Catalysis of α-Hydrogen Exchange. XIII. Bifunctional Catalysis of the Dedeuteration of Isobutyraldehyde-*2-d* by Polyethylenimines[1]

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Abstract: Catalysis of the dedeuteration of isobutyraldehyde-*2-d* by polyethylenimines (PEI's) in aqueous solution is interpreted in terms of the reversible transformation of the aldehyde to an iminium ion by a primary amino group on the polymer followed by rate-controlling internal removal of a deuteron by another amino group in the same molecule. The pseudo-first-order rate constant for the reaction of aldehyde at a given concentration increases with increasing PEI concentration at first and then levels off as the aldehyde becomes completely complexed. Analogously, the rate of reaction at a given concentration of PEI increases with increasing aldehyde concentration and then levels off. The amount of aldehyde complexed under various conditions is followed by uv measurements. The catalytic activities of PEI's with molecular weights in the range 600–1800 are (on a per amino group basis) similar and are 12–36 times those of ethylenediamine and its various *N*-ethyl derivatives, model compounds that cannot act as bifunctional catalysts. Poly(*N*-ethylaziridine), a polymeric tertiary amine, is a much poorer catalyst. The catalytic efficiency of PEI-1800 is at a maximum near pH 8. Added 1,4-diazabicyclo[2.2.2]octane or 3-quinuclidinone increases the rate of dedeuteration of the aldehyde in the presence of excess PEI by attacking the aldehyde that is complexed as iminium ions; added disodium phosphate is ineffective. Lauroylating the PEI to increase the effectiveness of complexing the aldehyde is also ineffective.

Earlier articles in this series reported that in the presence of moderate concentrations of a primary amine salt and a buffer the dedeuteration of isobutyraldehyde-*2-d* is largely a third-order reaction, first order in aldehyde, first order in buffer base, and first order in amine salt.[2–5] Evidence was described that this reaction involves the reversible transformation of the deuterated aldehyde into the corresponding *N*-alkylisobutyraldiminium ion followed by rate-controlling removal of deuterium by buffer base (B). The

$$Me_2CDCHO + RNH_3^+ \rightleftharpoons Me_2CDCH{=}NHR^+ + H_2O$$

$$Me_2CDCH{=}NHR^+ + B \longrightarrow Me_2C{=}CHNHR + BD^+$$

earlier investigations were carried out with the plan that they would be extended to studies of polyfunctional catalysis of α-hydrogen exchange reactions. If the primary amine whose salt is used as a catalyst contains another basic group (B) suitably oriented in the molecule, the compound may act as a bifunctional catalyst. In such a case, the removal of deuterium from carbon would take place intramolecularly, as shown in eq 1. This paper gives evidence that polyethylenimines act as bifunctional catalysts for the dedeuteration of isobutyraldehyde-*2-d* by the mechanism described above.

$$\underset{\text{D}}{Me_2CCH{=}\overset{+}{N}HR} \longrightarrow \underset{\text{D—B}^+}{Me_2C{=}CHNHR} \qquad (1)$$
$$\quad\ \text{B}$$

The polyethylenimines (PEI's) used were obtained from the Dow Chemical Co., where they were prepared by the polymerization of ethylenimine. Although the simplified formula $(-CH_2CH_2NH-)_n$ is sometimes written for these polymers, they have a degree of branching such that the ratio of primary to secondary to tertiary amino groups is about 1:2:1.[6] We shall designate a PEI with a number average molecular weight of X as PEI-X.[7]

Results and Discussion

Effect of Concentrations of Polyethylenimines and Isobutyraldehyde-*2-d* on the Dedeuteration Rate. The dedeuteration of isobutyraldehyde-*2-d*, followed as described previously,[2–5] obeyed a first-order rate equation in a given run. With a given initial concentration of isobutyraldehyde-*2-d*, the first-order rate constants increased with increasing PEI concentrations[8] at low PEI concentrations but levelled off at high PEI concentrations, as shown in Figure 1. An obvious interpretation of these results is that the dedeuteration is occurring almost entirely *via* a complex formed between the aldehyde and PEI. The rate increases as increasing concentrations of PEI transform more aldehyde to complex and essentially levels off as complex formation approaches 100%. This interpretation is supported by measurements of the absorbance at 285 nm (the aldehyde absorption maximum) using the PEI solutions without aldehyde as references. As shown in Figure 1, the decrease in absorbance fairly closely reflects the increase in rate of de-

(1) (a) This work was supported in part by Public Health Service Research Grants AM 10378 from the National Institute of Arthritis and Metabolic Diseases and GM 18593 from the National Institute of General Medical Sciences. (b) For part XII, see J. Hine, J. L. Lynn, Jr., J. H. Jensen, and F. C. Schmalstieg, *J. Amer. Chem. Soc.*, 95, 1577 (1973). (c) Abstracted in part from the Ph.D. Dissertation of E. F. Glod, 1971. (d) For a preliminary communication of the present results, see J. Hine, F. E. Rogers, and R. E. Notari, *J. Amer. Chem. Soc.*, 90, 3279 (1968).

