Benzidine Rearrangement in the Presence and Absence of Micelles. Evidence for Rate-Limiting Proton Transfer

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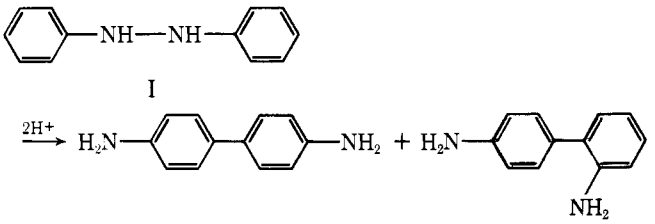
Abstract: The rearrangement of 1,2-diphenylhydrazine (I) in aqueous HCl or $HClO_4$ has a second-order dependence upon H^+ in dilute aqueous acid, and in more concentrated acid there is a second-order dependence on Hammett's acidity function, h_o, but at higher acidities, I becomes extensively monoprotonated and this dependence gives the acid dissociation constant, $K_a' \sim 6$. In very dilute aqueous acid, rearrangement of 1,2-di-*o*-tolylhydrazine (II) has a first-order dependence upon H^+, but with increasing acid concentration there is an incursion of a reaction which is second order in H^+, and at higher acidities the acid dependence becomes similar to that for reaction of I and gives $K_a' \sim 1$. In very dilute aqueous acid there is a one-proton rearrangement of 1,2-di-*o*-anisylhydrazine (III), but with increasing acidity there is incursion of a two-proton rearrangement. The second- and third-order rate constants, k_m (l. mol^{-1} s^{-1}) and k_d (l.^{2} mol^{-2} s^{-1}), in dilute aqueous HCl are, respectively: for I, ~0 and 16; for II, 15.6 and 160; and for III, 3400 and 1.5×10^5 at 25.0°. The second dissociation constants, K_a'', are estimated to be 10^6–10^7, and these values of K_a', K_a'', and k_d suggest that the second proton transfer cannot be a preequilibrium, but must be part of the rate-limiting step. In dilute acid, the two-proton rearrangement of I is inhibited by cationic micelles of cetyltrimethylammonium bromide (CTABr) and nonionic micelles of Brij, but anionic micelles of sodium lauryl sulfate (NaLS) very strongly catalyze this reaction. Micelles of NaLS also very strongly catalyze the two-proton rearrangements of II and III, but weakly catalyze the one-proton rearrangement of III. The maximum catalyses by NaLS of the two-proton rearrangements are: I, 2000-fold; II, 4300-fold; III, ~5000-fold. For the one-proton rearrangement of III the maximum catalysis is ~50-fold. These micellar catalyses depend markedly upon the bringing together of two or three reactants in the transition state. The micellar catalyses of the two-proton rearrangements of I and II decrease at high concentrations of NaLS, and rearrangement of II is inhibited by >0.1 M NaLS. This inhibition is explained in terms of a dilution of the reagents in high concentrations of anionic micelles.

The acid-catalyzed benzidine rearrangement is an intramolecular reaction of 1,2-diarylhydrazines (hydrazoarenes).[1] In the simplest system, the acid-catalyzed rearrangement of 1,2-diphenylhydrazine (I), the transition state contains two protons, but rearrangements of some 1,2-dinaphthylhydrazines and some 1,2-diarylhydrazines containing electron-releasing substituents require only one proton. Orders between one and two with respect to hydrogen ions have also been found.[2-4]

The simplest rearrangement gives biphenyls, but the so-called semidine rearrangement (giving diphenylamine derivatives) is sometimes observed, especially with 4,4′-disubstituted diphenylhydrazines. Additional complications are the formation of carbazoles, with elimination of ammonia, from some 1,2-dinaphthylhydrazines, and the formation of both azo compounds and primary amines by disproportionation. Photochemical or thermal rearrangement can also occur in nonacidic media.[2,3a]



Our primary interest in the benzidine rearrangement was in micellar effects upon rates and products,[5] but we have also examined the reaction in aqueous acid in the absence of surfactants.

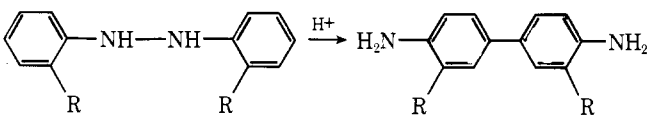
Micelles of surfactants can both catalyze and inhibit reactions, and the general principles are well understood. Micelles which do not contain functional groups have two distinct roles: (i) the micelles can take up the substrate and provide a favorable, or unfavorable, medium for reaction; (ii) the micelle may bring the reactants together, and in so doing increase the rate, or keep them apart.

We consider here this second role, which applies only to reactions of higher order than first. Generating a transition state from more than one reagent inevitably involves loss of translational entropy, and bringing them together on the micelle prior to reaction reduces this entropy loss. The importance of translational and rotational effects in governing the high rates of many intramolecular reactions and in enzymic catalysis has been noted by many workers.[9]

We do not in general know the concentration of reactants in the micellar phase (for a special case see ref 10), so that it is difficult to separate the concentration and the entropy effects of the micelle, and it may be best to consider them together as "effective concentration".[8] Micellar catalysis, or inhibition, should be greater for a reaction of higher order, other things being equal. However, in the course of our work we unexpectedly found that anionic micelles could inhibit reaction when in high concentration, although generally they are excellent catalysts of these reactions.

There has been considerable speculation and controversy regarding the source of the very large catalyses found in enzymic systems, and the importance of entropy effects has been stressed.[9] A major problem in testing this point for a chemical system is that the extents of micellar catalysis vary widely, depending especially on the hydrophobicity of the reagents,[6-8] so we have to compare micellar catalyses of reactions of similar substrates for which the transition states contain different numbers of reagent molecules or ions.

The benzidine rearrangement is an obvious candidate for this test. It should be catalyzed by anionic micelles and the order with respect to hydrogen ions can be changed by substitution.[2,3a,4,11] For the two-proton reaction we chose 1,2-diphenylhydrazine (I), and for the one-proton reaction we used 1,2-di-*o*-tolylhydrazine (II) and 1,2-di-*o*-anisylhydrazine (III),



I, R = H
II, R = Me
III, R = OMe

but a complication was a change of order when the reaction was run in anionic micelles.

In aqueous organic solvents the order with respect to hydrogen ions is between one and two for the rearrangement of II, and increases with increasing acid concentration, whereas that for III is first order.[2-4] Our choice of substrates was dictated by the requirement that the reactions be followed in water and that their rates in the presence and absence of anionic micelles be in an accessible range.

There is little agreement on the mechanism of the acid-catalyzed benzidine rearrangement, except that it is intramolecular with monoprotonation on nitrogen. Most workers have suggested that any second protonation is also on nitrogen,[2,3] although recently protonation on carbon has been suggested.[12,13] Although these mechanistic controversies do not complicate our test of the role of the micelles in catalyzing one- and two-proton benzidine rearrangements, we attempted to dissect the equilibrium and rate constants by carrying out rearrangements in the absence of surfactant, but with sufficient acid to monoprotonate the substrate extensively so that we would then be following decomposition of monoprotonated substrate. We also used a model compound ($PhNHNH_2$) to estimate the difference of pK_a' and pK_a'' for a protonated substrate.

It is often assumed that both proton transfers are preequilibria based on deuterium kinetic solvent isotope effects, $k_{H_2O}/k_{D_2O} \sim 0.25$,[2,3,14] for two-proton rearrangements, which suggest an inverse isotope effect of ca. 0.5 for each proton transfer. However, these isotope effects merely require that a proton be fully transferred in the transition state for overall reaction, not that the transfer be reversible.[15,16] In addition, early assumptions about the proton transfers must be reconsidered if the second transfer is to carbon.[12,13] We therefore hoped that a dissection of rate and equilibrium constants would throw light on these questions. To date, reactions have been followed kinetically using dilute acid in mixed solvents.[3,4,11,14]

Experimental Section

Materials. 1,2-Diphenylhydrazine (I) was recrystallized several times from EtOH and EtOH–H_2O, mp 127 °C (lit.[17] 126 °C) λ_{max} (H_2O) 238, 287 nm. The other diphenylhydrazines were prepared by general methods.[17] 1,2-Di-*o*-tolylhydrazine (II) was prepared by reduction of 2-nitrotoluene with Zn dust in NaOH–MeOH to give azotoluene, which was reduced in small batches in EtOH–NH_4Cl–Zn. The hydrazine was precipitated (H_2O) and recrystallized (twice) from EtOH–H_2O, mp 158 °C (lit.[17] 165 °C), λ_{max} (H_2O) 246, 283 nm. 2,2′-Dimethoxyazobenzene was prepared by the reduction of 2-nitroanisole with Zn dust in alkaline MeOH–H_2O[18] and it was reduced in small amounts with Zn dust and NH_4Cl in EtOH and 1,2-di-*o*-anisylhydrazine (III) precipitated with H_2O, mp 101 °C (lit.[17,18] 100, 102 °C); λ_{max} (H_2O) 242, 285 nm. The reductions and recrystallizations were done under N_2 for III.

