used to break the capillary and discharge its contents into the evacuated cell. The spectrum was scanned at 2 cm^{-1} resolution, and absorbances were recorded at the following frequencies (cm^{-1}): 3016 (CH_4), 2360 (CO_2), 2214 (N_2O), 2173, 2169 (CO), 713 (HCN). Peaks due to unreacted nitromethane were not recorded. Calibration plots obtained by spectral analysis of known amounts of each gas were used for quantitation. At densities above 0.10 g/cm^3 the only significant carbon-containing products were CO_2 and HCN. For the purpose of calculating rate constants, it was assumed that the sum of the number of moles of CO_2 and HCN is equal to the number of moles of CH_3NO_2 consumed.

Semiquantitative Analysis by GC/MS. Partially reacted sample tubes were broken on the inside of a closely fitting external tube which was closed at one end and fitted with a hypodermic needle at the other. The gases passed directly into the inlet port of the GC/MS instrument. In addition to unreacted nitromethane and the products identified by FTIR we found H_2O, N_2, and a trace of $(CN)_2$. No products boiling higher than nitromethane were found.

Measurement of Reaction Rates in Solution at a Known Pressure. Method A. Benzene and acetonitrile were chosen as solvents because they are stable under the reaction conditions and show no evidence of reaction with nitromethane or its degradation products except under low-density homolytic conditions as noted above. Another criterion which becomes crucial in connection with method B is that accurate PVT data for benzene[15] and acetonitrile[16] have been reported. The solutions contained 20% by volume of nitromethane. Approximately 30 μL of solution was placed in a 2-mm melting point capillary which had a flared opening. A 3-mm length of PTFE "spaghetti" was pressed into the mouth, and a tapered glass fiber was inserted in the central hole of the "spaghetti" to expand it snugly against the glass wall of the capillary. This formed a piston to transmit pressure from an external fluid (heptane) to the reaction mixture. The pressure vessel was a 15-cm length of $^1/_4$ in. stainless steel pressure tubing of 2.5 mm i.d. which had a standard high-pressure coned fitting at one end and a miniature conical plug seated by a 10–32 screw at the other end. The glass capillary containing the sample was placed in the pressure vessel which was then closed and pressurized by a hand operated pump. The heater was an aluminum block equipped for controlled heating to 400 °C as previously described. It could be moved vertically on a rail in order to lower it onto the pressure vessel which entered a close-fitting blind hole in the heating block. Thermal equilibration was attained in about 1 min, and reaction times were usually longer than 20 min. At the end of the reaction period the heater was withdrawn upward and the heater was rapidly quenched. Pressure was maintained while the reactor was cooled to −70 °C in order to minimize problems due to the dissolved gases which would frequently expel the piston after removal of the glass capillary. The reaction mixture was analyzed by capillary GC using a flame ionization detector. The solvent was used as an internal standard for determining the fraction of unreacted nitromethane. An acceptably small quantity of heptane pressurizing fluid was usually also present.

Method B. Since the conditions are severe even for PTFE and since leakage during the reaction was not completely suppressed and since dissolved gases created problems in handling, we explored the possibility of using sealed glass containers. Knowledge of the density makes it possible to determine the pressure from PVT data which are available for several suitable solvents. By themselves the capillaries will not withstand the highest pressures needed (130 MPa), but external pressurization enables them to do so. Sealed melting point capillaries rarely implode under an excess external pressure of 100 MPa. With the data of ref 16 we determined the pressures of acetonitrile solutions of nitromethane from the measured ullages at room conditions and compared reaction rates with those obtained from the moving piston device at the same pressures. This empirical validation was considered necessary because otherwise we would be forced to rely on the accuracy of the PVT data and would face uncertainties arising from the effect of the solute on the PVT relations as well as corrections for thermal expansion and mechanical deformation of the capillary. Figure 2 presents results obtained by method A and method B on a single graph and gives us confidence that the pressures derived from PVT data are reliable.

Experimental Errors. The digital display for the platinum resistance thermometer was checked by an absolute measurement of resistance by use of the freezing point of lead. Temperatures appear to be reliable to 1°. The activation energy, 170 kJ, for neat nitromethane at $d = 0.60$ is uncertain by about 8 kJ on the basis of temperature measurement and another 8 kJ on the basis of reproducibility of rates. The reproducibility of analyses by capillary GC is within 3% and by FTIR within 5%. The error in rate could possibly amount to 10%. Inspection of Figures 1 and 2 is probably the best basis for judging the reliability of the measurements. In determining activation volumes, it is fortunate that no error results from a constant multiplicative error in rates such as might be caused by an error in temperature or calibration of the FTIR and GC analyses. We would not be greatly surprised if a redetermination of activation volume in an independent laboratory were to give a value as high as −70 mL or as low as −100 mL. No change in interpretation would be required.