(2) J. Hine, B. C. Menon, J. H. Jensen, and J. Mulders, *ibid.*, 88, 3367 (1966).

(3) J. Hine, F. C. Kokesh, K. G. Hampton, and J. Mulders, *ibid.*, 89, 1205 (1967).

(4) J. Hine, J. Mulders, J. G. Houston, and J. P. Idoux, *J. Org. Chem.*, 32, 2205 (1967).

(5) J. Hine, B. C. Menon, J. Mulders, and J. P. Idoux, *ibid.*, 32, 3850 (1967).

(6) "Montrek Polyethylenimine Products," Dow Chemical Co., Midland, Mich., 1966, p 2.

(7) The Dow trade name for PEI-X is Montrek-X/100; thus PEI-1800 is Montrek-18.

(8) Normalities of polyamines refer to the number of equivalents of amino groups per liter.

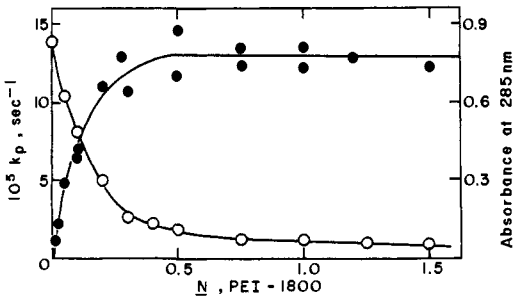


Figure 1. Isobutyraldehyde (0.053 *M*) in water at 35° and pH 8.48 ± 0.06 in the presence of various concentrations of PEI-1800: (●) first-order rate constants for the dedeuteration of the 2-deuterio derivative; (○) absorbance at 285 nm.

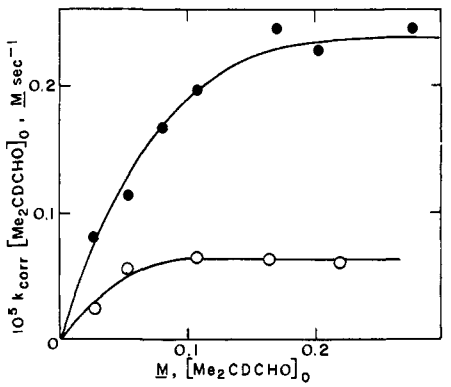


Figure 2. Plot of corrected initial reaction rates *vs.* initial concentrations of isobutyraldehyde-*2-d*: (○) in the presence of 0.0100 *N* PEI-1800 at pH 8.49 ± 0.05; (●) in the presence of 0.0267 *N* PEI-1800 at pH 8.50 ± 0.05.

deuteration; above PEI concentrations of about 0.4 *N* there is little further decrease in absorbance or increase in rate with increasing concentration of PEI. The uv measurements showed that the rate of complexing is much greater than the rate of deuterium exchange.

Just as the aldehyde can be saturated with catalyst, the catalyst can be saturated with aldehyde. Saturation of catalyst with reactant is often observed in enzymatic reactions and illustrated by plotting the reaction rate *vs.* the reactant concentration at constant catalyst concentration.[9] Figure 2 contains plots of corrected initial rates of dedeuteration (namely, the first-order rate constant for dedeuteration, corrected for catalysis by water and hydroxide ions, and then multiplied by the initial concentration of isobutyraldehyde-*2-d*) *vs.* initial concentrations of isobutyraldehyde-*2-d*. The corrections never amounted to more than 9% of the overall reaction rate. The rate of dedeuteration in the presence of 0.0100 *N* PEI no longer increases significantly above aldehyde concentrations of about 0.1 *M*. In the presence of 0.0267 *N* PEI the rate approaches constancy more slowly, suggesting that the complexed PEI can still dedeuterate the aldehyde, presumably by acting as a simple basic catalyst. Such an effect would be smaller in the more dilute PEI solutions and also more difficult to detect because the rate constants in the presence of large concentrations of aldehyde are so small as to be particularly difficult to determine experimentally.

(9) *Cf.* J. B. Neilands and P. K. Stumpf, "Outlines of Enzyme Chemistry," 2nd ed, Wiley, New York, N. Y., 1958, Chapter 8.

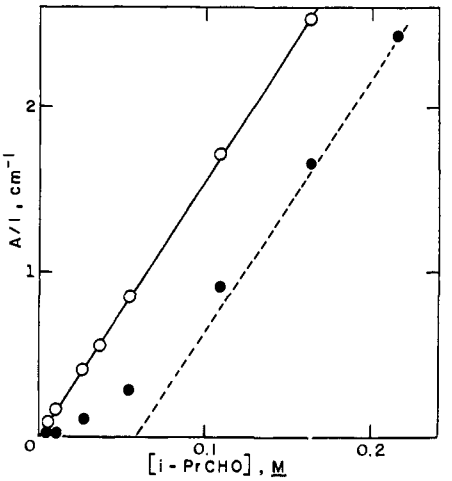
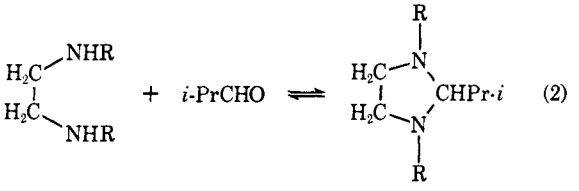


Figure 3. Plot of absorbance divided by cell path length *vs.* concentration of added isobutyraldehyde in water at 35°: (○) in the absence of PEI; (●) in the presence of 0.200 *N* PEI-1800 at pH 8.50 ± 0.04.

