essentially as described previously,[1a] using HO⁻ in H_2O and DO⁻ in D_2O, with the following differences. A 2.5-ml RGI, Inc., ultra-precision micrometer buret was used for titration with standard hydrochloric acid. The indicator was Neutral Red~Methylene Blue except with phenoxide solutions, in which case Bromocresol Purple was used. All kinetic runs were carried out in flasks made of alkali-resistant glass (Corning Glass No. 7280), sealed with a needle puncture stopper. Aliquots, taken with a syringe, were 2 ml and were measured gravimetrically for each point. The bath temperature was 60.00 ± 0.005° (NBS Certified thermometer).

Olefin yields were 100 ± 4% (crosschecked with two different ultraviolet spectrophotometers), with the exception of the reaction of 4-(2-bromoethyl)phenyltrimethylammonium tosylate with phenoxide, in which case olefin yields were used to calculate percentage of E2 and SN2 processes.

References and Notes

(1) (a) Previous paper: L. J. Steffa and E. R. Thornton, *J. Am. Chem. Soc.*, **89**, 6149 (1967); (b) supported in part by the National Science Foundation through Grants GP-2937, GP-6047, and GP-34,491X; (c) for further details, cf. D. A. Winey, Ph.D. Dissertation in Chemistry, University of Pennsylvania, 1968.
(2) W. H. Saunders, Jr., and A. F. Cockerill, "Mechanisms of Elimination Reactions", Wiley, New York, N.Y., 1973.
(3) J. F. Bunnett, *Angew. Chem., Int. Ed. Engl.*, **1**, 225 (1962).
(4) J. F. Bunnett in "Survey of Progress in Chemistry", Vol. 5, A. F. Scott, Ed., Academic Press, New York, N.Y., 1969, p 53.
(5) R. A. More O'Ferrall, *J. Chem. Soc. B*, 274 (1970).
(6) A. Fry, *Chem. Soc. Rev.*, **1**, 163 (1972).
(7) F. G. Bordwell, *Acc. Chem. Res.*, **5**, 374 (1972).
(8) W. T. Ford, *Acc. Chem. Res.*, **6**, 410 (1973).
(9) F. H. Westheimer, *Chem. Rev.*, **61**, 265 (1961).
(10) See, for example, E. K. Thornton and E. R. Thornton in "Isotope Effects in Chemical Reactions", C. J. Collins and N. S. Bowman, Ed., Van Nostrand-Reinhold, New York, N.Y., 1970, Chapter 4.
(11) C. G. Swain and A. S. Rosenberg, *J. Am. Chem. Soc.*, **83**, 2154 (1961).
(12) L. Pentz and E. R. Thornton, *J. Am. Chem. Soc.*, **89**, 6931 (1967).
(13) R. L. Schowen, *Prog. Phys. Org. Chem.*, **9**, 275 (1972).
(14) E. R. Thornton, *J. Am. Chem. Soc.*, **89**, 2915 (1967).
(15) R. A. Bartsch and J. F. Bunnett, *J. Am. Chem. Soc.*, **91**, 1376, 1382 (1969).
(16) P. J. Smith and A. N. Bourns, *Can. J. Chem.*, **52**, 749 (1974).
(17) W. P. Jencks, *Chem. Rev.*, **72**, 705 (1972).
(18) S. T. Rashevskaya, E. S. Kashcheeva, and E. I. Mostoslavskaya, *Zh. Obshch. Khim.*, **33**, 3998 (1963).
(19) Micro-Analysis, Inc., Wilmington, Del.
(20) Prepared by the method of R. C. Elderfield, W. J. Gensler, F. Brady, J. D. Head, S. C. Dickerman, L. Wiederhold, III, C. B. Kremer, H. A. Hageman, F. J. Kreysa, J. M. Griffins, S. M. Kupchan, B. Newman, and J. T. Maynard, *J. Am. Chem. Soc.*, **68**, 1579 (1946).
(21) Procedure adapted from M. S. Kharasch, G. H. Williams, and W. Mudenberg, *J. Org. Chem.*, **20**, 937 (1955).
(22) C. H. DePuy and C. A. Bishop, *J. Am. Chem. Soc.*, **82**, 2535 (1960).
(23) (a) R. W. Strassburg, R. A. Gregg, and C. Malling, *J. Am. Chem. Soc.*, **69**, 2141 (1947); (b) E. Selegny, *Bull. Soc. Chim. Fr.*, 1275 (1959).