Acknowledgment. This work was supported by the Center for Explosive Technology Research at the New Mexico Institute of Mining and Research.

Registry No. CH_3NO_2, 75-52-5; D_2, 7782-39-0.

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Reactions of Weak Carbon Acids under Phase Transfer Catalysis Conditions: Oxidations and Hydrogen–Deuterium Exchange

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Received December 11, 1987

The hydrogen–deuterium exchange of very weak carbon acids ($pK_a \leq 38$) under extractive phase transfer catalysis (PTC) conditions is reported. Benzylic hydrogens, hydrogens of several heterocyclic systems [benzo[*b*]furan (**8**), benzo[*b*]thiophene (**9**), thiophene (**10**)], and aromatic hydrogens in di- and trihalobenzene derivatives could easily be exchanged. The reaction was performed in the presence of $(Bu)_4N^+HSO_4^-$ as the PTC catalyst and $NaOD/D_2O$, 60% w/w, as base and the deuterium source. A quantitative autoxidation reaction was performed on benzylic carbons in the presence of air. Of special significance is the nature of the PTC catalyst. The importance of the catalyst counteranion is emphasized.

Phase-transfer catalysis (PTC) has proved itself as a method of choice in a very wide scope of chemical reactions in various areas.[1] Of special significance is the hydroxide ion transfer process, which permits the application of

Table I. H/D Exchange of Benzylic Hydrogens[a,b]

substrate	pK_a[c]	% deuterium exchange 1 h	3 h	20 h	yield, %
xanthene (**1**)	27–30[d,e]	76	80	84	85
thioxanthene (**2**)	28.3[f]	69	79	84	93
diphenylmethane (**3**)	33.4[g]	68	73	84	85
dibenzosuberane (**4**)	31.2[g]	84	84	88	75
dibenzosuberene (**5**)		72	75	75	85
dibenzosuberone (**6**)		75		77	95
benzyl phenyl sulfide[h] (**7**)	30.8[e]			81	82

[a] Substrate (1.5 mmol), 0.3 mmol of $(Bu)_4N^+HSO_4^-$, 2:1 molar ratio of 60% $NaOD/D_2O$. [b] One run, percentage of exchanged benzylic hydrogens as derived from ^1H NMR. [c] Reference 14. [d] Reference 15. [e] Reference 16. [f] Reference 17. [g] Reference 18. [h] For reaction conditions, see Experimental Section.

simple and inexpensive bases, e.g., sodium and potassium hydroxide, in many base-catalyzed reactions.[2] Although this technique has been widely applied, there is still a limitation of the acidity of the substrate. Until very recently, the base-catalyzed PTC reactions were applicable only for substrates in the pK_a range of ca. 25.[2]

We were guided by the assumption that under the extraction conditions one should be able to extract into the depth of the organic phase "bare" hydroxide ions. Due to their limited hydration sphere,[3,4] these ions will manifest a much stronger basicity than that obtained in aqueous media. This goal can be achieved when an extraction PTC process is performed. We have previously demonstrated the applicability of this hypothesis,[5] which is also supported by an independent study of the comparison of the reactivity of various anions under PTC conditions[6] and recently by studies on the reactivity of OH^- in low-polarity media.[4,7] The application of the extraction-mechanism conditions involves the presence of an organophilic catalyst, hydrophilic counterion (HSO_4^-), and a high hydroxide concentration in the aqueous phase. Under these conditions, deuterium exchange processes of extremely weak carbon acids (pK_a = 38) as well as base-catalyzed air oxidations could be performed. The choice of catalyst is of utmost importance in these two classes of reactions. From a study of a wide variety of catalysts, it became obvious that only HSO_4^- as counteranion of the PTC catalyst gave positive results.

Results and Discussion

I. H/D Exchange. Hydrogen–deuterium exchange processes of weak carbon acids were carried out with tetrabutylammonium hydrogen sulfate [$(Bu)_4N^+HSO_4^-$] as catalyst and the pasty mixture of $NaOD/D_2O$ (60% w/w) as the base as well as the deuterium source. Such an exchange process under PTC conditions has been carried out in the past on a limited number of substrates in the pK_a range of <30.[8-12] We have also recently demonstrated that substituted toluenes undergo a deuterium exchange at the methyl group hydrogens.[5] The application of this process to a wider range of substrate families is reported here in order to demonstrate the generality of the approach. The simplicity of the method and the easily accessible deuterium source ($NaOD/D_2O$) render the method advantageous over other methods available for this process.[13] In selected examples studied, a repetition of the exchange process afforded a proportional increase in the degree of H/D exchange (vide infra).