To learn more about the stoichiometry of complex formation, the absorbance at 285 nm of solutions 0.200 *N* in PEI-1800 was measured in the presence of increasing concentrations of isobutyraldehyde with the results shown by the solid circles in Figure 3 (using the PEI solutions without aldehyde as references). At first the addition of aldehyde brings about little increase in absorbance because the aldehyde is transformed largely to complexes that absorb much more weakly. At higher aldehyde concentrations the absorbance increases more markedly. Absorbances of aldehyde solutions containing no PEI are shown by the open circles, which describe a line whose slope is equal to that of the theoretical asymptote to the curve described by the solid circles. From this fact the asymptote has been approximated as the dashed line, which was constructed so as to have the proper slope and to pass through the solid circle corresponding to the largest concentration of aldehyde. From the intercept of this asymptote on the [*i*-PrCHO] axis it follows that if the absorbance of the complex is negligible compared with that of the aldehyde, the amount of isobutyraldehyde complexed with PEI-1800 at 35° and pH 8.5 asymptotically approaches about 0.30 mol of aldehyde per equivalent of amine in the presence of excess aldehyde. If the complex does absorb at 285 nm, this number will be higher. Measurements in the presence of excess PEI show that the absorbance of the complex is certainly less than 6% that of the aldehyde. To the extent to which these observations may be extrapolated to the perhaps different complexes formed in the presence of excess aldehyde, there must be less than 0.32 mol of aldehyde complexed per equivalent of amine. The complexed aldehyde must be present largely in the form of imines, imidazolidines, which may be formed from any segment of the polymer in which two secondary amino groups or a primary and



(2)

secondary amino group are separated by one ethylene group, and perhaps imidazolidinium ions. The equilibrium constants for the formation of such adducts[10,11] are considerably larger than those for the formation of such other possibilities as iminium ions,[10,12] carbinolamines,[13] and probably the larger ring heterocycles. Since about 25% of the amino groups are primary, it should be possible to complex no more than 0.25 mol of aldehyde per equivalent of amine as imines. The 50% of secondary amino groups could complex as much as another 0.25 mol of aldehyde as imidazolidines if these secondary amino groups were all arranged in pairs with one ethylene group between the two nitrogen atoms of each pair. Deviations from this ideal behavior are no doubt partly responsible for the failure of the PEI to complex with any more aldehyde, but the fact that an appreciable fraction of the amino groups are protonated at pH 8.5 is also a significant contributing factor. A plot similar to that in Figure 3, but carried out on PEI-1800 solutions to which no acid had been added to adjust the pH, revealed that about 0.38 mol of aldehyde per equivalent of amine had been complexed in the presence of about 0.1 *M* excess aldehyde.

When the spectral data obtained in the presence of excess aldehyde were treated in a manner similar to that described for the reaction of primary amines with isobutyraldehyde,[10] the results obtained varied rather erratically and were highly sensitive to the value taken for the number of complexing sites per amino group. The data obtained in the presence of excess PEI (Figure 1) and the assumption of 0.30 as many complexing sites as amino groups gave an apparent equilibrium constant of about 80 M^{-1} for complexing of isobutyraldehyde to the active sites. This is an *apparent* equilibrium constant because the complexing sites are of more than one type, because the number of available sites must vary with the varying amounts of acid required to bring the pH to 8.5 in the presence of varying amounts of aldehyde, and because we do not know the number of sites available under any of the conditions that the calculations refer to. However, we do know that considerably more acid must be added to adjust the pH in the presence of excess PEI than in the presence of excess aldehyde. Hence the number of available sites for complexing must be lower than the figure 0.30 per amino group, which was obtained from measurements in the presence of excess aldehyde. With a smaller number of sites a larger equilibrium constant than 80 M^{-1} would be calculated; plausible estimates give values up to 200 M^{-1} or more. Since the equilibrium constant for imine formation from isobutyraldehyde and *N,N*-dimethylethylenediamine is only 31 M^{-1} and protonation should decrease it,[10] the values observed for complexing with PEI must include a significant component from imidazolidine formation, for which equilibrium constants are significantly larger.[11]

The absorption spectrum of isobutyraldehyde in the presence of excess PEI-1800 showed a maximum around 244 nm, which is plausible for a derivative of isobutyraldimine but not for a simple imidazolidine. The intensity of absorption was greater in the presence of small excesses than in the presence of large excesses of PEI, indicating that a larger fraction of the complex is present as imine when there is only a small excess of PEI (and the sites at which imidazolidines may be formed are more nearly saturated).