Phenylhydrazine was vacuum distilled. It had λ_{max} at 241 nm, log ϵ 3.19; and 283 nm, log ϵ 3.96 (lit.[19] 3.2 and 3.97, respectively).

Sodium lauryl sulfate (NaLS) and cetyltrimethylammonium bromide (CTABr) were recrystallized by standard methods.

Kinetics. The reactions were followed spectrophotometrically at 260 nm for 1,2-diphenylhydrazine, 265 nm for 1,2-di-*o*-tolylhydrazine, and 295 nm for 1,2-di-*o*-anisylhydrazine. The slower runs were followed using a Gilford spectrophotometer with addition of 20 μl of 10^{-2} M substrate to 3 ml of the reaction medium. The faster runs were followed in a Durrum stopped-flow spectrophotometer, using either a Polaroid camera to photograph the oscilloscope trace, or for the later experiments, a Biomation 805 data acquisition unit. One syringe contained the substrate made up with 1 ml of 10^{-2} M substrate in EtOH, diluted to 100 ml with H_2O, and the other syringe contained the acid (and surfactant). Because of its low solubility, we used half concentration of substrate for the reaction of 1,2-di-*o*-tolylhydrazine, and we had to be particularly careful to avoid precipitation for the experiments in the absence of surfactant. The reaction solutions were saturated with N_2, and freshly made solutions were always used because the substituted diphenylhydrazines are rapidly oxidized by air.

All of our reactions were in aqueous acid at 25.0°.

Determination of pK_a'' of Phenylhydrazine. The molar extinction coefficient of $PhNHNH_3^+$ at 275 nm in 0.005 M H_2SO_4 is 2130 and that of $PhNH_2^+NH_3^+$ in 70% H_2SO_4 ($-H_o' = 5.8$) is 606. Using 3.3×10^{-4} M base we determined $[PhNHNH_3^+]/[PhNH_2^+NH_3^+]$ in H_2SO_4 from $-H_o$ 0.95–3.24 and the slope of the log plot against $-H_o$ was 0.8, with $pK_a'' = 2.3$, on the assumption that monoprotonated phenylhydrazine behaves as a Hammett base. Protonation does not follow Hammett's acidity function precisely, but we use our value of pK_a'' only as an order of magnitude estimate. Both protonations of phenylhydrazine are on nitrogen.[13]

Products. The product compositions have already been determined for reactions in aqueous organic solvents, and we used either spectrophotometry or chromatography, following existing methods.[20]

Chromatography. Reaction was carried to completion at 25° in aqueous 10^{-3} M HCl in the presence or absence of 10^{-2} M NaLS. The acid was neutralized (Et_3N) and where necessary KCl was added to precipitate KLS. The products were extracted (Et_2O) and chromatographed on formamide impregnated Whatman No. 1 paper. The developing solvent was cyclohexane for 1,2-diphenylhydrazine and petroleum ether (bp 30–60 °C) for the other compounds. Two major spots with R_f 0.03 and 0.20 were found for the rearrangement products of 1,2-diphenylhydrazine. Our R_f values are close to those reported.[20] The spot with R_f 0.03 coincided with that of benzidine. Only one major spot was found with the other substrates. Our results agreed with those for reaction in aqueous EtOH or aqueous dioxane.[3,4]

Spectrophotometry. The reaction of 1,2-diphenylhydrazine was carried to completion in 10^{-3} M HCl in the presence or absence of 10^{-2} M NaLS, and solutions were neutralized (Et_3N) and treated with KCl. The solution (1 ml) was made up to 20 ml with EtOH, and the concentrations of benzidine and diphenyline were calculated from the spectra using known extinction coefficients.[4]

We found 81% benzidine (4,4′-diaminobiphenyl) and 19% diphenyline (2,4′-diaminobiphenyl) for the reaction in 10^{-3} M HCl, and 79% benzidine and 21% diphenyline for this reaction in the presence of NaLS. These product compositions are similar to those found in aqueous organic solvents.[3,4]

Results

It is convenient to give the results of the micellar and nonmicellar experiments and those in more concentrated acid separately because micelles were used only in dilute acid. In this section k_ψ, (s^{-1}) designates the observed first-order rate constants with respect to substrate.

Reactions in the Absence of Surfactants. Reactions in Dilute Acid. In dilute aqueous acid the rearrangement of 1,2-diphenylhydrazine is second order with respect to hydrogen ions, as shown by the plot of log k_ψ against log C_{H^+} with $k_\psi/[H^+]^2 = 16$ l.^{2} mol^{-2} s^{-1}, and those of 1,2-di-*o*-tolyl- and 1,2-di-*o*-anisylhydrazine are close to first order in dilute acid (Figure 1) with $k_\psi/[H^+] = 15.6$ and 3400 l. mol^{-1} s^{-1}, respectively, but the orders increase with increasing acidity. In aqueous organic solvents, the reaction of 1,2-di-*o*-tolylhydrazine has an order with respect to hydrogen ions of between one and two and a clean one-proton rearrangement was not observed,[4] although the order with respect to hydrogen ions is one for rearrangement of the methoxy derivative (III) in aqueous dioxane.[3,18] (This latter conclusion was based on the use of buffers for the low and strong acid at higher acidities, which can cause problems in aqueous organic solvents.[21])

The reactions in water (Figure 1) are considerably faster than in aqueous organic solvents, although quantitative comparisons cannot be made for all the substrates because of differences in temperature and the order with respect to hydrogen ion.

The rearrangement of 1,2-diphenylhydrazine in dilute aqueous acid is approximately 200 times faster than in 60% aqueous ethanol.[22] However, the rate goes through a minimum as the water content of the solvent is decreased,[2,3] and rearrangement is very rapid with HCl in aprotic solvents such as ether.[23] Acidity, as measured by H_o', initially decreases when organic solvents are added to aqueous acid[24] because they

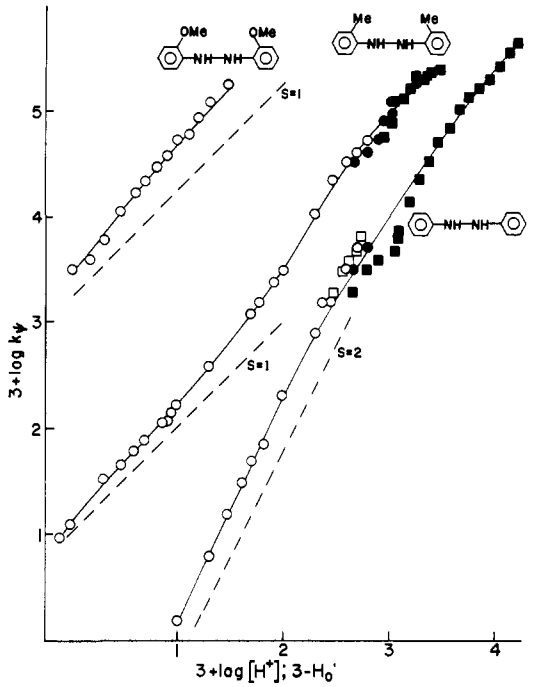


Figure 1. Variation of first-order rate constants of rearrangement with acidity. Open points, log [H$^+$]; solid points, $-H_o'$. ○ ●, HCl; □ ■, $HClO_4$.

Table I. Solvent Deuterium Isotope Effects[a]

Substrate	10^3[HCl], M[b]	$10^2k_{H_2O}$[c]	$10^2k_{D_2O}$[c]	k_{H_2O}/k_{D_2O}
I	16.3	0.46	1.84	0.25
I	22.7	0.89	3.51	0.25
I	32.1	1.88	7.71	0.24
II	1.41	2.25	5.20	0.43
II	1.96	3.28	8.02	0.41
II	3.14	4.90	11.2	0.44

[a] At 25.0° with 99% D_2O. [b] Or [DCl]. [c] First-order rate constants (s^{-1}).

stabilize the base, but in aprotic solvents desolvation of the proton dominates.

Deuterium Solvent Isotope Effect. The deuterium solvent isotope effects upon the rearrangements of 1,2-diphenyl- and 1,2-di-*o*-tolylhydrazine (I and II) in dilute aqueous hydrochloric acid in the absence of surfactant (Table I) are similar to those for reactions in aqueous organic solvents.[2,3,14] The value of $k_{H_2O}/k_{D_2O} \sim 0.42$ for the one-proton rearrangement of 1,2-di-*o*-tolylhydrazine is that expected for a reaction in which the hydrogen ion is fully transferred in the transition state.