Influence of Solvent on the Motion of Molecules "Immobilized" on Polystyrene Matrices and on Glass Surfaces[1]

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Abstract: The influence of solvent on the rotational motion of 2,2,6,6-tetramethyl-4-piperidinol-1-oxyl (1) covalently bound to cross-linked polystyrene, silica, and a polystyrene ion-exchange resin has been examined by electron paramagnetic resonance spectroscopy. The degree of swelling of the polymer supports, as defined by the solvent employed, is an important factor in determining the mobility of the attached spin label. In contrast, when immobilized on a rigid silica surface, the motion of 1 is considerably less sensitive to the nature of the solvent. Evidence is presented which suggests that hydrogen-bonding forces may be important in influencing the physical properties of molecules immobilized on silica.

Glass surfaces show considerable promise as support material for enzymes.[2] The successful application of polystyrene resins to organic synthesis,[3] transition-metal catalysis,[4] and photochemistry[5] suggests that silica may find similar use.[6] Until recently, little attention has been given to the role which the solvent plays in the chemistry of substrates "immobilized" on insoluble supports. It is now evident that the choice of solvent can have a dominant influence on the physical nature of molecules bound to polystyrene matrices, and that the primary function of the solvent is to define the degree of swelling of the polymer lattice.[7,8] Recent studies dealing with polymer-bound transition-metal catalysts and complexes strongly suggest that swelling is also an important factor in determining the chemical reactivity of immobilized molecules.[9] Silica, unlike polystyrene, is rigid and is not subject to swelling. One might expect that for molecules bound to this type of lattice, the choice of solvent would be of little consequence to their physical and, possibly, chemical behavior. Such a property could represent a subtle but important advantage of silica over polystyrene as support material.

The work reported in this paper was carried out in order to provide a basis for understanding how solvent influences the physical nature of molecules bonded to silica and to polystyrene supports. The approach which we have taken was based on the spin-labeling technique, where we have examined the rotational motion of a nitroxide radical attached to solvent-swelled 2% cross-linked polystyrene and to solvent-wetted silica.[10]

Results and Discussion

**Attachment to a Polystyrene Matrix.** The nitroxide 2,2,6,6-tetramethyl-4-piperidinol-1-oxyl (1) was covalently attached to polystyrene by reaction of its sodium salt with 2% cross-linked chloromethylated polystyrene 2 to yield nitroxide~polystyrene 3.

The room-temperature electron paramagnetic resonance (EPR) spectrum of 3 in the dry state exhibited a "powder" spectrum indicating slow rotational motion (Figure 1A). Swelling 3 with carbon tetrachloride caused a large increase in the rotational motion of the nitroxide moiety as evidenced by the change in the EPR spectrum (Figure 1C).

Table I. Influence of Solvent on Nitroxide Motion in 3, 4, 5a, and 5b[a]

