, when adsorbing from solution, bonds to the Pt surface via the nitrogen atom and has all of the substituents in the adjacent chiral carbon (the naphthalene and methyl groups and the extra hydrogen) pointing away from the surface.

It may even be that adsorption requires the breaking of one of the N–H bonds. Such dissociative adsorption, which would likely be reversible, may explain why some of the deformation modes of the C–H bonds in the aromatic ring (especially those with an out-of-plane motion) are seen at much lower frequencies than in the free molecule, and also account for the limited uptake on the surface seen with DNE (a tertiary amine with no N–H bonds). In fact, published IR data for the thermal decomposition of N-methylaniline on Pt(111) (under UHV) show that the strong peak for the ring deformation mode around 1530 cm^{-1} shifts toward higher frequencies, as seen here in going from vacuum to the liquid-solid interface, upon dehydrogenation of the amine group.[23] We are at present exploring this possibility in more detail.

The adsorption of NEA from solution onto Pt catalysts has been previously studied with ATR-IR absorption spectroscopy by the Baiker group.[16] In their report, the broadening of the peaks due to the vibrational modes of the naphthalene ring was taken to indicate the interaction of that aromatic moiety with the platinum surface. This is a conclusion different to that reached by us. It should be said, however, that ATR-IR is not intrinsically a surface-sensitive technique; the fact that the position of most of the peaks seen in Baiker's data match those for NEA in solution suggests that their ATR-IR spectra may correspond to species in solution, not adsorbed on the surface. As mentioned above, that possibility was ruled out in our work by carrying out blank experiments without the catalyst and with the pure solid support, without Pt. We have also attempted to study the adsorption of NEA from toluene (rather than CCl_4) solutions, as was done in the Baiker's case, but were unsuccessful: the high solubility of NEA in toluene leads to very low steady-state coverages of adsorbed NEA on the Pt surface.[24]

The activity and enantioselectivity of the chirally-modified Pt/Al_2O_3 catalysts were also tested for the hydrogenation of EtPy (the Orito reaction in Figure 1). Table 2 summarizes the kinetic data obtained with all of the modifiers in Figure 1 plus the four most common cinchona alkaloids used in this reaction (quinine, quinidine, cinchonine, and cinchonidine). An enhancement in activity is seen with all the cinchona alkaloids, as reported in the past,[25-27] and also with NMA and S-DNE, but not with quinoline, EtN, or NEA. In addition, none of the non-chiral modifiers (quinoline, EtN, or NMA) add enantioselectivity to the catalyst, as expected. However, no measurable enantioselective excess (ee) was seen with S-DNE either, even though that modifier is chiral. This is likely because S-DNE, a tertiary amine, does not adsorb on the surface (Figure 2); a similar poor performance was reported with another (pyrrolidine-based) tertiary-amine NEA in the past.[28] On the other hand, both S-NEA and R-NEA (but not the racemic mixture) promote enantioselectivity during the hydrogenation of EtPy, even if not as effectively as the cinchona alkaloids (the reaction conditions were not optimized in this study). There is a clear correlation between the ability of these modifiers to adsorb on the surface of the catalyst and their chiral modification behaviour: bonding through the amine group may be central to their performance in catalysis.

Table 2. Activity (% conversion) and enantioselective excess (% ee) for the hydrogenation of ethyl pyruvate with a 1 wt% Pt/Al_2O_3 catalyst as a function of the modifier used.[a]

Modifier	% Conversion (±1.0)	% ee (±1.0)
No Modifier	15.8	0.2
Quinoline	12.3	0.3
EtN	13.1	0.9
NMA	23.2	0.7
S-DNE	25.8	0.4
S-NEA	12.3	24.4 (S)
R-NEA	12.5	29.0 (R)
Rac-NEA	10.5	0.2
Quinine	54.5	68.5 (R)
Quinidine	68.8	62.5 (S)
Cinchonine	24.5	56.6 (S)
Cinchonidine	25.9	61.3 (R)

[a] Reaction conditions: t = 20 min, T = 300 K, $P(H_2)$ = 1 bar, 50 mg catalyst, 0.85 µmol modifier, Pt:Modifier:EtPy molar ratio = 3:1:750, Solvent: 6 mL acetic acid.

Experimental Section

The IR absorption spectra were obtained using a Tensor 27 Bruker Fourier-Transform infrared spectrometer (FTIR) and a commercial multiple-bounce attenuated total reflection (ATR) accessory purchased from Pike Technologies and equipped with a 60-mm long Ge prism. 3 mg of the catalyst, either a 1 wt% Pt/Al_2O_3 (Alfa Aesar) or a 1 wt% Pt/SiO_2 (Sigma-Aldrich) solid, were dispersed on the surface of the prism, and the ATR cell filled with the pure solvent (CCl_4, Sigma-Aldrich, 99.9% purity). The catalysts were preconditioned by bubbling H_2 gas (Liquid Carbonic, 99.995% purity) for 60 min, after which a background IR scan was taken. The cell was flushed with a 1 mM CCl_4 solution of the modifier (quinoline, >97% purity; EtN, >99% purity; S-DNE, 97% purity; NMA, 97% purity, S-NEA, >99% purity; all from Sigma-Aldrich), and spectra were taken periodically until reaching surface saturation (~ 2 h). The cell was then flushed with pure solvent, and another spectrum acquired to differentiate between weakly- and strongly-bonded adsorbates. The spectra were acquired by adding 256 scans taken with 4 cm^{-1} resolution, and were ratioed against the reference spectrum recorded at the start of the experiment.

For the catalytic measurements, the catalyst was first preconditioned via sequential treatments in Ar at room temperature for 90 min, O_2 at 300°C for 120 min, and H_2 at 350°C for 120 min, after which it was cooled down under a H_2 atmosphere and transferred to a two-necked flask and mixed with the solvent (acetic acid, >99.7% purity, Sigma-Aldrich). Solutions of the modifier and the reactant (EtPy, 98% purity, Sigma-Aldrich) were added while bubbling H_2 and stirring continuously using a magnetic bar. Small aliquots of the solution were taken periodically and analysed by gas chromatography using a chiral column (DB-WAX, Agilent).

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Keywords: Enantioselectivity • Chiral Modifier • Structure-Activity Relationships • IR Spectroscopy • Adsorption

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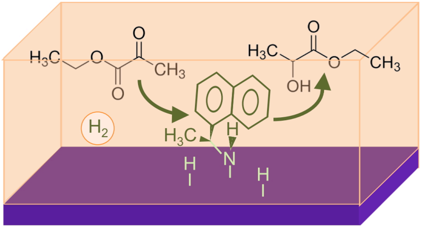
COMMUNICATION

Chiral modification of Pt hydrogenation catalysts by 1-(1-naphthyl)-ethylamine (NEA) requires adsorption via the amine nitrogen atom, not bonding through the aromatic ring as widely believed. The ability to adsorb requires NH_2 groups, as determined by studying a family of related compounds using in-situ infrared absorption spectroscopy, and correlates with the enantioselectivity of the catalyst.



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