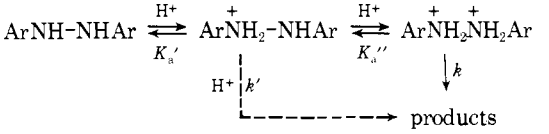
Reactions in Moderately Concentrated Aqueous Acids. In aqueous dioxane the rearrangement of 1,2-diphenylhydrazine (I) is approximately second order with respect to Hammett's acidity function, h_o, where this function diverges from stoichiometric acidity.[3,14] In aqueous acid it is difficult to evaluate acidity for concentrations between 0.4 and 1 M. In dilute solutions, hydrogen ion concentration gives a fair measure of protonating power, and for substrates whose protonation equilibria are similar to those of primary aromatic amines, Hammett's acidity function ($-H_o'$) is a satisfactory measure.[24a,b] But H_o' is evaluated for relatively high concentrations of acid (>1 M), so that it is difficult to choose a good measure of protonating power for 0.4–1 M acid. In Figure 1 the plot of log k_ψ against log [H$^+$] or $-H_o'$ is scattered for the reaction of 1,2-diphenylhydrazine at ca. 0.5 M acid, especially for runs in perchloric acid, although there is more consistency between results in hydrochloric and perchloric acid if the plot is based on log [H$^+$].

At higher acidities a plot of log k_ψ against $-H_o'$ has a slope of approximately two, as in aqueous dioxane, but with increasing acid concentration, the order with respect to h_o decreases, and the slope of the line in Figure 1 tends toward one. Therefore, in this reaction the order with respect to acidity *decreases* from two toward one with *increasing* acidity (cf. ref 25).

Changes of order with respect to acidity are very common in benzidine rearrangements, but the order hitherto has always *increased* with increasing acidity because if a rearrangement can follow both one- and two-proton mechanisms, the latter will dominate at high acidities.[2,3] The rearrangement of 1,2-di-*o*-tolylhydrazine follows this pattern over part of the acidity range, but again a decrease in order with respect to acidity is observed at the higher acidities (Figure 1). The rearrangement of di-*o*-anisylhydrazine is too fast to be followed over a wide acidity range (Figure 1).

Analysis of the Variation of Rate Constant with Acidity. The two-proton reaction, Scheme I, gives the following general rate

Scheme I



equation if both proton transfers are reversible and follow h_o (cf. ref. 3):

$$\log k_\psi + H_o' = \log k/K_a'' - H_o' - \log (h_o + K_a') \quad (1)$$

$$(-H_o' = \log h_o)$$

If the second proton transfer is part of the rate-limiting step, i.e., if the reaction follows the path shown by the broken arrow:

$$\log k_\psi + H_o' = \log k' - H_o' - \log (h_o + K_a') \quad (1a)$$

and in dilute acid, where $K_a' \gg h_o$

$$\log k_\psi + H_o' = \log k'/K_a' - H_o' \quad (2)$$

(Without prejudging the issue we will use eq 1a for simplicity, and not distinguish at this stage between k' and k/K_a''.) Therefore a plot of log $k_\psi + H_o'$ against $-H_o'$ should have unit slope in dilute acid (Figure 2).

For the rearrangement of 1,2-diphenylhydrazine in <0.5 M $HClO_4$, we estimate log $k'/K_a' \sim 1$ from the initial part of Figure 2. In more concentrated acid, where $K_a' \ll h_o$ eq 1a reduces to

$$\log k_\psi + H_o' = \log k' \quad (3)$$

We could not reach acidities high enough for the substrate to be completely monoprotonated, but the data in Figure 2 suggest that log k' is in the range 1.5–1.7, so that log K_a' is ~0.7 (cf. ref 3 and 25). Assuming that $K_a' = 6$, we calculated various values of log $k_\psi + H_o'$, and the line in Figure 2 is calculated taking log $k' = 1.55$. In an earlier report we calculated our rate constants using $K_a' = 5$,[26] but with additional results this new value fits the data a little better. The calculated points fit the experimental values as well as can be expected, because the reliability of the values of $-H_o'$ is ±0.05,[24a,b] and for the fastest reactions duplicate rate constants differ from the mean by 7%, although most agree better. The experimental results can be fitted reasonably well using other, but similar, rate and equilibrium constants than those chosen. However, to illustrate our approach, we include in Figure 2 lines calculated using

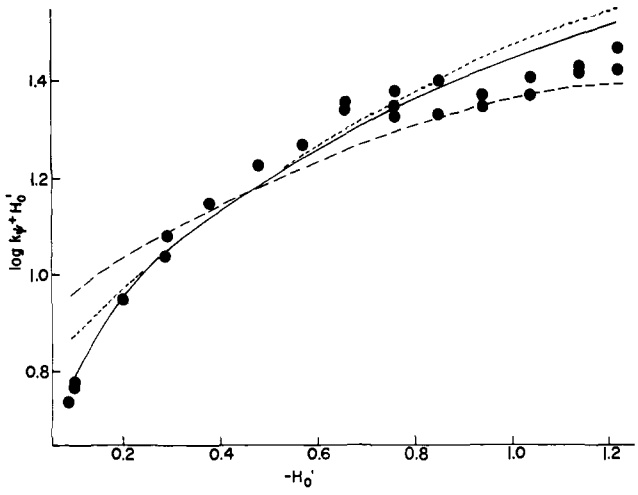


Figure 2. Rearrangement of 1,2-diphenylhydrazine in the H_o' region. The curves are calculated using eq 1a. — $K_a' = 5$ and log $k' = 1.55$; - - $K_a' = 2.5$ and log $k' = 1.45$; - - - $K_a' = 7$ and log $k' = 1.7$.

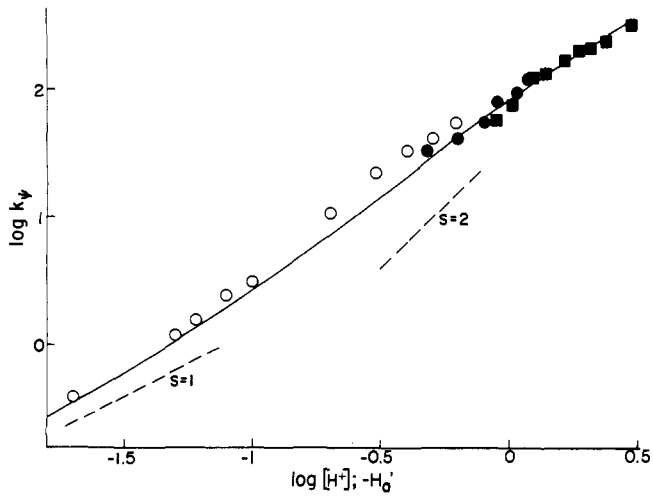
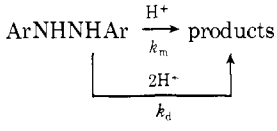


Figure 3. Rearrangement of 1,2-di-*o*-tolylhydrazine over a range of acidity. The solid line is calculated using eq 6. Open points, log [H+]; solid points, $-H_o'$. ○ ●, HCl; ■, $HClO_4$.

other values of the parameters, i.e., $K_a' = 2.5$ and log $k' = 1.45$ and 7 and 1.7, respectively.

In order to estimate the various rate and equilibrium constants for the rearrangement of 1,2-di-*o*-tolylhydrazine, we must first separate the second- and third-order rate constants, k_m and k_d, for the concurrent reactions in dilute acid.



In very dilute hydrochloric acid k_ψ is proportional to acid concentration, and the second-order rate constant for the one-proton rearrangement, $k_m = 15.6$ l. mol^{-1}s^{-1}. We then use eq 4 to calculate a value of k_d (for the two-proton rearrangement) of 170 l.^{2} mol^{-2} s^{-1}.

$$\log (k_\psi - k_m) = 2 \log [H^+] \quad (4)$$

A plot of log $(k_\psi - k_m)$ against log [H+] is linear with a slope of 2.03 up to 0.2 M acid.

Alternatively we use eq 5 to calculate k_m and k_d from overall rate constants in the above acidity range, and in dilute HCl $k_\psi/[H^+]$ varies linearly with [H+].

$$k_\psi/[H^+] = k_m + k_d[H^+] \quad (5)$$

This method gives $k_m = 15.6$ l. mol^{-1} s^{-1} and $k_d = 160$ l.^{2} mol^{-2} s^{-1}.

These equations fail at higher acidities where protonating power is greater than [H+] and the substrate is extensively monoprotonated. Assuming that both protonation steps follow h_o (and that monoprotonated substrate is the intermediate in both reactions) (Scheme II), we obtain the equation

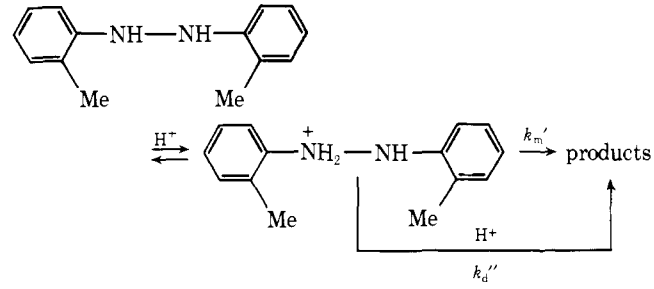
$$K_a' = \frac{h_o(k_m' + k_d''h_o)}{k_\psi} - h_o \quad (6)$$

(or $K_a' = \{[H^+](k_m' + k_d''[H^+])/k_\psi\} - [H^+]$ in dilute acid where $h_o \equiv [H^+]$).

