Addition of Hydroxide Ions to Nitrosobenzene: Equilibria and Some Reactions of the Adduct

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Nitrosobenzenes can be formed in biological systems by oxidation of arylhydroxylamines, resulting either from hydroxylation of anilines or reduction of nitrobenzenes. Nitrosobenzenes can under physiological conditions react with various nucleophiles. In this paper, we studied addition of hydroxide ions to nitrosobenzene as a model reaction.

The nitroso group is isoelectronic with the carbonyl group, but addition of nucleophiles to the former were much less extensively studied. For reactions of carbanions,[1] Grignard reagents,[2] cyanide ions,[3] and alkoxides[4] and alkylamines,[5] the studies were limited to identification of the structure of the adduct. For reactions of thiolates[6] some kinetic studies have been reported. Reactions with anilines yielding azobenzenes are acid-catalyzed,[7] but condensation in alkaline media has also been reported.[8] With hydroxylamine, nitrosobenzene yields in alkaline solutions syn diazotates.[9] The acid- and base-catalyzed reactions of nitrosobenzenes with phenylhydroxylamines[10] yielding azoxybenzene have been most extensively studied. Both with respect to catalysis and dehydration of the primarily formed adduct, reactions of nitrosobenzenes with amines resemble those of benzaldehydes.

In preparative and kinetic studies little attention has been paid to the position of the equilibria involved. Only for the 1:1 addition of reduction glutathione to nitrosobenzene has the value of the equilibrium constant been determined spectrophotometrically.[6a] At pH 7.4 at 37 °C the value of $K = 2.6 \times 10^3$ L mol^{-1} has been reported.

The study of the addition of hydroxide ions to nitrosobenzene is also of interest because of the possible role of the adduct as a reactive intermediate. Analogous products, geminal diol monoanions and dianions, formed by addition of hydroxide ions to benzaldehydes and by dissociation of the adduct, proved to be reactive intermediates in oxidations[11] and other reactions of benzaldehydes.[12] The adduct formed by addition of hydroxide ions to nitrosobenzene has also proven to be reactive both in the monoanionic and dianionic forms.[13]

In this paper the equilibrium constant of the reaction between nitrosobenzene and hydroxide ions has been determined and some reactions of the resulting adduct have been studied.

Experimental Section

Polarographic measurements were carried out using Polarographic Analyzer PAR Mark 174 with an MFE815 Plotomatic x-y recorder. The dropping mercury electrode used had the following characteristics: $t_1 = 5.0$ s, $m = 1.49$ mg s^{-1} at $h = 60$ cm. A Kalousek vessel with a SCE reference electrode separated by liquid junction was used.

For linear sweep and cyclic voltammetry an IBM voltammetric analyzer Mark EC1225 was used with an IBM x-y-t recorder 7424MT. The hanging mercury drop electrode (Metrohm Mark 6.1209.000) had electrode surface $A = 0.014$ cm^2. Measurements were carried out in a Metrohm cell with SCE as reference and platinum as third electrode.

Electronic spectra were recorded using Perkin-Elmer spectrophotometer Mark 559.

Nitrosobenzene (Aldrich), azoxybenzene (Lancaster Synthesis), nitrobenzene (Fisher), hydrogen peroxide (Aldrich), and sodium hydroxide (Baker) were all analytical-grade chemicals and used as supplied. Stock solutions (0.01 M) of nitroso-, azoxy-, and nitrobenzene were prepared in dry ethanol. Carbonate-free solutions of sodium hydroxide were prepared by dilution with an oxygen-free water from a saturated solution. All solutions were protected from diffuse light.

Reaction mixtures were prepared by addition of a stock solution of nitrosobenzene to a solution of sodium hydroxide (of chosen concentration, always at least 20-fold higher than that of nitrosobenzene) containing 10% (v/v) ethanol protected from light (if not otherwise indicated) and deaerated using nitrogen (unless otherwise indicated). Initial concentration of nitrosobenzene in the reaction mixture was $(1-2.5) \times 10^{-4}$ M. For electroanalytical experiments the reaction mixture was prepared directly in the electrolytic cell, for spectrophotometry it was rapidly transferred in the absence of oxygen into a spectroscopic cell. Polarographic or voltammetric curves or spectra were recorded in the reaction mixture as a function of time. Nature of the new waves or ab-

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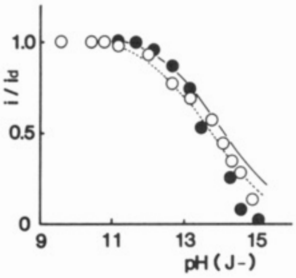

Figure 1. Reduction of nitrosobenzene in buffered and NaOH solutions containing 10% (v/v) ethanol. Dependence of relative peak current (i/i_d) on pH (J_-) in 0 (○) and 25 °C (●) obtained by cyclic voltammetry. Theoretical curves for 0 (---) and 25 °C (—).

sorption bands formed was identified by comparison with authentic samples.