The rate of the dedeuteration of isobutyraldehyde-*2-d* in the presence of 0.0100 *N* PEI-1800 at pH 8.5 is seen from Figure 2 to level off at about 6.1×10^{-7} M sec^{-1} in the presence of excess aldehyde. Since the concentration of complexed aldehyde must have been about 0.0030 *N* under these conditions, it follows that the first-order rate constant for loss of deuterium by the average complexed aldehyde must be $6.1 \times 10^{-7}/0.003$ or 2.0×10^{-4} sec^{-1}. Similar calculations on the reaction in the presence of 0.0267 *N* PEI-1800 give a rate constant of 3.0×10^{-4} sec^{-1} for the average complexed aldehyde. Part of the difference in these two rate constants probably arises from the ability of the completely complexed PEI to catalyze the reaction by acting as a simple base and part from experimental error. The rate constant $\sim 1.3 \times 10^{-4}$ sec^{-1}, at which the dedeuteration of isobutyraldehyde-*2-d* roughly levels off in the presence of excess PEI-1800 at pH 8.5 (Figure 1), should also be a first-order rate constant for the dedeuteration of the average complexed aldehyde. It is understandable that this rate constant could differ significantly from values obtained in the presence of excess aldehyde. In the presence of excess PEI the complexed aldehyde consists of a different mixture of imines and imidazolidines; furthermore, it is surrounded by amine groups. The average complexed aldehyde in the presence of excess aldehyde is surrounded by imine, imidazolidine, and tertiary amine groups but by smaller numbers of secondary amine and very few primary amine groups. The groups present in the presence of excess aldehyde are, on the average, more weakly basic and hence would be protonated to a smaller extent at a given pH. Hence the groups available to act as internal basic catalysts must differ greatly in the two cases.

Relative Catalytic Efficiencies of Polyethylenimines and Model Compounds That Can Act Only as Monofunctional Catalysts. PEI's may be considered to be collections of primary, secondary, and tertiary amino groups joined by ethylene groups. In order to learn more about the monofunctional catalytic activity to be expected of such collections, we have studied the catalytic activity of ethylenediamine and some of its *N*-methyl and *N*-ethyl derivatives. Some evidence that these compounds do not act as bifunctional catalysts (species having two functional groups that act on the substrate at the same time) has already been described;[14] more will be described here. If the simple ethylenediamine derivatives could act bifunctionally, the catalytic efficiencies observed for them would be maxima for their monofunctional catalytic efficiencies. The dependence of the reaction rate on the catalyst concentration and on the pH of the solution is not the same for all the catalysts studied. Nevertheless, we believe that useful conclusions may be drawn from the rate constants in Table I.

(10) J. Hine, C. Y. Yeh, and F. C. Schmalstieg, *J. Org. Chem.*, **35**, 340 (1970).
(11) K. W. Narducy, Ph.D. Dissertation, The Ohio State University, 1971.
(12) J. Hine, J. C. Craig, Jr., J. G. Underwood, II, and F. A. Via, *J. Amer. Chem. Soc.*, **92**, 5194 (1970).
(13) J. Hine and J. Mulders, *J. Org. Chem.*, **32**, 2200 (1967).
(14) J. Hine, M. S. Cholod, and J. H. Jensen, *J. Amer. Chem. Soc.*, **93**, 2321 (1971).

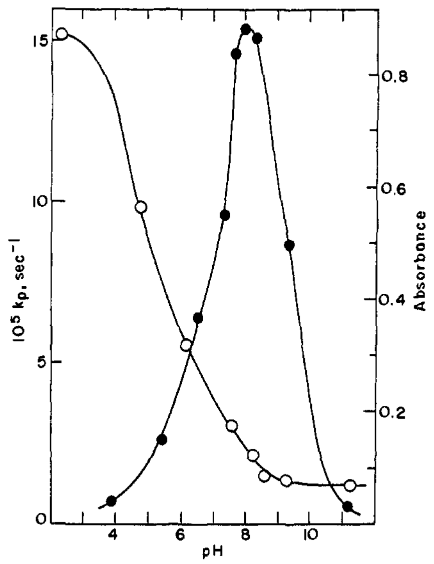


Figure 4. Isobutyraldehyde-*2-d* (0.053 *M*) in the presence of 0.97 ± 0.03 *N* PEI-1800: (●) rate constants for dedeuteration; (○) absorbance at 285 nm.

Table I. First-Order Rate Constants for the Dedeuteration of 0.053 *M* Isobutyraldehyde-2-*d* at 35° and pH 8.51 ± 0.04

Catalyst[a]	10^6k_p, sec^{-1}	Catalyst[a]	10^6k_p, sec^{-1}
$H_2NCH_2CH_2NH_2$	2.0	$EtNHCH_2CH_2NHEt$	4.6
$MeNHCH_2CH_2NH_2$[b]	3.0	$Et_2NCH_2CH_2NH_2$	3.7
$MeNHCH_2CH_2NHMe$	3.6	$Et_2NCH_2CH_2NHEt$	5.5
$Me_2NCH_2CH_2NH_2$	15	$Et_2NCH_2CH_2NEt_2$	3.3
$Me_2NCH_2CH_2NHMe$	23	PEI-600[c]	75
$Me_2NCH_2CH_2NMe_2$	35	PEI-1200[d]	79
$EtNHCH_2CH_2NH_2$	3.4	PEI-1800[e]	70

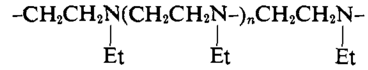
[a] 0.100 ± 0.001 *N* unless otherwise noted. [b] 0.097 *N*. [c] 0.103 *N*. [d] 0.113 *N*. [e] 0.104 *N*.