In eq 6, $k_m = k_m'/K_a'$ and $k_d = k_d''/K_a'$, and the experimental values of k_ψ for acid concentrations greater than 10^{-2} M were fitted to eq 6 using the value of k_m determined above, treating k_d and K_a' as disposable parameters, and the best least squares fit gave $k_d = 150$ l.^{2} mol^{-2} s^{-1} and $K_a' = 1$ mol l.$^{-1}$. The agreement between experimental and theoretical values is satisfactory (Figure 3) and again the poorest fit is in 0.2–0.5 M acid.

In dilute acid, where monoprotonated 1,2-di-*o*-anisylhydrazine does not build up (Figure 4), a least-squares fit gives $k_m = 3400$ l. mol^{-1} s^{-1} and $k_d = 1.5 \times 10^5$ l.^{2} mol^{-2} s^{-1}. The deviations in the more acidic solutions are probably caused by experimental errors, because these rates approached the limits of the stopped-flow spectrometer, and the absorbance changes during reaction were not large.

Scheme II



It is generally accepted that the one-proton rearrangement involves a rapid preequilibrium formation of the monoprotonated species, which then decomposes spontaneously in the rate-limiting step.[2,3] Our concern, therefore, is the timing of the second proton transfer, and we consider first the rearrangement of 1,2-diphenylhydrazine. If the second proton transfer is an equilibrium step, a diprotonated species ($ArNH_2^+NH_2^+Ar$) must revert to the monoprotonated species much more rapidly than it goes on to products. In order to test this point, we must estimate K_a'', and hence k, which is the first-order rate constant for the (hypothetical) rearrangement of $ArNH_2^+NH_2^+Ar$ to products (Scheme I).

We used the following methods to estimate K_a'': (i) our spectroscopically determined values of pK_a for ionization of diprotonated phenylhydrazine of ca. −2 is approximately 7 log units more negative than pK_a for monoprotonated phenylhydrazine,[27] showing the effect of an adjacent positive charge, (ii) the acid dissociation constants for anilinium ions are larger than those for ammonium or alkylammonium ions by factors of ca. 10^5, and the diphenylammonium ion is more acidic than the anilinium ion by a factor of ca. 10^4, so that substituting a phenyl group for hydrogen on nitrogen reduces basicity by a factor of 10^4–10^5. Therefore K_a'' should be in the range 10^6–10^7.

In dilute acid for a two-preequilibria reaction of 1,2-diphenylhydrazine (Scheme I):

$$k_\psi/[H^+]^2 = 16 \text{ l.}^2 \text{ mol}^{-2} \text{ s}^{-1} = k/K_a'K_a''$$

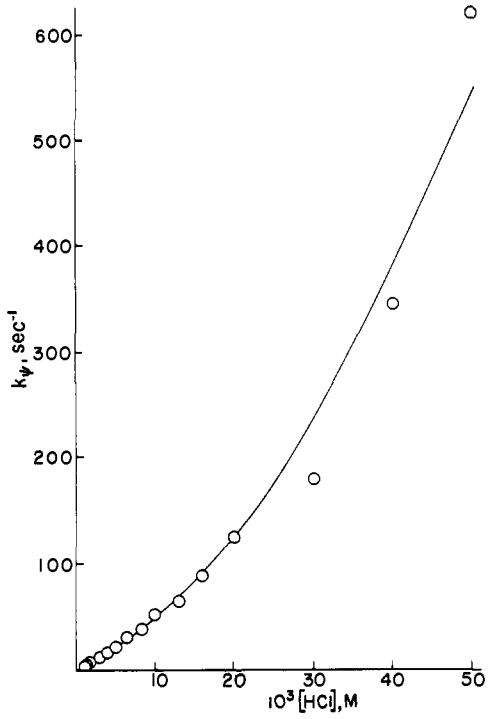
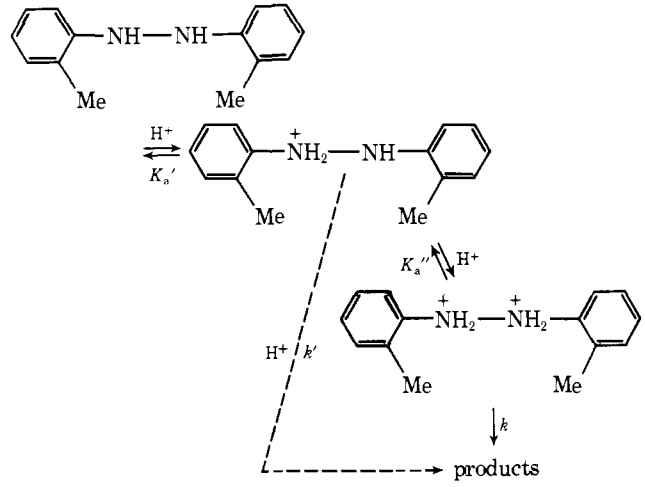
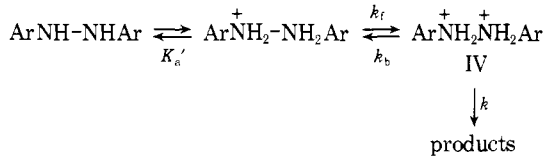


Figure 4. Rearrangement of 1,2-di-*o*-anisylhydrazine. The solid line is calculated using eq 5.

Scheme III



Scheme IV



so that if $K_a' \sim 6$ and $K_a'' = 10^6$–10^7, the first-order rate constant, k, must be in the range 10^8–10^9 s^{-1}. Alternatively, we can use the values of log k/K_a'' (or log k') of 1.55 calculated from reaction rates in moderately concentrated acid to give k in the range 4×10^7–4×10^8 s^{-1}. The important point is that proton loss from the diprotonated species to water cannot be faster than diffusion controlled,[28] and is usually much slower than that for protonated amines,[29] so that it is difficult to see how proton loss can be much faster than the hypothetical forward reaction to products (Scheme I). In that event $ArNH_2^+NH_2^+Ar$ would not be in equilibrium with its conjugate base, the second proton would be transferred during the rate-limiting step.

Similar arguments can be applied to the two-proton rearrangement of di-*o*-tolylhydrazine (Scheme III), for which we estimate $K_a' = 1$. The third-order rate constant for the two-proton rearrangement in dilute acid is

$$k_d = k/K_a'K_a'' = 160 \text{ l.}^2 \text{ mol}^{-2} \text{ s}^{-1}$$

for a hypothetical two-proton preequilibria reaction. If $K_a'' = 10^6$–10^7, k would have to be in the range 2×10^8–2×10^9 s^{-1} for both proton transfers to be preequilibria, and we believe that the second proton transfer is part of the rate-limiting step of the reaction of di-*o*-tolylhydrazine.

We were unable to follow the rearrangement of di-*o*-anisylhydrazine at acidities high enough for us to calculate K_a' kinetically. However K_a' and K_a'' should be similar to those of 1,2-diphenyl- or di-*o*-tolylhydrazine, i.e., $K_a' \sim 1$ and $K_a'' \sim 10^6$–10^7. If both protons are transferred in preequilibria, then

$$k_d = 1.5 \times 10^5 \sim k/10^6$$

$$\text{or} \sim k/10^7$$

(depending on the assumed value of K_a'') on the more conservative estimate $k \sim 10^{11}$ s^{-1}, and it is highly improbable that proton loss could be considerably faster than 10^{11} s^{-1}, so the second proton transfer to 1,2-di-*o*-anisylhydrazine also appears to be part of the rate-limiting step.

The values of K_a' and (the hypothetical) K_a'' would have to be lower than our estimates by orders of magnitude for the second proton transfer to be an equilibrium step, and proton loss from a diprotonated diarylhydrazine should not be faster than diffusion-controlled loss from strong oxygen acids to water.[28] Deprotonation of an alkylammonium by water is often slow,[29a,b] and proton loss from an anilinium ion is rate limiting in various nucleophilic aromatic substitutions.[29c] Rate constants for proton transfer through water to or from nitrogen or oxygen seem to be generally less than 10^8 s^{-1} for the thermodynamically favored reaction.[29d] A (hypothetical) diprotonated diarylhydrazine should be a very strong acid because of slow proton transfer to monoprotonated substrate rather than fast transfer from diprotonated substrate.