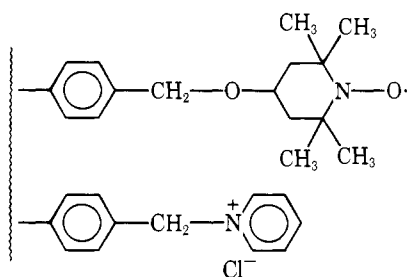| Solvent	Nitroxide–polymer 3 $10^{10}\tau$, sec	q^b	Nitroxide–polymer 4 $10^{10}\tau$, sec	q^b	Nitroxide–silica 5a $10^{10}\tau$, sec	Nitroxide–silica 5b $10^{10}\tau$, sec
Dry state	300	1.0	900	1.0		
n-Pentane	300	1.1	900	1.0		36
Cyclohexane	300	1.1	900	1.0		26
Ethanol	300	1.1	11	2.7	7	21
2-Propanol	300	1.1	26	2.1	10	25
Acetonitrile	130	1.2	900	1.0	19	17
Acetone	6.8	2.0	900	1.0	22	15
Ethyl acetate	4.6	2.6	900	1.0	11	8
Carbon tetrachloride	6.1	3.4	900	1.0		24
Tetrahydrofuran	3.0	3.7	900	1.0	16	11
Pyridine					5	11

[a] Rotational correlation times, τ, are accurate to $\pm 10\%$. [b] Degree of swelling values (swelled volume/dry volume) is accurate to $\pm 5\%$.
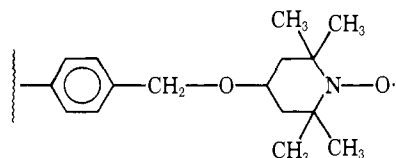
nitroxide–polystyrene–2% divinylbenzene
3, $<4 \times 10^{-2}\%$ ring substitution

Rotational correlation times, τ, calculated from the observed room-temperature EPR spectra of 3 swelled in a variety of solvents, are presented in Table I, along with corresponding degree of swelling values q (swelled volume/dry volume).[11-15] As was noted previously,[7] solvents which swelled the polymer lattice appreciably caused a large increase in the rotational motion of the spin label; those solvents which brought about little or no increase in swelling had a negligible effect on the nitroxide's motion.

Attachment to an Ionic Polystyrene Matrix. The introduction of charged sites along the polystyrene backbone would be expected to lead to a substantial alteration in the swelling properties of the resin. Such a modification could cause major differences in the physical and chemical properties of attached substrates. We have explored this possibility by examining the influence of certain solvents on the motion of the nitroxide moiety in the spin-labeled ion-exchange resin 4. Table I includes data which summarize our results. In brief, we found that only ethanol and 2-propanol swelled the ion-exchange resin significantly, and only with these solvents did we note a large increase in the motion of the spin label. In addition, it is clear from inspection of these data that certain of the solvents tested had an opposite influence on polymer swelling and nitroxide motion for 3 as compared with 4. One example of this is illustrated in Figure 1. Polymer 3 underwent extensive swelling in carbon tetrachloride with an accompanying increase in motion of the nitroxide moiety. When 3 was swelled in ethanol, we ob-

nitroxide–polystyrene ion-exchange resin–
2% divinylbenzene
4, $<4 \times 10^{-2}\%$ nitroxide ring substitution;
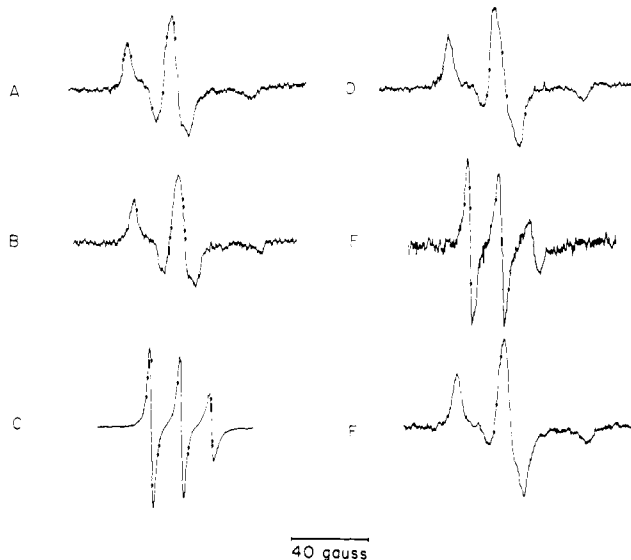96% pyridine ring substitution