If ethylenediamine and its N-ethylated derivatives are taken as the best models, the PEI's may be seen to be 12–36 times as effective as catalysts as they would be expected to be if they were acting monofunctionally. This increase in reactivity is much smaller than those observed with many enzymes. It is more nearly comparable with the bifunctionally catalyzed mutarotation of tetramethylglucose by 2-pyridone, which, at a concentration of 0.05 *M*, is about 50 times as effective a catalyst as a mixture of 0.05 *M* phenol and 0.05 *M* pyridine.[15] The decreased activity of triethylethylenediamine and tetraethylethylenediamine relative to that of the corresponding methyl compounds is presumably largely due to steric hindrance. The decreased reactivity of ethylenediamine and its *N*-methyl and *N,N'*-dimethyl derivatives, relative to that of the more highly methylated derivatives, must be due, at least in part, to the ability of these diamines to transform much of the aldehyde into unreactive imidazolidines.[11]

The fact that a change of threefold in the molecular weight of the PEI had no major effect on the catalytic activity will be discussed in a future paper dealing with the probable length of the polymer chain between the primary amino group that transforms the aldehyde into an iminium ion and the amino group that removes the α deuteron.

(15) C. G. Swain and J. F. Brown, Jr., *J. Amer. Chem. Soc.*, 74, 2534, 2538 (1952).

To test the possibility that all polymeric amines are particularly effective catalysts in the dedeuteration of isobutyraldehyde-*2-d*, we measured the catalytic activity of poly(*N*-ethylaziridine), a polyethylenimine derivative with all its amino groups tertiary and with a straight-chain structure. The results of measure-

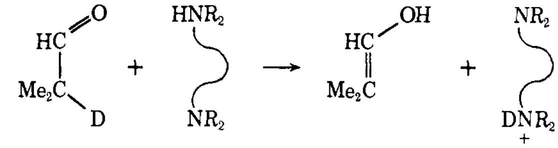


ments at several pH's are shown in Table II, where

Table II. Kinetics of the Dedeuteration of Isobutyraldehyde-2-*d* in the Presence of Poly(*N*-ethylaziridine)

$[Me_2CDCHO]_0$, *M*	[Poly(*N*-ethylaziridine)], *N*	pH	10^6k_p, sec^{-1}
0.073	0.236	9.72	15
0.091	0.243	8.45	5.1
0.055	0.192	8.45	4.5
0.121	0.405	8.00	6.3

the catalytic efficiency at pH 8.45 may be seen to be less than one-tenth that of PEI-1800 solutions that are only half as strong. These results support our hypothesis of bifunctional catalysis *via* intermediate iminium ions. Catalysis *via* a push-pull mechanism[16] such as that shown in eq 3 could also occur with poly(*N*-ethylaziridine).



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Effects of pH, External Bases, and Hydrophobic Bonding on the Dedeuteration Rate. If the PEI's are acting simply as basic catalysts, their catalytic efficiency should decrease with decreasing pH as more of the amino groups on the catalyst are protonated and the basicity of the remaining amino groups is decreased by the introduction of nearby positively charged substituents. Instead, as shown in Figure 4, the catalytic efficiency of 0.97 *N* PEI-1800 (toward 0.053 *M* isobutyraldehyde-*2-d*) is at a maximum near pH 8.0. This behavior is that expected from the bifunctional mechanism for catalysis proposed (or from any mechanism involving the dedeuteration of an iminium ion by an amine). Above pH 8 the reaction rate is slower because a smaller fraction of the imines formed are protonated to give iminium ions. Below pH 8 the rate is slowed by the decreased number and basicity of the free amino groups available for internal dedeuteration. Another relevant factor may be seen in the absorbances of isobutyraldehyde in the presence of 1.00 *N* PEI-1800 at various pH's, also plotted in Figure 4. This plot shows that below about pH 9 the amount of aldehyde complexed decreases with increasing acidity. This decreasing efficiency of complexing with aldehyde results from the decreasing number of free amino groups present in the polymer. It must contribute to the decrease in efficiency of catalysis, but it cannot be the

(16) *Cf.* G. E. Lienhard and F. H. Anderson, *J. Org. Chem.*, 32, 2229 (1967).

only cause since at pH 4.7, where about one-third of the aldehyde is complexed, the catalytic efficiency is only about one-tenth of its maximum. The absorbance observed at pH 2.3 is greater than that found in pure water, suggesting that the large concentration of hydrophilic polymer salt has so decreased the activity of water that less than the usual 30% of the aldehyde is hydrated.