Results and Discussion

Equilibria in the Addition of Hydroxide Ions to Nitrosobenzene. The applications of three techniques have been attempted in the study of the equilibria between nitrosobenzene and hydroxide ions. These include electronic absorption spectroscopy, linear sweep voltammetry, and d.c. polarography. The absorption bands of nitrosobenzene and of the product of its reaction with one hydroxide ion overlapped and precluded the use of spectrophotometry.

Linear sweep voltammetry enabled accurate measurements of the height of the nitrosobenzene peak at −0.2 V, which is a linear function of nitrosobenzene concentration and unaffected by the peaks of products at more negative potentials. For preliminary measurements voltammetry offered the additional advantage of a rapid voltage scan, enabling an estimation of the concentration of unreacted nitrosobenzene during a short period after preparation of the reaction mixture. Nevertheless, it has been proved that nitrosobenzene at 25 °C and even 0 °C is volatile and can be removed from aqueous solutions by a stream of nitrogen, both introduced into and above the reaction mixture. Such losses, in agreement with earlier observation,[13] present some 10–20% of the initial concentration of nitrosobenzene. Furthermore, in addition to the formation of the adduct, which in the absence of air and light is predominantly converted into azoxybenzene, nitrosobenzene can undergo some competitive reactions. To correct the equilibrium data for loss by volatility and competitive reactions, the measurement of the sum of the concentrations of nitrosobenzene and azoxybenzene becomes important. The peak of azoxybenzene is located on the ascending portion of the nitrosobenzene peak, and the measurement of its height from voltammetric curves is not accurate. The plot of the ratio i/i_d as a function of pH or (at higher concentration of sodium hydroxide) of acidity function[14] J_- shows (Figure 1) at 25 °C at pH > 13 deviations to lower values, when compared with the theoretical dissociation curve for pK 14.1. To minimize such deviations, due to the effects of consecutive reactions, the voltammetric studies were carried out at 0 °C where a better fit to a dissociation curve with pK 13.8 was found (Figure 1).

The most accurate equilibrium data have been obtained by d.c. polarography, where the reduction waves of nitrosobenzene (i_1) and azoxybenzene (i_2) are well-separated (Figure 2), additive, and suitable for determination of the total current.

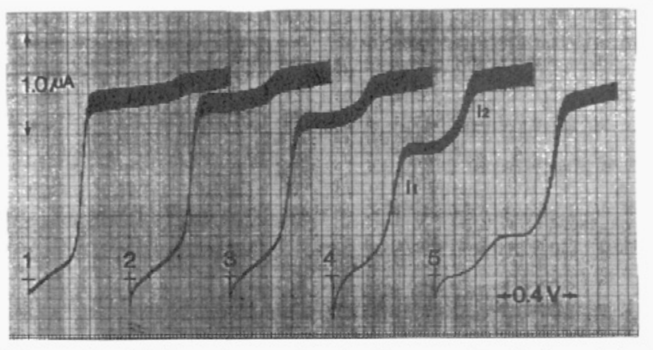

Figure 2. pH-dependence of cathodic waves in solution of 2.5 × 10^{-4} M nitrosobenzene in NaOH (+Na_2SO_4 to μ = 0.3) solutions containing 10% (v/v) ethanol pH (J_-): 11.1 (1), 12.6 (2), 13.2 (3), 13.8 (4) and 14.3 (5). Dropping mercury electrode had the following characteristics: t_1 = 5.0 s, m = 1.486 mg s^{-1} at h = 60 cm, controlled drop time t_1 = 2 s, mercury(II) sulfate reference electrode, Kalousek cell with liquid–liquid junction. Curves started at +0.05 (1), 0.00 (2), −0.05 (3–4), and −0.10 V (5) vs SCE, mV/s after 3 min at 25 °C.