We can illustrate the problem posed by the assumption of two-proton preequilibria in another way because for rearrangement of di-*o*-anisylhydrazine $k_d = 1.5 \times 10^5$ l.^{2} mol^{-2} s^{-1}. For the hypothetical reaction with two-proton preequilibria (Scheme IV), $k_b \gg k$. If we suppose that $k_b \sim 10^{10}$, i.e., transfer is diffusion controlled,[28] then $k_f \sim 10^4$ l. mol^{-1} s^{-1} (taking $K_a'' \sim 10^6$), but then the maximum value of the third-order rate constant for the *formation* of the dication (IV) would be k_f/K_a', i.e., 10^4 l.^{2} mol^{-2} s^{-1} (if $K_a' \sim 1$), which is less than the observed rate constant (k_d) for the overall reaction.

Our conclusions apply only to these rearrangements in aqueous acid and not necessarily to other rearrangements of diarylhydrazines. There is no reason to believe that all two-proton benzidine rearrangements follow the same mechanism.

Our kinetic values of p$K_a' \sim 0$ are similar to those assumed by others,[3b,25,30] but our estimate of pK_a'' is somewhat more conservative than earlier estimates of a difference of 10^{12} between K_a' and K_a'' (cf. ref 3b).

Micellar Catalysis. The first-order rate constants for rearrangement of 1,2-diphenylhydrazine (I) increase sharply in the presence of anionic micelles of NaLS (Figures 5 and 6), and rate maxima were found at all concentrations of dilute acid. Preliminary results on the micellar catalysis of the rearrangement of 1,2-diphenylhydrazine have been given.[31]

The effects of anionic micelles on the rearrangements of 1,2-di-*o*-tolyl and di-*o*-anisylhydrazine (II and III) are shown

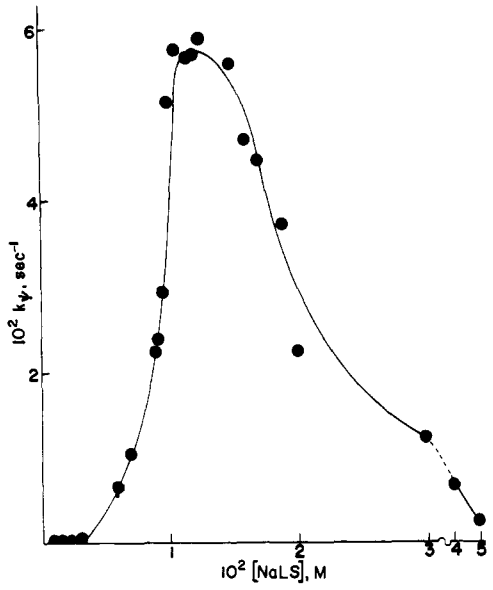


Figure 5. Catalysis of the rearrangement of 1,2-diphenylhydrazine over a range of concentration of NaLS in 1.65×10^{-3} M HCl.

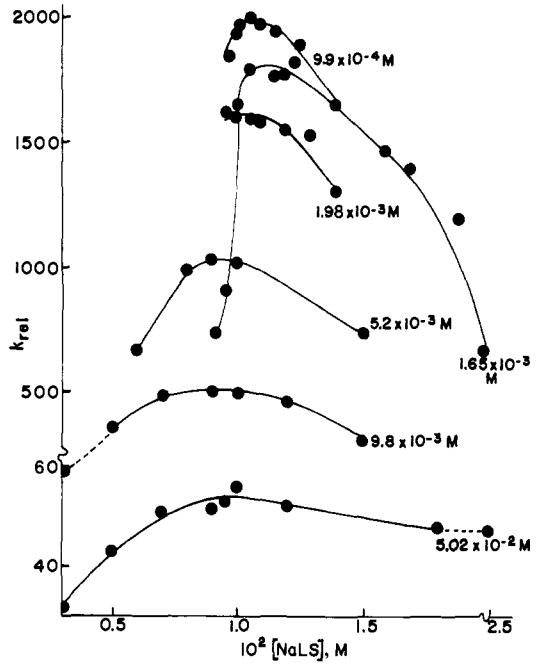


Figure 6. Rate enhancements of the rearrangement of 1,2-diphenylhydrazine by anionic micelles near to the rate maxima, at various molarities of HCl.

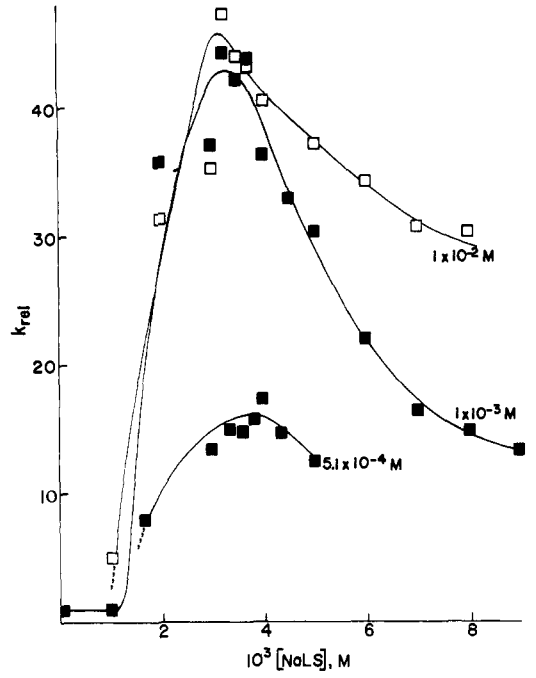


Figure 7. Rate enhancements of the rearrangement of 1,2-di-*o*-tolylhydrazine over a range of concentrations of NaLS at various molarities of HCl.

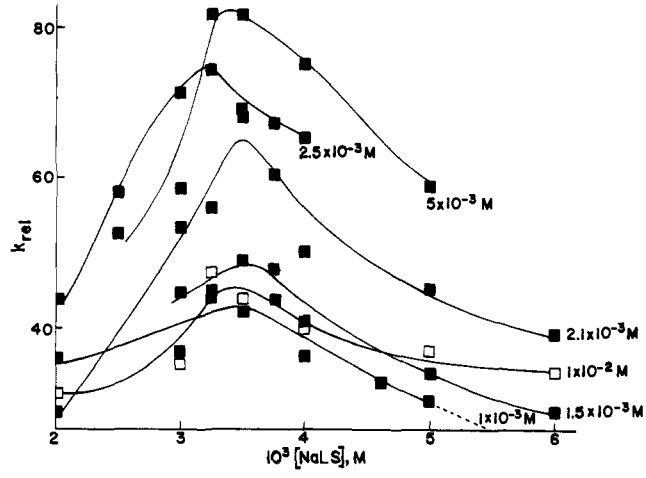


Figure 8. Rate enhancements of the rearrangement of 1,2-di-*o*-tolylhydrazine by anionic micelles of NaLS near to the rate maxima at various molarities of HCl.

in Figures 7-9. The results are summarized in Table II, which gives the first-order rate constants for the overall reactions in the absence of anionic micelles (k_ψ) and at the optimum surfactant concentration (k_ψ^M) over a range of acid concentrations. Rate enhancements are found at NaLS concentrations well below the critical micelle concentration (cmc), which is 8×10^{-3} M in water.[32] Acid and especially hydrophobic diarylhydrazines could lower the cmc, and this kinetic behavior is very common.[6-8]

In dilute acid the orders with respect to hydrogen ion are similar for the micellar and nonmicellar rearrangement of 1,2-diphenylhydrazine. The maximum value of k_ψ in the presence of micelles is denoted k^M, the first-order rate constant for reaction in the micellar pseudophase, and a plot of log k^M against log [H^+] is shown in Figure 10. The order with respect to acidity is apparent[10] because it is based on the stoichiometric acid concentration, although this problem should not be of major importance in dilute acid. For the other substrates the situation is more complex in that micelles of NaLS change the apparent reaction order, which becomes approximately second for the rearrangement of 1,2-di-*o*-tolylhydrazine even with low concentrations of acid, but is mixed for the rearrangement of 1,2-di-*o*-anisylhydrazine (Figure 10).

There is bending of some of the rate plots in Figure 10 with increasing acid concentration, due in part to substrate protonation.

Effects of Cationic and Nonionic Surfactants. The rearrangement of 1,2-diphenylhydrazine (I) is, as expected, strongly inhibited by cationic micelles of CTABr (Table III), which take up the hydrophobic substrate and protect it from hydrogen ions.[6-8] This behavior is typical of micellar inhibition in that a small amount of CTABr has little effect on the rate, which then falls sharply as micelles are formed and incorporate substrate.