If the iminium ion derived from PEI-1800 and isobutyraldehyde-*2-d* were dedeuterated by PEI molecules other than the ones to which the aldehyde is attached, the reaction rate would continue to increase with increasing PEI concentration even at concentrations above those at which almost all the aldehyde has been complexed. Since no such increase is observed, it follows that catalysis by the action of PEI as an external base is not significant. In view of the unusual steric and electrostatic effects that might inhibit such catalysis, it seemed that attack by more suitable external bases might nevertheless be observable.

Since unhindered tertiary amines were found to be the most effective catalysts, for their basicity, in the simple base-catalyzed dedeuteration of isobutyraldehyde-*2-d*,[17] the reaction in the presence of 1.00 *N* PEI-1800 was carried out with 0.119 *M* Dabco (1,4-diazabicyclo[2.2.2]octane) added. As shown in Table III,

Table III. Rate Constants for the Dedeuteration of Isobutyraldehyde-2-*d*[a] in the Presence of 1.00 *N* PEI-1800 and Added Bases[b]

Added base[c]	$10^6 k_p$, sec^{-1}	$10^4 k_{cat}$, M^{-1} sec^{-1}
None	144	
0.119 *M* Dabco	253	32
0.270 *M* 3-Quinuclidinone	275	4.9
0.0236 *M* Na_2HPO_4[d]	119	
0.117 *M* Na_2HPO_4	100	
0.236 *M* Na_2HPO_4[d]	130	

[a] 0.053 *M*. [b] pH 8.35 ± 0.01 except where noted otherwise. [c] Total concentrations, without regard to states of protonation. [d] pH 8.40.

the added Dabco increased the reaction rate by about 75%. We then tried adding 0.270 *M* 3-quinuclidinone in the hope that the carbonyl group would become attached to the PEI by linkages with the amino groups so that the concentration of catalyst in the vicinity of the complexed aldehyde would be increased. The reaction rate was almost doubled by the added quinuclidinone. The concentration of uncomplexed aldehyde in these reaction solutions is estimated to be 0.002 *M*. The concentrations of unprotonated Dabco and quinuclidinone were calculated from the p*K* values of their conjugate acids at 35°, 8.78[18] and 6.93, respectively. From these data and the rate constants for dedeuteration of isobutyraldehyde-*2-d* by Dabco[17] and quinuclidinone[19] it follows that only about 7% of the rate increase due to Dabco and about 3% of that due to quinuclidinone come from attack of these bases on free aldehyde.[21] Division of the remainder of the rate increases by the concentrations of free base gives the rate constants k_{cat} for the attack of base on complexed aldehyde listed in Table III. This rate constant should be equal to the average rate constant for the attack of base on the various iminium ions present multiplied by the fraction of the aldehyde present in the form of iminium ions. The value of k_{cat} for quinuclidinone is not large enough to provide significant evidence that the reactivity of quinuclidinone is increased by complexing of its carbonyl group with the amino groups of the PEI. Although k_{cat} for quinuclidinone is 0.15 of that for Dabco whereas the rate constant for attack of quinuclidinone on isobutyraldehyde-*2-d* is only 0.07 of that for Dabco, a smaller degree of selectivity would be expected (and has been observed in another instance[4]) for attack on an iminium ion than for attack on aldehyde.

The preceding data on attack of two bicyclic amines on isobutyraldehyde-*2-d* complexed to PEI-1800 gives a basis for estimating how much of the deuterium exchange catalyzed by PEI-1800 arises from attack by the ubiquitous bases water and hydroxide ion. Log *k* for attack of Dabco on isobutyraldehyde-*2-d* minus log *k* for the same reaction of water is 7.4.[17] Such Δ log *k* values are about 0.84 as large for the attack of bases on the *N*-methylisobutyraldiminium ion as for attack on aldehyde.[4] Hence, we estimate that log k_{cat} for attack of water on aldehyde complexed to PEI-1800 at pH 8.5 is −8.7. Thus, basic catalysis by water is estimated to contribute less than 0.1% to catalysis by PEI-1800. An analogous estimate gives the same result for hydroxide ions at pH 8.5, although at higher pH the action of hydroxide ions probably becomes more significant. Thus, near the pH of maximum effectiveness, catalysis by PEI-1800 appears to consist very largely of rate-controlling attack of internal amino groups on isobutyraldehyde-*2-d* complexed to the PEI in the form of iminium ions.

In view of the catalytic activity of anionic micelles on some hydrogen ion catalyzed reactions and of cationic micelles on some hydroxide ion catalyzed reactions,[22,23] it seemed possible that anionic bases would be particularly effective at removing deuterons from isobutylidene groups attached to a multipositively charged PEI cation. For this reason we studied the doubly negative monohydrogen phosphate ion. In spite of the fact that this anion is somewhat more basic than quinuclidinone, no increase in reaction rate accompanied the addition of as much as 0.236 *M* disodium phosphate to isobutyraldehyde-*2-d* exchanging in the presence of 1.00 *N* PEI-1800 (*cf.* Table III). Apparently the hydrogen phosphate anion, like the acetate anion,[17] is slower at removing protons from carbon than an unhindered tertiary amine of equal basicity.