Chart I

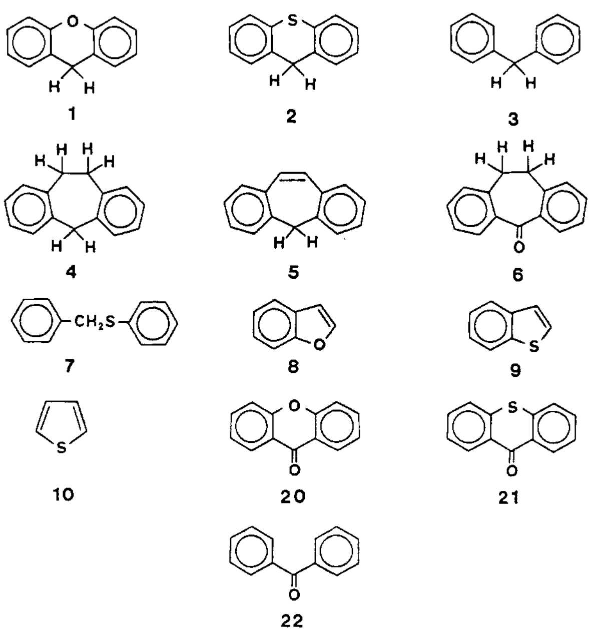

Table II. H/D Exchange in Heterocyclic Compounds[a,b]

substrate	pK_a	position	% deuteration
benzo[*b*]furan (**8**)	36.8	H-1	88
		H-2	52
benzo[*b*]thiophene (**9**)	37	H-1	76
		H-2	26
thiophene (**10**)	38.4	H-1	91
		H-2	12

[a] For reaction conditions, see Experimental Section. [b] One run, percentage of H/D exchange as derived from ^1H NMR.

a. Benzylic (Methylene) Hydrogens. Benzylic hydrogens were exchanged in hydrocarbon substrates and in substrates that contain hetero atoms, e.g., oxygen and sulfur. The results are presented in Table I. It can be seen that most of the exchange occurs during the first hour of reaction. The reactions are carried out under argon as oxidation products may be formed in the presence of oxygen (air) (vide infra). When more than one hydrogen can be exchanged, the ratio between singly exchanged and higher exchanged species is obtained from the mass spectrum at low energy (13–20 eV, see supplementary material). A variety of PTC catalysts have been explored. The catalysts that were operative in the H/D exchange

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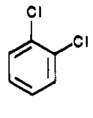
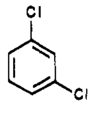
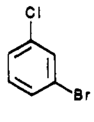
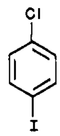
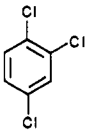
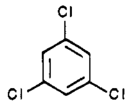
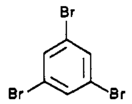
Table III. H/D Exchange of Aromatic Hydrogens of Halobenzene Derivatives[a]

									
	11	12	13	14	15	16	17	18	19
% deuteriation[b,c]	30 (72)	41 (63)	33 (77)	79 (73)	79 (76)	76 (78)	82 (72)	81 (73)	79 (75)

[a] Substrate (2 mmol), 0.4 mmol of $(Bu)_4N^+HSO_4^-$, 2:1 molar ratio of 60% $NaOD/D_2O$ to active aromatic hydrogens, 1 cm^3 of hexane, 20 h, room temperature. [b] One run, percentage of exchange of aromatic hydrogens as derived from ^1H NMR. [c] Chemical yield in parentheses.

process of diphenylmethane (DPM) (**3**) (Chart I) in good yields were $(Bu)_4N^+HSO_4^-$ and $Me(Oct)_3N^+HSO_4^-$. Other catalysts, e.g., $(Bu)_4N^+Br^-$, $(Bu)_4P^+Br^-$, $(Bu)_4N^+I^-$, $(Hex)_4N^+Br^-$, $(Oct)_4N^+Br^-$, $(Et)_4N^+HSO_4^-$, $(Et)_4N^+Cl^-$, and 15-crown-5, afforded negligible yields (<5%). The extent of exchange is deduced mainly from the ^1H NMR spectrum. The aromatic protons served as an internal standard for the benzylic protons. Mass spectroscopic measurements and ^{13}C NMR studies assisted the assignments and the estimation of the degree of exchange.