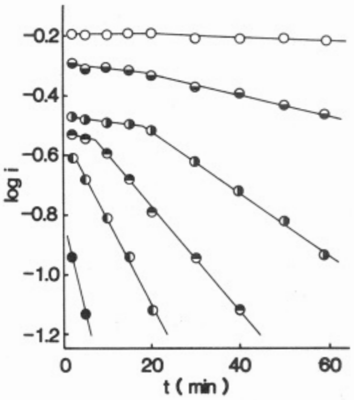

Figure 3. Logarithm of reduction currents of nitrosobenzene as a function of time for the decrease in cathodic wave obtained by d.c. polarography. Reaction mixtures contained 2 × 10^{-4} M nitrosobenzene and 10% (v/v) ethanol in solutions containing 0.1 (○), 0.3 (◒), 0.6 (◑), 1.0 (◓), 1.5 (◐), and 2.5 (●) M NaOH.

To minimize the effect of the consecutive reaction, the currents i_1 and i_2 were furthermore extrapolated to $t = 0$ using $\log i = f(t)$ plots. The relative concentration of the free nitrosobenzene is then given by the ratio $(i_1)_{t\to 0}/i_d$. The experimental points obtained for $(i_1)_{t\to 0}/i_d$ under varying conditions at 25 °C as a function of pH (J_-) fit the theoretical dissociation curve for pK 13.8. The agreement of data within experimental error indicates that the presence of oxygen or light, which affects not only the rate but the nature of products of consecutive reactions, has no effect on the addition of the first hydroxide ion. Hence, the value pK_a 13.8 for constant $K_a = [ArN(OH)O^-][H^+]/[ArNO] = [ArN(OH)O^-][K_w/[ArNO][OH^-]$ or $K = 1.58 = [ArN(OH)O^-]/[ArNO][OH^-]$ seems to be the best value, little different at 25 and 0 °C.

To prove the reversibility of the studied addition reaction, the reaction mixture in 0.1 M NaOH was acidified after selected time intervals by phosphoric acid to pH 10.5 and d.c. polarographic curves were recorded. The fraction of nitrosobenzene converted in alkaline solution was quantitatively reconverted into free nitrosobenzene; the reaction producing azoxybenzene is irreversible.

Some Reactions of the Adduct $ArN(OH)O^-$. At pH > 11 nitrosobenzene is converted in a reversible reaction into an adduct $ArN(OH)O^-$. At pH > 12 $ArN(OH)O^-$ undergoes irreversible reactions: (1) in the absence of dioxygen, azoxybenzene is the predominate product accompanied by small amounts of azobenzene; (2) in the

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presence of dioxygen nitrobenzene is formed predominantly together with some hydrogen peroxide.

Formation of 2–12% of nitrobenzene has been reported[15] in the reaction of arylhydroxylamines with dioxygen in a medium-pH range. At pH 5.3–7.8 yields of 70–95% nitrosobenzene and 1–20% azoxybenzene have been found. As both nitrosobenzene and azoxybenzene do not react under these conditions with dioxygen and participating of hydrogen peroxide was excluded, a direct attack of dioxygen on phenylhydroxylamine was postulated.

Our studies were restricted to pH > 11 where the adduct $ArN(OH)O^-$ predominates. The decrease in concentration of nitrosobenzene in alkaline solutions in the dark and in the absence of dioxygen was followed at 0 and 25 °C by cyclic voltammetry (CV) and at 25 °C by d.c. polarography (DCP). The log $i = f(t)$ plots show two linear segments (Figure 3) indicating the presence of two consecutive competitive processes following first-order kinetics.

The rate of the first process is practically pH-independent with $k_1 = 3.8 \times 10^{-5}\ s^{-1}$ (0 °C) and $1.3 \times 10^{-4}\ s^{-1}$ (25 °C). DCP indicated the presence of both azoxy- and azobenzene. Due to a strong adsorption of azoxybenzene the waves of azoxy- and azobenzene are not additive and only their total concentration can be estimated. The length of the time period during which the first process predominates ("induction period") decreases at a given concentration of nitrosobenzene with increasing concentration of hydroxide ions and at a given $[OH^-]$ with increasing initial concentration of nitrosobenzene.