It was thought that hydrophobic bonding[24] might increase the catalytic efficiency by increasing the effec-

(17) J. Hine, J. G. Houston, J. H. Jensen, and J. Mulders, *J. Amer. Chem. Soc.*, 87, 5050 (1965).

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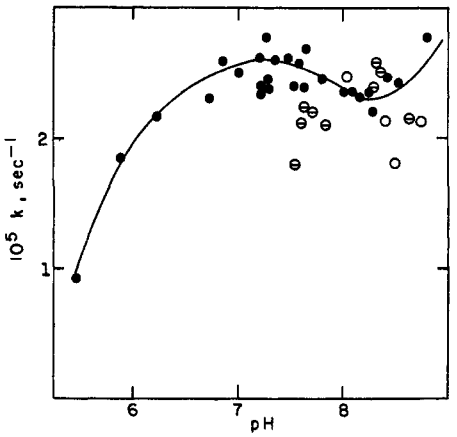

Figure 5. Dedeuteration of 0.005 *M* isobutyraldehyde-*2-d* in aqueous solution at 60° in the presence of 0.00193 ± 0.0005 *N* PEI-1800: (●) unlauroylated PEI; (⊖) 2.46% lauroylated PEI; (○) 4.8% lauroylated PEI.

tiveness with which PEI's complex with isobutyraldehyde. Royer and Klotz found that the lauroylation of PEI-600 increases its reactivity toward esters of *p*-nitrophenol.[25] We have therefore investigated the catalytic activity of lauroylated PEI-1800 in the deuterium exchange of isobutyraldehyde-*2-d*. Since complexing between isobutyraldehyde and PEI-1800 is rather efficient at moderate concentrations of reagents, we studied the reaction at relatively high dilutions (at 60° because the reaction at high dilution would be inconveniently slow at 35°). Since hydrophobic bonding is ordinarily an endothermic process at room temperature, it should be more effective at 60°. The rate constants for exchange of 0.005 *M* isobutyraldehyde-*2-d* in the presence of 0.0019 *N* PEI-1800 are plotted, as solid circles, against pH in Figure 5. We interpret these results to mean that the rate maximum that occurred near pH 8.0 in the data shown in Figure 4 has shifted to about pH 7.3. Such a shift should not be surprising; the average ammonium ion of p*K* 8.0 at 35° should have a p*K* of 7.4 at 60°.[26] It is not entirely clear that the rate decreases at pH's higher than 7.3. This is largely a result of the much greater importance of hydroxide ion catalysis in the present case. The hydroxide ions have less than 0.2% as much PEI-1800 to compete with as in the runs covered in Figure 4. Furthermore, since pK_w is 13.0 at 60°,[27] there are almost five times as many hydroxide ions in a solution at a given pH at 60° as in a solution at the same pH at 35°. Hence, in going up in pH from 7.3 the rate hardly has a chance to decrease because of less catalysis by PEI before it starts to increase because of hydroxide ion catalysis. Thus, above pH 8.7 the reaction is probably not largely the PEI-catalyzed process that we are interested in. Below pH 7.7, however, attack of hydroxide ions on free aldehyde should contribute no more than 10% to the overall reaction. From the rate constant for the water-catalyzed reaction[17] it follows that less than 2% of any of the reactions is due to attack of water on free aldehyde. Also shown in Figure 5 are the results obtained with PEI-1800 samples that were 2.46 and 4.8% lauroylated, the latter corresponding to an average of about two lauroyl groups per molecule. The lauroylation may decrease the catalytic activity of the PEI slightly; it certainly does not increase it. It might be argued that lauroylation, which would work by increasing the efficiency of binding the aldehyde to the PEI, was ineffective because the binding sites on the PEI were already saturated with aldehyde in the absence of lauroylation. This possibility was disposed of by the results of runs in which the aldehyde concentration was doubled. If the PEI were already saturated with aldehyde this should not increase the rate of the PEI-catalyzed reaction. Hence, under conditions where the reaction is all due to PEI, the first-order rate constant for exchange should be halved. Experimentally it was found that in the presence of 0.0019 *N* PEI-1800 at pH 8.35, 0.011 *M* isobutyraldehyde-*2-d* exchanged with a rate constant of 2.0×10^{-5} sec^{-1} whether the PEI was unlauroylated or 2.3% lauroylated. That is, the rate constant for dedeuteration was not decreased by more than about 10%; the rate of dedeuteration was almost doubled. Hence, the PEI was not saturated with aldehyde. Saturation of the PEI at these aldehyde concentrations would be even less likely at lower pH's, where the binding is less efficient.