b. Heterocyclic Systems. A further step toward the estimation of the scope and limitations of the method was the study of the exchange process of the ring protons of furan and thiophene derivatives. These protons possess pK_a values ranging from 36 to 38 as follows:[19] benzo[*b*]furan (**8**) (pK_a = 36.8); benzo[*b*]thiophene (**9**) (pK_a = 37); and thiophene (**10**) (pK_a = 38.4). The results are shown in Table II. The protons that are exchanged are at the α and β positions (H-1 and H-2). The exchange process of benzo[*b*]furan (**8**) was analyzed by the comparison of the ^1H NMR band area (at 200 MHz) of the five membered ring protons with the benzo ring protons. It can be seen in the ^{13}C NMR spectrum that the carbon atom that appears at 146.5 ppm (C-1) is split by the deuterium to a triplet and is shifted to high field. The extent of the H/D exchange of benzo[*b*]thiophene (**9**) in the α and β positions (H-1 and H-2 respectively) was deduced from their ^1H NMR spectrum (200 MHz), relative to H-4 and H-7, which do not undergo exchange. The extent of the exchange of the β-hydrogens was obtained from the relative decrease of the band areas at 7.28–7.37 ppm, which include three protons (one β-hydrogen and two aromatic protons). This decrease was attributed to an exchange of the β-hydrogens only. The proton spectrum was in line with the literature data.[20] The assignment of the carbon spectra did not agree with the literature assignment.[21] This literature assignment was also not in line with the proton spectrum. The α-carbon atom which appears at 126.89 ppm is split to a triplet centered at 126.69 ppm (J = 28.2 Hz). The β-carbon (to sulfur) is covered by other bands, but some splitting could still be observed. The parent system, viz., thiophene (**10**), was also studied, but due to its volatility, the H/D exchange was studied only in solution, and the extent of the exchange was obtained from the relative band areas as compared with the mesitylene aromatic band, which served both as an internal standard and solvent. The exchanged products show a high-field shift of the band of the α-hydrogens which appears as a triplet while the β-hydrogens appear as a singlet. In the carbon spectrum it is deduced that the α-protons were exchanged, as the proton-decoupled band of the α-carbon appears as a triplet due to its coupling to a deuterium.

Table IV. H/D Exchange: Comparison between First and Second Rounds

substrate	% deuteriation first round	% deuteriation second round
benzyl phenyl sulfide (**7**)	81	95
benzo[*b*]thiophene (**9**) H-1	76	91
benzo[*b*]thiophene (**9**) H-2	26	46
4-bromochlorobenzene (**15**)	79	>90
1,3,5-trichlorobenzene (**18**)	81	95
1,3,5-tribromobenzene (**19**)	79	90

c. Aromatic Hydrogens of Halobenzene Derivatives. Aromatic hydrogens are known to undergo exchange under acidic conditions.[22] Employment of this reaction under basic conditions requires extremely strong bases in aprotic media.[23] In Table III it is demonstrated that a high yield of exchange (ca. 80%) is obtained in some aromatic systems which contain two or three halogen atoms. There is no significant effect of the halogen whether it is chlorine, bromine, or iodine. However, in disubstituted benzenes, the relative position of the halogens is important. Only the para-disubstituted benzenes afford high yields (Table III). Ortho- and meta-substituted dihalobenzenes undergo the reaction in yields around 30%. In all experiments when no catalyst was applied, the yields were less than 2%. Here again the degree of exchange is deduced from ^1H NMR relative to an internal standard (hexamethylbenzene). That an exchange has occurred at all can be deduced from ^{13}C NMR spectroscopy. The carbon whose hydrogen was exchanged shows a band split to a triplet or to an even more complex pattern according to the degree of exchange.

Hydrogen atoms located between two halogen atoms are exchanged prior to other hydrogens in the molecule. This phenomenon can be rationalized by a higher acidity of such protons. When an exchange of 80% of the hydrogens of a dihalobenzene derivative (as deduced from ^1H NMR) is achieved, it does not necessarily mean that three hydrogens were exchanged. In such cases we could see from the carbon spectra that a mixture of species of variable degrees of exchange is present. Mass spectroscopy has been ap-

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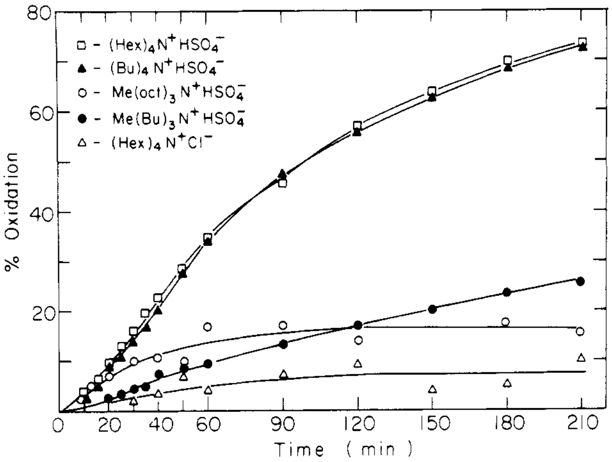

Figure 1. The influence of the nature of the PTC catalyst on the progress of the autoxidation of diphenylmethane (DPM). Reaction conditions: 9.6 mmol of DPM, 1 mmol of PTC catalyst, 3.2 g of 50% NaOH, 10 cm^3 of toluene, air, 25 ± 1 °C.