Nonionic micelles of Brij 58 inhibit the rearrangement of

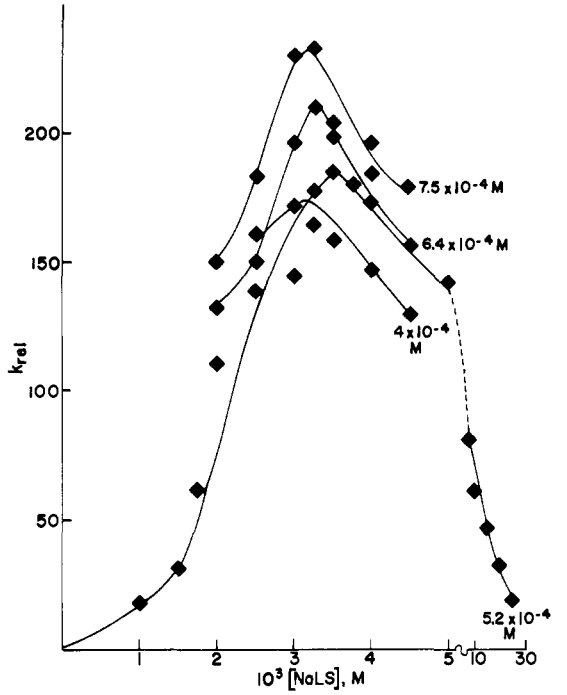


Figure 9. Rate enhancements of the rearrangement of 1,2-di-*o*-anisylhydrazine by anionic micelles at various molarities of HCl.

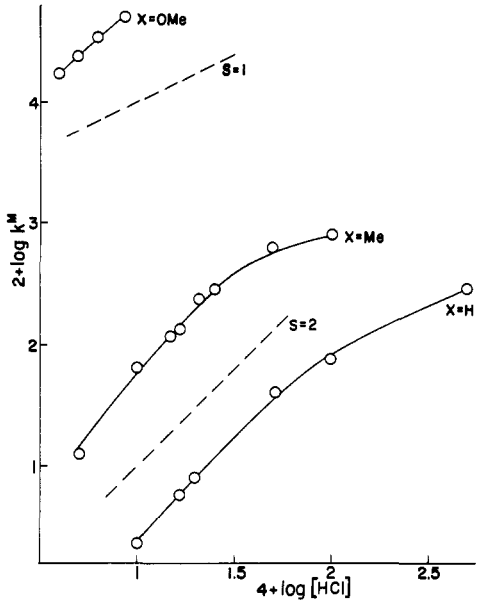
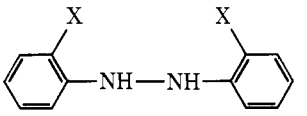


Figure 10. Variation of the maximum rate constants in anionic micelles of NaLS with acid concentration.

1,2-diphenylhydrazine, but their relatively small effect may be due to a change in the solvent rather than incorporation of substrate in the micelles, because initial addition of organic solvents to water slows rearrangement.[2,3,22] Some ionic reactions are inhibited by nonionic micelles, which incorporate a substrate and protect it from an ionic reagent.[6-8,33]

Micellar Inhibition by NaLS and Salt Effects. We know of no reaction which is catalyzed by a surfactant in one concentration and inhibited at another, and we believe that special circumstances are needed for its observation. We observed this behavior with 1,2-di-*o*-tolylhydrazine (Figure 11), probably because this compound is very hydrophobic and is taken up strongly by the micelles. It reacts at a rate which is convenient for conventional measurement, and we might have had mixing problems had we been forced to use a stopped-flow apparatus

Table II. Rate Constants of Rearrangements in Presence and Absence of Anionic Micelles[a]



	10^3[HCl], M	$10^2 k_{\psi}^{M}$, s^{-1} [b]	$10^2 k_{\psi}$, s^{-1}	k_{rel} [c]
X = H	0.99	2.3	0.0012	2000
	1.65	5.9	0.0032	1830
	1.98	7.9	0.0048	1650
	5.20	40	0.039	1030
	9.80	76	0.151	503
	50.2	282	5.01	56
X = Me	0.51	12.6	0.73	17
	1.00	65	1.47	44
	1.50	118	2.40	49
	2.10	237	3.48	68
	2.50	283	3.80	57
	5.00	634	7.74	82
	10.0	811	17.1	47
X = OMe	0.40	17400	97.7	178
	0.52	24600	132	185
	0.64	35900	170	211
	0.75	50000	214	234

[a] Rearrangement at 25.0°. [b] First-order rate constant at optimum concentration of NaLS. [c] Relative to k_{ψ} in the absence of surfactant.

Table III. Inhibition of the Rearrangement of 1,2-Diphenylhydrazine by CTABr and Brij 58[a]

$10^4 C_D$, M	CTABr	Brij 58
	38.8	38.8
1.00	38.6	31.3
2.00	13.4	
4.00		22.4
5.00	4.6	
10.0	2.31	14.5
80.0		4.0

[a] Values of $10^4 k_{\psi}$ (s^{-1}) at 25.0° with 1.63×10^{-2} M HCl.

for reactions in high concentrations of surfactant.

Rate maxima are typical of micellar-catalyzed reactions which involve attack upon a substrate in the rate-limiting step. It has been suggested that the counterion of an ionic surfactant acting as an inhibitor could be responsible for these maxima,[7,34] and added electrolytes typically reduce micellar catalysis and may suppress it completely if concentrations of hydrophobic counterions are used.[6-8]

Another explanation treats the micelles as if they were a separate phase, thus initial addition of a catalyzing surfactant "extracts" the reactants from water into the micellar phase with an increase in rate of a bimolecular reaction, but eventually addition of more surfactant merely dilutes the reagents in the micellar phase, and the rate then falls.[8,10,35] This dilution effect should be especially important in these two-proton benzidine rearrangements, especially with a hydrophobic substrate. Berezin and his co-workers have emphasized the importance of incorporation of both reactants in the micelle in their discussion of the reactions of oximes and esters.[36] It is noteworthy that rate maxima have not been observed for unimolecular micellar-catalyzed reactions.

For a micellar reaction to occur, the substrate and two hydrogen ions must be in the same micelle. We can reasonably assume that all the substrate and most of the hydrogen ions will be taken up in the micelles for these relatively high concentrations of NaLS (>0.05 M).[10] The observed first-order rate constant will be approximately proportional to the probability of finding substrate and two hydrogen ions in the same micelle,

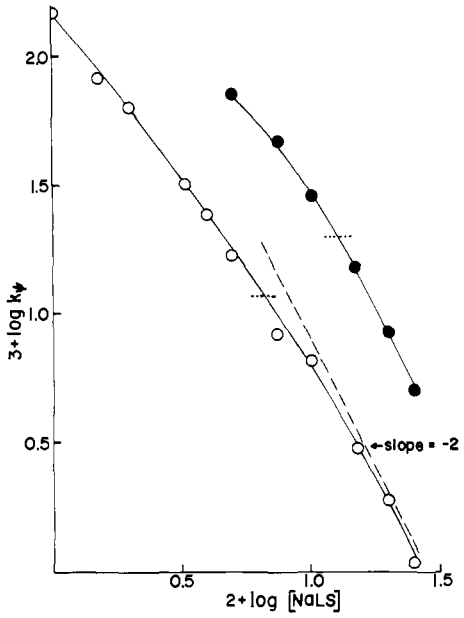


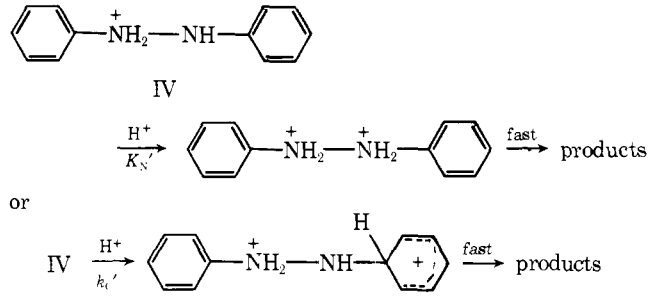
Figure 11. Inhibition of the rearrangement of 1,2-di-*o*-tolylhydrazine by high concentrations of NaLS. ○, 0.84×10^{-3} M HCl; in the absence of NaLS, $10^2k_\psi = 1.2\ s^{-1}$. ●, 1.8×10^{-3} M HCl; in the absence of NaLS, $10^2k_\psi = 2.98\ s^{-1}$. The values of k_ψ in the absence of NaLS are indicated as . . .

Table IV. Salt Effects upon the Micellar-Catalyzed Rearrangement of 1,2-Di-*o*-tolylhydrazine[a]

[NaLS], M	[NaCl], M	10^2k_ψ, s^{-1}
0.0033		177
0.0033	0.10	4.62
0.0033	0.15	4.08
0.0033	0.20	2.78
0.0033	0.25	2.27
0.10		2.86
0.15		1.51
0.20		0.84
0.25		0.50

[a] At 25.0° in 0.0018 M HCl. In the absence of surfactant and NaCl $10^2k_\psi = 2.98\ s^{-1}$.