The rate of the second reaction yielding predominantly azoxybenzene increases with increasing pH. The rate of this reaction is practically independent of the initial concentration of nitrosobenzene and follows first-order kinetics. First-order rate constant (k_{exp}) is a linear function of hydroxide ion concentration ($k_{exp} = k_{OH^-}[OH^-]$ with $k_{OH^-} = 9.3 \times 10^{-4}\ L\ mol^{-1}\ s^{-1}$ (0 °C, CV, $r = 0.989$); $4.1 \times 10^{-3}\ L\ mol^{-1}\ s^{-1}$ (25 °C, CV, $r = 0.999$) and $5.9 \times 10^{-3}\ L\ mol^{-1}\ s^{-1}$ (25 °C, DCP, $r = 0.996$). DCP allows the observation of the increasing concentration of azoxybenzene, which seems to follow first-order kinetics with the same rate constant as the decrease in that of nitrosobenzene. Nevertheless, the yield of azoxybenzene is only about 50–60% of converted nitrosobenzene indicating either an accumulation of a nonreducible intermediate or a side reaction yielding a nonreducible species.

The rate of decrease of nitrosobenzene or the increase of azoxybenzene is practically independent of the presence of metallic mercury, chloride ions, addition of glass wool, or the size of the reaction vessel. It seems that in the dark radical reactions do not play a predominant role. Illumination by diffuse light in the absence of oxygen resulted in a decrease in the induction period and faster cleavage of nitrosobenzene yielding a nonreducible product rather than azoxybenzene and revealing a competitive photocatalyzed path.

One reaction scheme corresponding to the kinetic behavior of the second reaction is:

$$ArNO + OH^- \rightleftharpoons ArN(OH)O^- \qquad (1)$$

$$ArN(OH)O^- + OH^- \rightleftharpoons ArN(O^-)_2 + H_2O \qquad (2)$$

$$ArN(O^-)_2 + ArN(OH)O^- \xrightarrow[\text{several fast steps}]{+5H^+} ArN(O){=}NAr + 3H_2O \qquad (3)$$

This scheme corresponds to a rate equation $-d[ArNO]/dt = k_{OH}(1 + K/[OH^-])[OH^-]S_{ARNO} = (k[OH^-] + k_{OH}K)S_{ArNO}$, where S_{ArNO} is the analytical concentration of nitrosobenzene and $K = [ArN(OH)O^-]/[ArNO][OH^-] = 1.58$ (see above). Any mechanism involving interaction of $ArN(O^-)_2$ with either $ArN(OH)O^-$ or ArNO as the rate-determining step would be manifested by kinetics second order in nitrosobenzene. Slow formation of dianion (2) may be due to coulombic repulsion in the product, increasing the rate of the reverse reaction. Participation of radicals in competing processes cannot be excluded.

Oxidation of nitrosobenzene in the presence of dioxygen or hydrogen peroxide yields predominantly nitrobenzene. Even when the reaction with H_2O_2 is faster, some H_2O_2 is formed, as both anodic and cathodic waves of H_2O_2 are observed in alkaline reaction mixtures of nitrosobenzene containing O_2. The increase in H_2O_2 formation is faster in solution exposed to diffused daylight than in the dark. Catalytic reduction of H_2O_2 in alkaline solution of nitrosobenzene is being studied.

The rate of the decrease in nitrosobenzene concentration in the presence of O_2 in the dark is practically equal to the rate of increase in nitrobenzene concentration. Moreover, the rate of nitrobenzene formation depends on pH in a way analogous to that of azoxybenzene formation. The value of k_{OH} for formation of nitrobenzene in the presence of O_2, obtained by measurement of the decrease in absorbance at 306 nm with time ($k_{OH} = 5.2 \times 10^3\ L\ mol^{-1}\ s^{-1}$ at 25 °C, $r = 0.999$) is practically identical with that obtained for formation of nitrobenzene by DCP ($k_{OH} = 5.6 \times 10^{-3}\ L\ mol^{-1}\ s^{-1}$ at 25 °C, $r = 0.991$) for formation of azoxybenzene. In another analogy of the processes in the presence and absence of O_2, the product of a photocatalyzed reaction in the presence of air in diffuse light is not nitrobenzene and not reducible.

These observations indicate that both the formation of azoxybenzene in the absence and of nitrobenzene in the presence of air involve a common intermediate, e.g., $ArN(O^-)_2$.

Kinetics of reactions of nitrosobenzene in alkaline solutions, mechanisms of such reactions, the effect of substituents on reactions in absence and presence of dioxygen, as well as analogous reactions with other nucleophiles are under investigation.

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Registry No. PhNO, 586-96-9; HO^-, 14280-30-9; $PhN(OH)O^-$, 135189-78-5.

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