Table V. Autoxidation of Benzylic Hydrogens[a]

substrate	conversion[b] $^1/_2$ h	1 h	2 h	product
xanthene (**1**)	85	95	99	xanthone (**20**)
thioxanthene (**2**)	95	100		thioxanthone (**21**)
diphenylmethane (**3**)	45	68	91	benzophenone (**22**)

[a] Substrate (1.5 mmol), 0.3 mmol of $(Bu)_4N^+HSO_4^-$, 450 mg of 50% NaOH, 1.5 cm^3 of benzene, air, room temperature. [b] One run, conversion of the oxidation product as derived from 200-MHz ^1H NMR.

plied to further confirm the exchange process. In all cases studied, a second run afforded high yields as shown in Table IV.

II. Oxidation Reactions at Benzylic Carbons. Base catalyzed oxidation reactions under PTC conditions have been known to take place with carbon acids of relatively high acidity.[24-27] These reactions were performed with oxygen under pressure and very often at temperatures of 40–50 °C. Weak carbon acids were reacted with oxygen in polyethylene glycol (PEG) catalysis, under oxygen pressure, in the presence of potassium *tert*-butoxide as base.[28] In these reactions, only PEG 6000 gave good results (67% conversion) while $(Bu)_4N^+Br^-$ afforded less than 1% conversion. The oxidation under PTC conditions of weak carbon acids seems preferable as it avoids the application of strong and expensive bases and aprotic polar solvents, e.g., DMSO[29] and DPSO.[30] The application of PTC conditions by using quaternary ammonium salts for oxidation reactions seemed attractive. We find that the oxidation under these conditions can easily be performed with $(Bu)_4N^+HSO_4^-$ as catalyst, NaOH as base (50% solution), and molecular oxygen as oxidant. Table V shows that quantitative yields can be obtained at room temperature when the reaction is run by contact with air for short periods of time. When the reaction is performed under the same conditions in the absence of the PTC catalyst, the yields are negligible. The catalyst plays a very important role in this reaction as demonstrated in Figure 1.

Table VI. Effect of the Catalyst, Substrate, and Oxygen Concentration on k_{obsd} in the Autoxidation of Diphenylmethane (DPM)

variable[a]	k_{obsd}
10 mol% $(Bu)_4N^+HSO_4^-$ [b]	9.95×10^{-5} M s^{-1}
7.5 mol% $(Bu)_4N^+HSO_4^-$	6.98×10^{-5} M s^{-1}
5 mol% $(Bu)_4N^+HSO_4^-$	4.88×10^{-5} M s^{-1}
4.8 mmol of DPM	9.20×10^{-5} M s^{-1}
2.4 mmol of DPM	9.20×10^{-5} M s^{-1}
oxygen atmosphere	16.82×10^{-5} M s^{-1}

[a] Only the value of the variable is noted. [b] Standard conditions: 9.6 mmol of DPM, 1 mmol of $(Bu)_4N^+HSO_4^-$, 3.2 g of 50% NaOH, 10 cm^3 of toluene, air, 25 ± 1 °C.

A necessary condition for a successful process is the right choice of the catalyst counteranion. The only catalysts that gave high yields when diphenylmethane (DPM) (**3**) was used as the standard substrate consisted of the lipophilic tetrabutyl- and tetrahexylammonium cations and hydrogen sulfate (HSO_4^-) anion. In the presence of a wide range of catalysts, e.g., $(Hex)_4N^+Br^-$, $(Bu)_4N^+Cl^-$, $(Bu)_4N^+Br^-$, $(Bu)_4N^+I^-$, $(Bu)_4P^+Br^-$, $(Et)_4N^+HSO_4^-$, $(Me)_4N^+HSO_4^-\cdot H_2O$, $Bz(Et)_3N^+Cl^-$, and 15-crown-5, we could obtain only negligible yields of oxidation products (<5%). The importance of the counteranion is demonstrated by the reactivity of a series of similar ammonium cations with different counteranions [e.g., $(Hex)_4N^+X^-$, $(Bu)_4N^+X^-$; X = I^-, Br^-, Cl^-, HSO_4^-]. It can be seen that only those catalysts in which X = HSO_4^- were reactive.

