Chiral Amplification

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Changes in the Enantiomeric Composition of Chiral Mixtures Upon Adsorption on a Non-Chiral Surface

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Abstract: *The adsorption of propylene oxide, a chiral molecule, on a Pt(111) single-crystal surface was studied as a function of enantiomeric composition by temperature programmed desorption (TPD) and molecular beams. Two opposing trends were observed leading to variations in the enantiomeric excess (ee) of the chemisorbed layers with respect to the composition of the gas-phase mixtures: a kinetic effect dominant during the initial uptake, with a preference toward the formation of enantiopure layers, and a steady-state effect seen after approximately monolayer half-saturation, at which point the preference is toward racemization. These effects may account for important phenomena such as the bias toward one chirality in biological systems and the selective crystallization of some chiral compounds, and may also be used in practical applications for chemical separations and catalysis.*

When molecules contain at least one carbon atom coordinated to four different moieties, they can exist in two chemically identical but non-superimposable mirror-image forms. The two so-called enantiomers, denoted S and R, are said to be chiral, a property that is critical in the synthesis of pharmaceuticals and other biological applications because life on earth has, for reasons not fully understood to date, chosen to operate exclusively with one type of chirality.[1,2] There is an ongoing quest to find efficient ways to produce enantiopure compounds in order to avoid complex enantiopurification steps.

Efficient chiral and green chemical synthesis may be achieved by using enantioselective heterogeneous catalysts. However, that requires a better understanding of the details of the adsorption of chiral molecules on solid surfaces.[3–7] A number of surface-science experiments have shown that the enantiocomposition of the adsorbed layers of chiral compounds may vary relative to those in the gas or liquid phases. In particular, Yu and Gellman have recently shown that the enantiomeric excess (*ee*) of chiral mixtures of aspartic acid can be amplified upon adsorption on achiral Cu(111) surfaces.[8] We have also shown that the *ee* of surface layers of chiral compounds can be amplified by adding non-chiral adsorbates.[9]

In this study, we report interesting variations in enantiocomposition induced by adsorption of enantio mixtures of propylene oxide (PO) on a Pt(111) single-crystal surface. The coverages of the adsorbates have been determined by quantifying the yields from temperature programmed desorption (TPD) experiments, as done in the past by us and others.[10–17] The two enantiomers of PO were differentiated by using isotope labeling, mixing regular PO-d_0 with either PO-d_2 or PO-d_6. Typical data on the enantiocomposition of the adsorbates as a function of the extent of exposure of the surface to the PO gas mixture are shown in Figure 1, in this case for a 1:1 mixture of R-PO-d_0 (denoted as R-PO in the figures) + Racemic-PO-d_6 (a 1:1 mixture of the *S* and *R* enantiomers, denoted as Rac-PO-d_6) and a surface temperature of 160 K. Representative TPD traces from which these data were extracted are provided in Figure S1 of the Supporting Information.

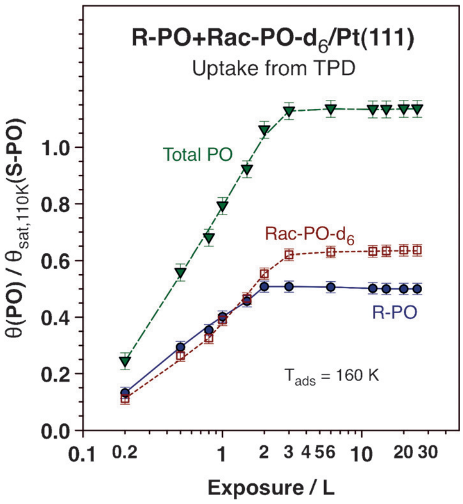

Figure 1. Enantiocomposition of the adsorbed PO layers that build up on a Pt(111) single-crystal surface upon exposure to increasing doses of a 1:1 mixture of R-PO-d_0 + Racemic-PO-d_6, as determined from the molecular desorption yields in TPD experiments. A preference for the uptake of the enantiopure R-PO is seen in the initial stages, but a reversal toward selective adsorption of the racemic mixture is observed after monolayer saturation.

Two opposing trends are observed in the uptake curves reported in Figure 1. In the initial dosing stages there is a clear bias toward the adsorption of the enantiopure R-PO-d_0. This behavior has been reported by us before, and explained by a kinetic effect that relies on adsorbate-assisted adsorption with different probabilities for homo- versus hetero-enantiomeric pairs.[18,19] The interesting new observation here is that

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such preference is reverted at doses of between 1 and 2 L (1 L = 1×10^{-6} torr s), after which the adsorption of Rac-PO-d_6 is clearly preferred. The final saturated monolayer in this case consists of approximately 44 % R-PO-d_0 and 56 % Rac-PO-d_6.