Experimental Section

Reagents. The polyethylenimines used were hygroscopic, viscous, colorless liquids.[7] According to nitrogen analyses they contained less than 3% water. The poly(*N*-ethylaziridine) was a very pale yellow viscous liquid with a faint odor and an unstated molecular weight. The ethylated ethylenediamines (Aldrich and Ames) were purified by preparative glpc. The methylated ethylenediamines used were all found by glpc on a 6-ft Carbowax 20M column at 150° to be at least 99% pure. Aldrich 1,4-diazabicyclo[2.2.2]-octane was vacuum sublimed and quinuclidinone hydrochloride was recrystallized twice from 1-propanol.

The 2.46% lauroylated PEI was prepared by drying 4.35 g of PEI-1800 for 15 hr at 100° and then adding 0.540 g of methyl laurate and reheating to 100°. This product and 4.8% lauroylated material prepared similarly gave clear solutions in water, as did some of the lauroylated PEI prepared from lauroyl chloride. Some of the material prepared from lauroyl chloride, especially in cases where the reagents had not been thoroughly dried, gave cloudy solutions, attributed to the presence of lauric acid. Such material was not used in the kinetic studies.

pK_a of the Conjugate Acid of 3-Quinuclidinone. A Radiometer Model 26 pH meter, automatic titrator, G202B glass electrode, and K401 reference electrode were used to titrate duplicate 18-ml samples of 0.0248 *M* 3-quinuclidinone hydrochloride with 0.5009 *M* carbonate-free sodium hydroxide at 35°. From the pH's (6.98 and 7.02) at half-neutralization, the assumption that the observed pH is $-\log a_{H^+}$, and the use of the Davies equation[28] to calculate ionic activity coefficients, the p*K* of the conjugate acid of 3-quinuclidinone was calculated to be 6.93 ± 0.02.

Kinetic Measurements. Kinetic runs were carried out as described previously[2-5] with excess acetic acid added to stop the reaction and chloroform extraction used to obtain solutions for nmr analysis of the deuterium content of the aldehyde. Since the reaction still proceeded at a moderate rate in some cases at the pH produced by adding the acetic acid, the chloroform extractions were carried out promptly. Because the addition of aldehyde decreased the pH of many of the amine solutions significantly, preliminary experiments were made to learn what the initial pH should be to get the desired pH for the reaction solution. Some kinetic runs started with isobutyraldehyde-*2-d* concentrations above 0.26 *M* could not be carried out because the reaction solutions became heterogeneous before very much exchange had taken place.

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Ultraviolet Spectral Measurements. Absorbance measurements were made on Cary recording spectrophotometers, Models 14 and 16.

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Deuterium Isotope Effects on the $^1T \rightarrow {}^0S$ Radiationless Decay Rate in Stilbene[1a]

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Abstract: The effect of azulene on stationary states of the benzophenone-sensitized photoisomerization of vinyl-substituted stilbene-d_2 and aromatic-substituted stilbene-d_{10} has been determined in benzene solutions at 298°K. Comparison with previous observations concerning stilbene-d_0 and stilbene-d_{12} leads to the conclusion that deuteration of the vinyl positions increases the effective lifetime of stilbene triplets by 30%, while ring deuteration has no effect. The lifetime increase is tentatively attributed to a change in the radiationless decay rate of twisted stilbene triplets. The positional dependence of the deuterium isotope effect for radiationless decay from transoid triplets has been determined by flash kinetic spectrophotometry in 3-methylpentane and isopentane–3-methylpentane glasses at 77°K and in glycerol at 195°K. Once again deuteration at the vinyl positions has the most substantial effect, but in this case some lengthening of the lifetime is also observed upon ring deuteration. This positional dependence of the deuterium isotope effect is in good agreement with previous measurements in EPA at 77°K. The experimental observations are discussed in terms of a previously proposed potential energy curve for twisting about the central bond in the lowest stilbene triplet state, and possible implications of the positional dependence of the deuterium isotope effects are considered in relation to existing theories of radiationless intersystem crossing.

The observation that longer triplet lifetimes result upon perdeuteration of aromatic hydrocarbons has played an important role in the development of theories of radiationless transitions.[2-4] More recently, measurements on partially deuterated hydrocarbons have shown that the effectiveness of deuterium substitution in decreasing the rate of radiationless $^1T \rightarrow {}^0S$ intersystem system crossing depends upon the position of substitution.[5-9] This positional dependence of the deuterium isotope effect has been proposed to provide a diagnostic tool in distinguishing between various mechanisms of intersystem crossing.[10,11]

The present paper describes the positional dependence of deuterium substitution on the decay characteristics of stilbene triplets. It complements previous observations concerning the effect of perdeuteration on the lifetime of stilbene triplets in solution at room temperature,[12] and in rigid media at low temperatures,[13] and parallels, in part, recent observations on partially deuterated stilbenes.[9]

Results

Steady-State Observations in Solution. The effect of azulene on photostationary states for the benzophenone sensitized photoisomerization of vinyl-substituted stilbene-d_2 and ring-substituted stilbene-d_{10} in benzene was determined at 25°.[14] As a check of previous observations[12] and in order to extend the azulene concentration range, additional measurements were made using stilbene-d_0. A few, less refined and probably less accurate measurements were also made at 60°. Photo-

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