The significantly reduced reactivity as a result of the catalyst counteranion has been observed also in other processes[31] which were performed under extractive conditions. The rationale is that there is a competition, in this mechanism, between the inorganic anions which are being extracted by the ammonium ion (quat) into the organic phase. This is in contrast to the competition between the inorganic and the organic anions which are being detached by the quat from the boundary between the phases in the interfacial mechanism. The effect of the concentration of the catalyst, the concentration of the substrate, and the amount of oxygen is shown in Table VI. From these kinetic studies the following mechanism is assumed:

$$\text{step 1:}\quad Q^+HSO_4^-{}_{(aq)} + NaOH_{(aq)} \rightleftharpoons Q^+OH^-{}_{(aq)} + Na^+HSO_4^-{}_{(aq)}$$

$$\text{step 2:}\quad Q^+OH^-{}_{(aq)} \rightleftharpoons Q^+OH^-{}_{(org)}$$

$$\text{step 3:}\quad Q^+OH^-{}_{(org)} + RH_{(org)} \rightleftharpoons Q^+R^-{}_{(org)} + H_2O$$

$$\text{step 4:}\quad Q^+R^-{}_{(org)} + O_{2(org)} \xrightarrow[{[H_2O]}]{[OH^-]} Q^+OH^- + R{=}O$$

From the observation that the reaction rate depends on the concentration of both the oxygen and the catalyst but is not sensitive to the substrate, it is suggested that the rate-determining step is the one in which the chemical reaction occurs (step 4). The extraction step (step 2) is a fast equilibrating process which gives rise to a low $Q^+OH^-{}_{(org)}$ concentration and in turn results in the formation of a steady-state concentration of $Q^+R^-{}_{(org)}$ (step 3). The extent of transfer of the hydroxide anion into an organic nonpolar phase, e.g., toluene, is small and even smaller in

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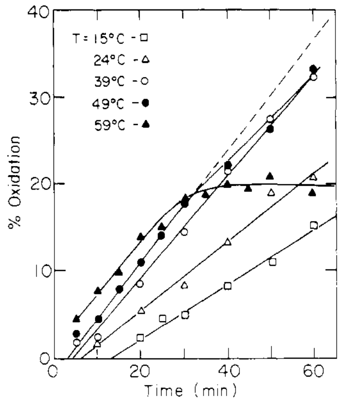

Figure 2. The influence of temperature on the reaction progress of the autoxidation of diphenylmethane (DPM).

the presence of lipophilic inorganic anions such as bromide and iodide. Even the chloride anion presents a problem as the extraction constants of the hydroxide anion are lower by a factor of 10^4 as compared with the chloride anion.[32] This is the rationale for the importance of a hydrophilic counteranion, e.g., HSO_4^-, in the extraction process. Another interesting factor that governs the reaction is the structure of the quat. The higher the organophilicity of the quat, the more the equilibrium in step 2 is shifted toward higher concentrations of the $Q^+OH^-{}_{(org)}$, and a faster rate is obtained. However, this organophilicity arrives at an optimum as the extraction of the hydroxide anion arrives at a maximum.[31,32] When a long alkyl chain of the quat is replaced by a methyl, a drastic decrease is observed in the reaction rate. $(Me)_4N^+HSO_4^-$ and $(Et)_4N^+HSO_4^-$ did not show any activity. Although it has the hydrogen sulfate as counteranion, its low lipophilicity avoids its extraction. When air is introduced into the reaction mixture, the process is slower than when pure oxygen is applied. Reactions with oxygen are known to be fast,[33] and we assume that the slower reaction rate stems from the lower oxygen concentration in the organic phase. We applied magnetic stirring, which is expected to supply an optimum concentration of $Q^+OH^-{}_{(org)}$. However, the effect of the stirring rate cannot be ruled out.

The observed induction periods originate from the time required to achieve a steady state of Q^+OH^- in the organic phase. These periods are decreased as the temperature is elevated (Figure 2) due to an increase in the rate of the transport between the phases. On the other hand, high temperatures increase the decomposition rate of the catalyst. It can be seen from Figure 2 that at 49 °C a deviation from linearity can be observed after 30 min of reaction, while at 59 °C the reaction does not proceed at all after this period of time. Moreover, even at room temperature there is a deviation from linearity. In the graph of product concentration vs reaction time, such a deviation is observed at room temperature after 1–2 h of reaction time. A similar result was reported in other PTC studies and is attributed to a partial decomposition of the catalyst.[31] In order to study the effect of the catalyst decomposition, we added an additional amount of catalyst after $2^1/_2$ h, and it can be seen (Figure 3) that, after the addition, the system retained its normal behavior. The decomposition process explains the observation that while there is always an excess of $NaOD/D_2O$ per exchangeable hydrogen, one cannot achieve complete exchange. The reaction does not reach a full equilibrium, and hence, completed exchange cannot be achieved even after 20 h. However, most of the reaction products are formed during the first 2 h.

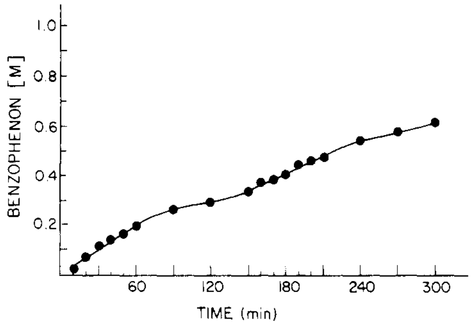

Figure 3. The influence of one and two additions of PTC catalyst. Reaction conditions: 9.6 mmol of DPM, 0.5 mmol of $(Bu)_4N^+$-HSO_4^-, 3.2 g of 50% NaOH, 10 cm^3 of toluene, air, 25 ± 1 °C.