Scheme V



which should vary approximately as the inverse square of the number of micelles, and therefore, as the inverse square of the concentration of NaLS, and for the higher surfactant concentrations a plot of log k_ψ against log [NaLS] has a slope of −2 (Figure 11). This approach is qualitative because it neglects changing micellar structure and cmc with increasing surfactant concentration[37] and the changing distributions of hydrogen ions between water and the micelles.[10] However, even at these very high surfactant concentrations, the apparent order with respect to hydrogen ions is still approximately two (Figure 11).

An increase in the surfactant concentration inevitably increases the concentration of sodium ions, and sodium chloride sharply reduces the micellar catalysis (Table IV), which is understandable because the two-proton rearrangement of 1,2-di-*o*-tolylhydrazine in NaLS should be much more sensitive to added cations than the one-proton reactions studied to date. But the first-order rate constants in moderately concentrated NaLS are considerably lower than those in dilute NaLS of a constant concentration of sodium ions, so that the inhibition by high concentrations of NaLS is not due solely to added sodium ions, suggesting that the decrease of rate, and eventual inhibition, at high concentrations of NaLS is due at least in part to a "dilution" of the reactants in the micellar pseudophase. We believe that this inhibition by high concentrations of a "catalyzing" surfactant has not been observed to date because for many reactions the surfactant would not be sufficiently soluble for a high enough concentration to be reached.

Discussion

Reaction in the absence of surfactant has been followed over a wide range of acidity, and because the variation of rate with acidity gives information on the rate-limiting steps for the one- and two-proton reactions this problem is considered first.

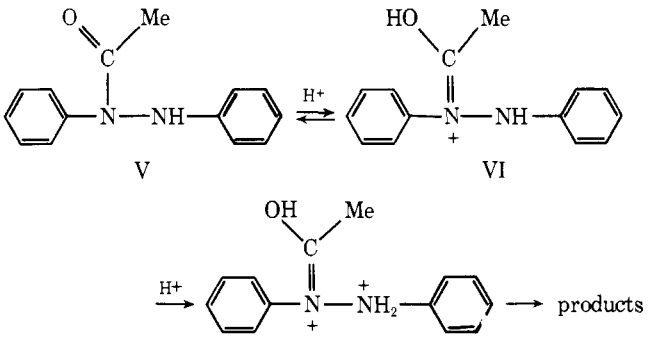
It is generally accepted that the first proton transfer to a 1,2-diarylhydrazine is a preequilibrium giving IV (Scheme I),[2,3] and 1,2-diphenylhydrazine hydrochloride has been isolated.[23] Our rate data show that under our reaction conditions the second proton transfer, either to nitrogen or to carbon with rate constants k_N' and k_C', occurs in the rate-limiting step, and leads to products either directly or by a series of rapid irreversible reactions (Scheme V). (If protonation is at the ipso position we would expect there to be some deuterium exchange in the aryl groups during rearrangement, unless this protonation is concerted with some other process. However, no exchange has been observed.[13]) There have in the past been a number of suggestions of slow proton transfers in benzidine rearrangements, but they were based on inferential rather than direct evidence.[38] (Other sites of carbon protonation are possible.[39])

The Question of Two-Proton Preequilibria. The assumption of two-proton preequilibria has been questioned implicitly by those who suggest that the second proton is transferred to carbon[12,13,39] (Scheme V), because such a transfer would probably be irreversible. Alternatively, we could suppose that the second proton is transferred to nitrogen, but this transfer is concerted with nitrogen–nitrogen scission leading irreversibly to products, or the diprotonated substrate rapidly gives products.

There are several two-proton benzidine rearrangements, mostly of dihalodiphenylhydrazines, in which the solvent isotope effect $k_{H_2O}/k_{D_2O} > 0.25$,[40] and it was suggested that here the second proton transfer to a weakly basic amino group may be part of the rate-limiting step.[3b] (Again one could postulate carbon protonation.) In another case, the rearrangement of *N*-acetyldiphenylhydrazine (V), one group reports $k_{H_2O}/k_{D_2O} \sim 1.25$,[41] but there is disagreement over the magnitude of the solvent isotope effect and the number of protons in the transition state of this reaction.[40,41] Banthorpe and co-workers report this to be a two-proton rearrangement,[40] but Cox and Dunn claim that V is hydrolyzed in dilute acid to 1,2-diphenylhydrazine, which then rearranges, and that V rearranges in more concentrated acid (e.g., 6 M $HClO_4$) in a one-proton reaction.[41] Professor Shine has pointed out to us that protonation could be on the amide residue, e.g., VI.[42] Amide protonation should be complete in 6 M $HClO_4$,[43,44] so that VI would then be the initial state, and the second protonation could be on the hydrazine nitrogen (Scheme VI) or on the ring, and the last two steps concerted with N–N scission.

For a one-proton rearrangement of di-*o*-tolylhydrazine acid

Scheme VI

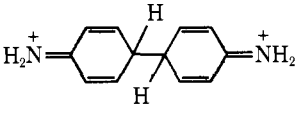


k_{H_2O}/k_{D_2O} = 0.43 (Table I), but for a two-proton rearrangement of diphenylhydrazine, it is 0.25, i.e., numerically larger than 0.43 × 0.43. The isotope effect on equilibrium monoprotonation should be essentially the same for both substrates, and therefore $k_{H_2O}/k_{D_2O} \approx 0.6$ for the second proton transfer. If the proton is transferred in the rate-limiting step, the overall isotope effect will be a combination of primary and secondary effects.[15c] The primary effects will give $k_{H_2O}/k_{D_2O} > 1$, and the secondary effects $k_{H_2O}/k_{D_2O} < 1$, so that our estimate of the isotope effect for the second protonation is consistent with, but does not require, a small contribution from a primary isotope effect.

Most workers have neglected the secondary isotope effects due to deuterium substitution in the hydrazine nitrogens of the substrate (cf. ref 25). Secondary deuterium isotope effects due to changes in hybridization are very important at C-H groups,[45] but they are probably less important at nitrogen, because the bending and stretching of N-H frequencies in amines and ammonium ions are not very different,[46] and they should be small relative to the observed solvent isotope effect.

Reactions which involve slow proton transfers are often subject to general catalysis. Although buffer effects have been observed in benzidine rearrangements,[38a] mixed solvents were used, and there seems to be no compelling evidence for general acid-catalysis (cf. ref 3a and 21). If the Bronsted exponent, α, is close to unity, general catalysis would not be observed.[47,48]

Mechanism of the Acid-Catalyzed Rearrangement. Our evidence suggests that under our conditions, proton transfer is part of the rate-limiting step. Olah and his co-workers have identified the dication (VII) in SbF_5-FSO_3H-SO_2 at low



VII

temperatures, and have shown that it readily generates diprotonated benzidine,[13] so that these final proton transfers should be rapid in hydroxylic solvents.[2,3] Thus VII must be formed in or after the rate-limiting step of a two-proton rearrangement.

It has been suggested that π-complexing holds the aryl groups together in the rearrangement,[25,30] and the claim that this theory fails to explain the kinetic form of a two-proton rearrangement was based on the assumption of preequilibrium proton transfers,[3] so that our evidence for rate-limiting proton transfer is consistent with the modified π-complex theory.[25,52] Several of the theories of both the one- and two-proton benzidine rearrangements are based on models in which one of the rearrangement partners is electron deficient, and the other is electron rich. To this extent distinctions between the π-complex and polar theories may be semantic rather than real (cf. ref 2a).

There is little or no evidence pointing to a change in hybridization in the transition state of the carbon atoms which give the new σ-bond. For example, substrate deuterium kinetic isotope effects are small or nonexistent,[2,3] except for a reaction in the naphthalene series which generates a carbazole by elimination of ammonia[3a] and the rearrangement of the *N*-acetyl derivative (V), where $k_H/k_D = 1.07$.[41] whereas an inverse secondary isotope effect should be found for a reaction in which the hybridization at the reaction center changes from sp^2 to sp^3 in the transition state.[45]

Intramolecularity merely requires that the two partners recombine much faster than they escape through the walls of a solvent cage. This description has been applied to many carbocation rearrangements[53] and to the *N*-nitramine rearrangement,[54] and because acid benzidine rearrangements are generally carried out in structured hydroxylic solvents, it is possible that solvent structure-induced interactions and π-complexing help to preserve intramolecularity.[55] (Some leakage from a solvent cage would be expected if there were no favorable interaction between the rearranging partners.)