Because heavy isotopes were used in these experiments to differentiate among the various enantiomeric mixtures, the ≈12 % difference between the R-PO-d_0 and Rac-PO-d_6 coverages reported above could in principle be explained by isotope effects affecting the relative adsorption equilibrium constants. To evaluate the extent of this effect, independent experiments were carried out with 1:1 mixtures made out of S-PO-d_0 + S-PO-d_2, S-PO-d_0 + R-PO-d_2, and Rac-PO-d_0 + Rac-PO-d_6. The results, reported in Figures S2, S3, and S4 of the Supporting Information, point to deviations in PO uptake due to this isotope effect of only between 2 and 4 % (± 1 %), much less than the difference reported in Figure 1. Clearly, there is a true enantioselectivity in the adsorption of chiral mixtures on the platinum surface, with a bias towards racemization at high surface coverages.

An independent way to evaluate these enantiobiases in adsorption is by measuring sticking coefficients using molecular beams, in an approach initially advanced by King and Wells.[20,21] The results obtained for the uptake of the same R-PO-d_0 + Rac-PO-d_6 mixture used in Figure 1, extracted from the raw data shown in Figure S5 (Supporting Information), are reported in Figure 2, and information from experiments with other PO-d_0 + PO-d_6 mixtures are provided in Figure S6 (Supporting Information). Particularly noteworthy in Figure 2 is the crossing of the two curves, for R-PO-d_0 and Rac-PO-d_6, at the point of approximately half saturation: in the initial stages the sticking probability of the enantiopure R-PO-d_0 component is higher than that of Rac-PO-d_6, but at higher exposures the opposite becomes true. In the end, the final coverage of Rac-PO-d_6 exceeds that of R-PO-d_0 by the same ≈12 % estimated before. It should be noted that the sticking coefficient data in Figure 2 is plotted against the coverage of each individual PO isotopomer. Sticking is in fact expected to be affected by the total coverage of PO on the surface, not only those of the individual isotopomers, but the same trends are seen if the data are reported that way (Figure S7 in Supporting Information). We also recorded post-mortem TPDs after the molecular beam experiments to obtain a third set of corroborating data (not shown); the coverages estimated this way agree well with those from the studies in Figure 1 and Figure 2.

The results reported here can be used to estimate the changes in *ee* in the saturated adsorbed layers relative to the gas-phase mixtures. For that, additional experiments were carried out with 1:2 and 2:1 S-PO-d_0 + Rac-PO-d_6 mixtures. The uptake data from the TPD traces and the sticking coefficient versus coverage curves extracted from the molecular beam runs are reported in Figures S8 and S9 of the Supporting Information, respectively, and a plot of the final ee's on the surface versus the ee's in the gas-phase, derived from the TPD and beam data, is shown in Figure 3. The main conclusion is that, under steady-state adsorption-desorption conditions, the saturated monolayers of propylene oxide on the Pt(111) surface reach enantiocompositions closer to racemic than those of the gas-phase mixtures. In fact, in the uptake curves, Figures S2 and S8, it is clearly seen that the enantiopure component is displaced by the racemic mixture after reaching monolayer saturation (displacement of PO adsorbates by incoming PO molecules from the gas phase is only possible at that point).[9] It should be indicated that in these calculations it was assumed that there is no preference in the displacement of one PO enantiomer over the other. Consequently, the deviations from the expected *ee*'s shown in Figure 3 represent a lower bound of the true values: if such preference were to exist (something that we cannot determine

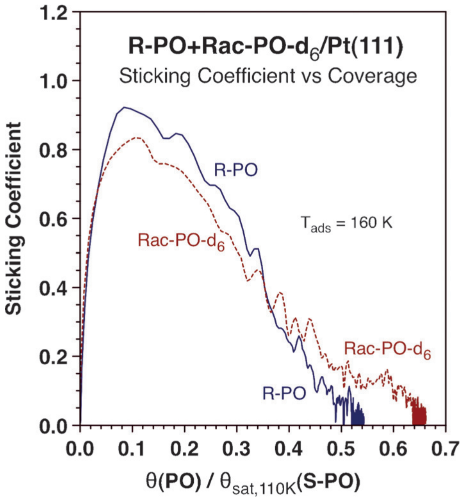

Figure 2. Apparent sticking coefficient versus coverage, measured by using the King and Wells method, for the uptake of a 1:1 R-PO-d_0 + Rac-PO-d_6 mixture on Pt(111) at 160 K. The same switch in adsorption preference from enantiopure at low coverages to racemic above monolayer half-saturation reported in Figure 1 is seen here as well.