Experimental Section

Materials. The substrates are commercial and of a high degree of purity. They were applied without further purification. $(Hex)_4N^+HSO_4^-$, $Me(Bu)_3N^+HSO_4^-$, and $Me(Oct)_3N^+HSO_4^-$ were prepared according to literature procedures.[34,35] Sodium deuterioxide (NaOD) was prepared by a careful addition of sodium metal to D_2O under a nitrogen atmosphere. Heating is required toward the end of the reaction. The pasty $NaOD/D_2O$ solution was titrated with a standard solution of HCl to estimate that the solution contained 60% w/w of NaOD.

H/D Exchange Experiments. Standard Procedure. The reactions were carried out in a standard reaction vial (48-mm height and 21-mm diameter) with strong magnetic stirring. The reaction workup was performed by methylene chloride extraction. The organic layer was separated, washed with water, dried over magnesium sulfate, and filtered. The filtrate was chromatographed on a short column (10 × 1 cm of Florisil) and evaporated to dryness under vacuum. In the case of the thiophene (**10**), the deuteriated substance was not isolated and its extent of deuterium exchange was ascertained from the ^1H NMR spectrum of a sample taken from the reaction mixture.

a. Exchange of Benzylic Hydrogens. General: 1.5 mmol of substrate, 0.3 mmol of $(Bu)_4N^+HSO_4^-$, 2:1 molar ratio of 60% $NaOD/D_2O$ to each active hydrogen, 1.5 cm^3 of benzene, argon atmosphere, room temperature.

Benzyl Phenyl Sulfide (7). First round: 600 mg (3 mmol) of substrate, 204 mg (0.6 mmol) of $(Bu)_4N^+HSO_4^-$, 1.1 g of 60% $NaOD/D_2O$, 1 cm^3 of hexane, 20 h, room temperature. **Second round:** 287 mg (1.43 mmol) of substrate, 98 mg (0.29 mmol) of $(Bu)_4N^+HSO_4^-$, 563 mg of 60% $NaOD/D_2O$, 0.48 cm^3 of hexane, 20 h, room temperature.

b. Heterocyclic Compounds. Benzo[*b*]thiophene (9) and Benzo[*b*]furan (8). First round: 3 mmol of substrate, 204 mg (0.6 mmol) of $(Bu)_4N^+HSO_4^-$, 1.1 g of 60% $NaOD/D_2O$, 1 cm^3 of hexane, 20 h, room temperature. **Second round:** 263 mg (1.95 mmol) of substrate, 133 mg (0.39 mmol) of $(Bu)_4N^+HSO_4^-$, 759 mg of 60% $NaOD/D_2O$, 0.65 cm^3 of hexane, 20 h, room temperature.

Thiophene (10): 262 mg (3.1 mmol) of substrate, 204 mg (0.6 mmol) of $(Bu)_4N^+HSO_4^-$, 2.35 g of 60% $NaOD/D_2O$, 433 mg (3.6 mmol) of mesitylene, 20 h, room temperature.

c. Halobenzene Derivatives. General: 2 mmol of substrate, 0.4 mmol of $(Bu)_4N^+HSO_4^-$, 2:1 molar ratio of 60% $NaOD/D_2O$ to active aromatic hydrogens, 1 cm^3 of hexane, 20 h, room temperature.

In the following experiments, a second round was performed.

1,3,5-Tribromobenzene: 236 mg (0.75 mmol) of substrate, 51 mg (0.15 mmol) of $(Bu)_4N^+HSO_4^-$, 529 mg of 60% $NaOD/D_2O$,

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0.66 cm^3 of hexane, 20 h, room temperature.

1,3,5-Trichlorobenzene: 129 mg (0.71 mmol) of substrate, 49.5 mg (0.146 mmol) of $(\mathrm{Bu})_4\mathrm{N}^+\mathrm{HSO}_4^-$, 392 mg of 60% NaOD/D$_2$O, 0.4 cm^3 of hexane, 20 h, room temperature.

4-Bromochlorobenzene: 53 mg (0.28 mmol) of substrate, 23.5 mg (0.069 mmol) of $(\mathrm{Bu})_4\mathrm{N}^+\mathrm{HSO}_4^-$, 177 mg of 60% NaOD/D$_2$O, 0.25 cm^3 of hexane, 20 h, room temperature.

Autoxidation Experiments. Reaction conditions: 1.5 mmol of substrate, 0.3 mmol of $(\mathrm{Bu})_4\mathrm{N}^+\mathrm{HSO}_4^-$, 450 mg of 50% NaOH, 1.5 cm^3 of benzene, air, room temperature.