The one-proton rearrangement apparently requires electron-donating substituents,[2,3] which is consistent with a polar transition state being generated from the N-monoprotonated substrate, or with a transition state akin to a π-complex or a radical-radical cation pair. There is extensive evidence for radical formation in some reactions of substituted hydrazines,[2,56] and formation of a pair of radical cations could be involved in benzidine rearrangements.[57a,b] This step should not be concerted with a slow proton transfer to nitrogen in a two-proton rearrangement, but it could follow it. Benzidine rearrangements are often accompanied by disproportionations or reductive N-N scission[2,3] which sometimes involve radicals,[57b] but these reactions may be independent processes, and most tests for radical formation in the benzidine rearrangement have failed.[2,3]

There are gaps in our understanding of the mechanism of the acid benzidine rearrangement, especially regarding N-N bond breaking, and evidence on heavy atom isotope effects would be particularly helpful. Substituent effects suggest a polar mechanism,[3] but there could be electronic, and sometimes steric, effects on protonation as well as on transition state formation from monoprotonated substrate. However the marked rate enhancements by strongly electron-donating substituents such as alkoxy[2,3,58] fit nicely with rate-limiting carbon protonation (see, however, ref 59), and maybe this is the mechanism for two-proton reactions of methoxy derivatives, whereas substrates not containing strongly electron-donating groups decompose with a second protonation on nitrogen.

Micellar Catalysis. Micellar effects upon the two-proton rearrangements of 1,2-diphenylhydrazine are much larger than that for a one-proton rearrangement and those typical of reactions having monoprotonated transition states.[6-8] The micellar catalysis decreases with increasing acid concentrations for reaction of 1,2-diphenylhydrazine, but increases for the dianisyl compound and goes through a maximum for the di-*o*-tolyl compound (Table II), in part because of a decrease in the fraction of micellar-bound hydrogen ions as acidity increases.[10] In addition, the mechanism may change with increasing acidity for substrates which can rearrange by both one- and two-proton mechanisms.

The rearrangement of 1,2-diphenylhydrazine is a two-proton reaction in the presence and absence of NaLS. Anionic micelles should assist both monoprotonation and conversion of a conjugate acid into a dicationic transition state. In dilute acid in the absence of surfactant, there is no build up of monoprotonated substrate ($pK_a \sim 0$ in aqueous acid) and micellar catalysis is large, but the micelle increases protonation so markedly that even in 0.05 M HCl in NaLS, 1,2-diphenylhydrazine is probably extensively protonated.[60] Under these conditions (e.g., 0.05 M HCl in NaLS), the micelle is merely

Table V. Summary of Catalysis of One- and Two-Proton Rearrangements by Anionic Micelles[a]

Substrate	k_m^M/k_m	k_d^M/k_d
1,2-Diphenylhydrazine[c]		2000[b]
1,2-Di-*o*-tolylhydrazine[d]	Small	4300[b]
1,2-Di-*o*-anisylhydrazine[e]	~50	~5000

[a] The subscripts m and d denote the second- and third-order rate constants for the one- and two-proton rearrangements, respectively, and the superscript M denotes reaction in the micelles. [b] In 10^{-3} M HCl. [c] $k_d = 16$. [d] $k_m = 15.6$ and $k_d = 160$. [e] $k_m = 3400$ and $k_d = 1.5 \times 10^5$. k_m, l. mol^{-1} s^{-1}; k_d, l.^{2} mol^{-2} s^{-1}.

assisting attack of the second hydrogen ion on the monoprotonated substrate, and the rate enhancement falls. The situation is similar for rearrangement of 1,2-di-*o*-tolylhydrazine (Figure 10), except that in the absence of micelles there is an extensive contribution from the one-proton rearrangement, whereas in micelles only the two-proton rearrangement is observed.

The micellar catalysis of the rearrangement of 1,2-di-*o*-anisylhydrazine increases with increasing acidity (Table II). There is in water an incursion of a two-proton rearrangement, which should be catalyzed very much more strongly than the one-proton rearrangement by the micelles, so that its contribution steadily increases with increasing acidity for the micellar-catalyzed reaction, but there is no build up of monoprotonated substrate in the dilute acid. Thus here and elsewhere the micelles change the reaction mechanism.

We can estimate the micellar catalyses of the two-proton rearrangements of both 1,2-diphenylhydrazine and 1,2-di-*o*-tolylhydrazine directly. For the former the rate enhancement is the value of k_{rel} (Table II) in dilute acid. For the ditolyl compound (II) the one-proton rearrangement makes almost no contribution to the micellar reaction (Figure 10), and in the absence of surfactant, the third-order rate constant is 160 l.^{2} mol^{-2} s^{-1} (Results). Using this value and those of k_ψ in the presence of surfactant we estimate the micellar rate enhancement for the *two-proton* rearrangement given in Table V. We cannot estimate the (small) micellar catalysis of the one-proton rearrangement for this compound.

The situation is more complicated for rearrangement of 1,2-di-*o*-anisylhydrazine, which is close to first order with respect to H^+ in dilute aqueous acid (Figures 1 and 4), but has an apparent order of 1.73 with respect to total hydrogen ion concentration for the reaction catalyzed by micelles of NaLS (Figure 10). We could follow the micellar-catalyzed rearrangement only over a limited range of acidity, but we use the apparent order to give the following equations

$$k_\psi = k_{app}[H^+]^{1.73} \quad (7)$$

$$k_\psi = k_M^M[H^+] + k_D^M[H^+]^2 \quad (8)$$

so that

$$k_{app} = k_M^M[H^+]^{-0.73} + k_D^M[H^+]^{0.27} = 1.5 \times 10^8 \quad (9)$$

From eq 9 and using all the data points, we estimate k_d^M/k_m^M in the range 4000–6440 with a mean of 4860, and solving eq 8 then gives the values of k_d^M and k_m^M in Table VI. Alternatively, we can solve eq 9 directly, and both sets of values are given in Table VI.

Because of the small range of acid concentrations used, these values of k_m^M and k_d^M are approximate, but combined with the values of k_m and k_d in the absence of anionic surfactant, they give rate enhancements by micelles of NaLS of ca. 50 for the one-proton rearrangement and ca. 5000 for the two-proton rearrangement of 1,2-di-*o*-anisylhydrazine (Table V), confirming our initial hypothesis that micelles should be much more effective catalysts for the two- than for the one-proton

Table VI. Estimation of Second- and Third-Order Rate Constants for Rearrangement of 1,2-Di-*o*-anisylhydrazine in Anionic Micelles

10^4 [H$^+$], M	4.0	5.2	6.4	7.5	Av value
$10^{-5}k_m^M$ *a*	1.48	1.34	1.36	1.44	1.4
$10^{-5}k_m^M$ *b*	1.68	1.71	1.70	1.69	1.7
$10^{-8}k_d^M$ *a*	7.18	6.52	6.63	6.97	6.8
$10^{-8}k_d^M$ *b*	8.16	8.32	8.28	8.23	8.2

[a] Calculated using eq 8. [b] Calculated using eq 9.

rearrangement, and showing that the low catalysis of the overall rearrangement of 1,2-di-*o*-tolylhydrazine (Table II) arises simply from a mechanistic change brought about by the anionic micelles. As is generally found, hydrophobic substituents increase the micellar catalysis.

We used the overall rates of rearrangement in aqueous acid and the estimated basicities of the substrates as evidence that the second protonation could not be an equilibrium reaction. The apparent third-order rate constants for rearrangement in the presence of micelles are large (Tables V and VI), which provides supportive rather than compelling evidence for slow proton transfers in these micellar-catalyzed reactions. Unless the micellar effects on basicity are much larger than in other systems,[61] our results for reactions in the anionic micelles are incompatible with the hypothesis that both protons are transferred in preequilibria.

It is often difficult to separate the roles of the micelle as a microsolvent[35] and as the agent which brings reagents together, but the large difference between the micellar catalysis of one- and two-proton rearrangements suggests that this second factor is very important, because organic solvents retard benzidine rearrangements.[2,3,22] Some of the factors which control micellar catalysis should be similar to those which control enzymic catalysis and the high rate of many intramolecular reactions.[9] It has been argued that proximity effects cannot be large for reaction on an enzyme or other submicroscopic aggregate, assuming that there are no specific interactions between catalyst and reagent (cf. ref 62).

Formation of a transition state from two or more reagents requires loss of translational and possibly rotational entropy, and in general entropies of activation are more negative for bimolecular than for unimolecular reactions.[63] Thus if the reactants can be brought together on a micelle so that the entropy loss is offset by beneficial interactions between the micelle and the reactants, there will be a smaller entropy loss in generating the transition state (cf. ref 33).

For the benzidine rearrangement, it may not be profitable to attempt to separate the rate enhancement due to increased reagent concentration in the micellar phase from that due to a reduced entropy loss in transition state formation. Reagent concentration in bulk solvent can be measured either in terms of moles per unit volume (molarity) or per mole of solvent (molality or mole fraction). On the micelle, if reagents are close to the surface we could measure their concentrations using either the volume of the Stern layer, or the number of ionic head groups of the micelle, and the problem is compounded by that of the distribution of hydrogen ions and substrate over all the surface of the micelles. But it is difficult to ascribe all the micellar rate enhancements of the two proton rearrangements merely to enhanced reactant concentration in the micelles.

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