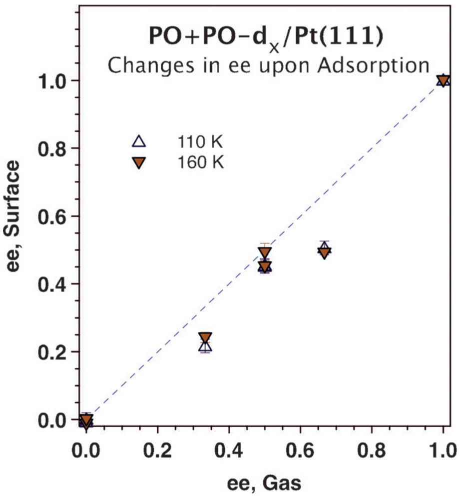

Figure 3. Enantioselective excess (*ee*) of the final saturated PO layers, calculated from both TPD and molecular beam data, as a function of the *ee* of the PO gas mixture used. Data are shown for two surface temperatures, 110 K (open up-pointing triangles) and 160 K (solid down-pointing triangles). In all cases, a deviation in composition is seen on the surface relative to the gas phase towards a more racemic mixture.

with the available data), the surface *ee*'s would deviate from the gas-phase *ee*'s to a greater extent, toward lower values (to even more racemic-like monolayers).

In conclusion, we have demonstrated that, for the case of the adsorption of propylene oxide on Pt(111) surfaces, two opposing effects lead to variations in the enantiomeric composition of the adsorbed layer compared to that of the gas-phase mixture. The early effect is kinetic in nature, and favors adsorption of enantiopure layers. However, after higher exposures, the surface enantiocomposition reverses, and under steady-state conditions the monolayer is closer to racemic than the gas. This latter effect, which may be driven by thermodynamics, goes in the opposite direction to that reported recently by Yu and Gellman for aspartic acid on Cu(111).[8] More work is needed to fully explain this discrepancy, but it is worth pointing out that aminoacids can exhibit strong intermolecular interactions, via hydrogen bonding for instance, and consequently tend to arrange in ordered suprastructures on surfaces.[22–26] The intermolecular forces among PO adsorbates are weak, and that seems to lead to the formation of disordered layers instead.[18] It may also help that the studies with aminoacids have been carried out primarily on the weakly-interacting surfaces of coinage metals, whereas our work was performed on a more active platinum substrate.

One other puzzling aspect of the results reported here is that the deviations in the steady-state enantiocomposition of the adsorbed layers are not particularly large. If specific differences in intermolecular interactions between homo- and hetero-enantiomer pairs were to play a role in this phenomenon, the thermodynamic end result may be expected to be the formation of racemic adsorbed layers in all cases regardless of the composition of the gas used. One possible explanation for why that does not happen is that the absolute density of the monolayers that form on the Pt surface increases slightly after large exposures and/or if the uptake is done at higher temperatures. It may be that the displacement of adsorbed molecules is only possible if there are empty adsorption sites still available to initiate the molecular exchange, as is the case in the initially disordered saturation monolayer, but that the displacement stops once all openings are blocked, as the monolayers become more closely packed. However, the results from experiments carried out at two surface temperatures, 110 and 160 K (the latter being quite close to the onset for molecular desorption, see TPDs in Figure S1) did not indicate large differences in the final *ee*'s. A better understanding of the forces driving the racemization of these monolayers is needed to explain its limited extent.

The two effects reported here may have significant practical implications for the design of chiral adsorption, separation, and catalysis processes, since the direction of the variations in enantiocomposition on adsorbates, toward either enantio-amplification or racemization, may be controlled by choosing to operate under processing conditions limited by kinetics versus thermodynamics. In fact, non-linear phenomena in chiral heterogeneous catalysis have been already reported in the past.[27] The insight reported here may also be relevant to explain enantioselective crystallizations,[28,29] and perhaps even the processes that led to the homochirality of life on Earth.[1,2]

Experimental Section

The experiments described here were carried out in an ultrahigh vacuum (UHV) instrument equipped with a mass spectrometer for gas analysis, an effusive molecular beam setup, and an ion gun for sample cleaning. A Pt single crystal cut and polished in the (111) direction was used as the surface for the adsorption experiments. More details are provided in previous publications.[18,30] The racemic propylene oxide-d_6 gas (Sigma Aldrich, 99 % purity, 98 D atom %) was dosed as supplied, whereas the liquid R-, S-, and Rac-PO-d_0 (Sigma Aldrich 99 % purity) were subjected to freeze-pump-thaw cycles for purification before use. The R-, S-, and Rac-PO-d_2 were made in house by a two-step synthesis adapted from the literature:[31] the corresponding S-, R-, or Rac-2-chloropropanoic acid (Sigma Aldrich, 99 % purity) was first reduced with $LiAlD_4$ in diethyl ether, and the resulting 2-chloropropan-1,1-d_2-1-ol distilled out of the reaction mixture and reacted with a KOH aqueous solution to produce the final PO-1,1-d_2. The product was collected in a vacuum trap and distilled, and its identity, purity, and isotope positioning evaluated using ^{1}H NMR.

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