The reaction was carried out in an open vial with magnetic stirring as described previously. A sample was taken, evaporated, and dissolved in an acetone-d_6/CCl$_4$ mixture. The ^{1}H NMR spectrum of this solution was recorded. PLC was run on Kieselgel 60 F 254 (Merck), the product was extracted with methylene chloride, and the solvents were evaporated.

Autoxidation of Diphenylmethane (DPM) (3). Kinetic Studies. The kinetic studies were performed in an open round-bottomed flask (25 mL) with vigorous magnetic stirring. The organic layer (20 μL) was sampled with a syringe. The solvent was evaporated, and the sample was dissolved in acetone-d_6/CCl$_4$ (0.3 mL, 1:3) for ^{1}H NMR estimations. In order to obtain the rate constants, at least two runs were taken.

Reaction conditions: 1.61 g (9.6 mmol) of DPM, 1 mmol of PTC catalyst, 3.2 g of 50% aqueous NaOH w/w, 10 mL of toluene, 25 °C. The effect of the catalyst was studied at the following concentrations: 0.5, 0.75, and 1.0 mmol. The effect of substrate concentration was studied at 9.6, 4.8, and 2.4 mmol. The temperature effect was studied in a thermostated bath (±0.5 °C). Bubbling of oxygen was performed in a 25-cm^3 flask with side arms, one of which was stoppered with a septum stopper and the other connected to an oil trap. The air was first removed by evacuation, the oxygen was then introduced, and the reaction was started. The effect of an additional amount of catalyst was studied as follows: the first amount of catalyst added was 0.5 mmol and reacted for 150 min. After this period of time, a second portion of catalyst (0.5 mmol) was added and the reaction parameters were studied.

NMR Spectra. NMR spectra were recorded at 200.133 MHz and 300.133 MHz (for protons) with the aid of WP-200 and WH-300 NMR spectrometers, respectively (Bruker Physik). The field/frequency regulations were maintained by ^{2}H locking to internal standard acetone-d_6. The free induction decay (FID) signals were digitized and accumulated on an Aspect-2000 computer. The extent of exchange was determined from the relevant peak areas relative to an internal standard before and after reactions. In order to avoid saturation, a relaxation delay (RD) of 5 s was programmed. The acetone peak is taken as standard at 2.04 ppm. For benzylic hydrogens, benzo[*b*]thiophene (**9**), and benzo[*b*]furan (**8**), the aromatic nonexchangeable protons were taken as internal standards, while mesitylene was taken as standard for thiophene (**10**) and hexamethylbenzene for halobenzenes.

Carbon-13 NMR spectra were recorded at 50.46 MHz. The position of the exchanged protons was deduced from proton-decoupled spectra. The $^1J_{\mathrm{C\text{-}D}}$ (as well as $^2J_{\mathrm{H\text{-}D}}$) coupling constants allowed the assignment of the particular carbon whose protons were exchanged as well as the estimation of the degree of exchange.

Mass Spectroscopy. Electron-impact mass spectra were recorded on a Varian MAT 311 mass spectrometer. In those cases where the mass spectra were performed at low energies (13–20 eV), the ratio between singly and doubly exchanged molecules could be estimated.

Supplementary Material Available: Table VII reporting the ^{1}H and ^{13}C NMR and mass spectral data of the exchanged and oxidized products (4 pages). Ordering information is given on any current masthead page.

Preparation of 4-Unsubstituted β-Lactams from 4-Acetoxyazetidin-2-ones. A Formal Approach to Monobactams and Nocardicins[1]

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Received December 23, 1987

The synthesis of 4-unsubstituted azetidin-2-ones is described. Treatment of Schiff bases derived from α-methylcinnamaldehyde and amines with acetic acids in the presence of phenyl dichlorophosphate and triethylamine followed by ozonolysis of the resulting β-lactams afforded *cis*-4-acetyl β-lactams in good yields. Baeyer–Villiger oxidation of the latter gave the corresponding 4-acetoxy β-lactams, which upon treatment with a sixfold excess of a hydrosilane in the presence of trimethylsilyl trifluoromethanesulfonate as catalyst afforded 4-unsubstituted azetidin-2-ones. Application of this methodology to Schiff bases derived from α-methylcinnamaldehyde and phenylglycine as well as protected *p*-hydroxyphenylglycine for the synthesis of (±)-3-aminonocardicinic acid is also described.

Since the discovery of the monobactam family **1** (Chart I) of monocyclic β-lactam antibiotics,[2] intense effort has been made to achieve their total synthesis.[3] Nocardicins **2**, discovered in 1976 by a group at Fujisawa laboratories,[4] are the first example of monocyclic β-lactams to exhibit high antibacterial activity.[5] The structural features of this

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