Figure 1. EPR spectra of: (A) 3 in the dry state, (B) 3 swelled in ethanol, (C) 3 swelled in carbon tetrachloride, (D) 4 in the dry state, (E) 4 swelled in ethanol, (F) 4 swelled in carbon tetrachloride.

served slow nitroxide tumbling and little solvent uptake. Examination of the influence of ethanol and carbon tetrachloride in 4 revealed exactly the reverse effects. Evidently, the introduction of charged sites along the polymer backbone makes the lattice more compatible with ethanol and less compatible with carbon tetrachloride.

Lagercrantz has recently reported a study of the motion of the nitroxide 2,2,5,5-tetramethyl-3-pyrrolin-1-oxyl-3-carboxylic acid *ionically* bound to certain polystyrene ion exchange resins.[16,17] We have prepared a similar nitroxide-resin using AG 1-X2 (a strong anion exchanger with quaternary ammonium groups attached to a styrene-divinylbenzene polymer lattice) and 2,2,5,5-tetramethylpyrrolidin-1-oxyl-3-carboxylic acid and have found that, for this system, the degree of swelling of the resin, as defined by the swelling solvent employed, appears to have a significant effect on the rotational motion of the label. Thus, when poor swelling solvents were used such as acetone and benzene, no detectable change was observed in the EPR spectrum from that produced by the sample in the dry state. By employing better swelling solvents, the rotational motion of the label increased accordingly (Table II).

Attachment to Silica. In order to measure the influence of solvent on the mobility of molecules bound to glass surfaces, we have examined the rotational motion of spin label 1 covalently attached to silica. The sodium salt of nitroxide 1 was

Table II. Influence of Solvent on the Motion of 2,2,5,5-Tetra-methylpyrrolidin-1-oxyl-3-carboxylic Acid Ionically Bound to Ag 1-X2[a]

| Solvent	$10^{10}\tau$, sec	q^b
Dry state	900	1.0
Acetone	900	1.1
Benzene	900	1.0
Ethanol in benzene (10% v/v)	40	1.4
Ethanol in benzene (20% v/v)	13	1.9
Ethanol in benzene (30% v/v)	9.5	2.1
1-Propanol	5.0	2.2
Ethanol	4.0	2.9

[a] Rotational correlation times, τ, are accurate to ±10%. [b] Degree of swelling values (swelled volume/dry volume) is accurate to ±5%.

Table III. Hyperfine Splitting for Spin Labels[a]

Spin label	A_N
DTBN in toluene	34.6 ± 0.2[21]
DTBN adsorbed on silica	38.6 ± 0.2[21]
5a	33.3 ± 0.3
5b	34.5 ± 0.5
3	32.5 ± 0.3

[a] Hyperfine splitting constants in gauss; T = 77 K.

allowed to react with 4-bromomethylphenylsilica suspended in DMF and yielded the nitroxide-silica **5a**.[18] The room-

nitroxide-silica
5a, R = H
b, R = Si(CH₃)₃
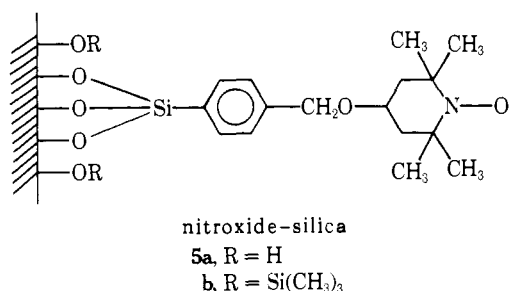
temperature EPR spectrum of nitroxide–silica **5a** in the dry state exhibited a typical "powder" spectrum as shown in Figure 2. When nonhydrogen-bonding solvents such as carbon tetrachloride, pentane, or cyclohexane were used to wet the glass surface, the resulting EPR spectra were similar to that of the dry sample. When hydrogen-bonding solvents were employed, a three-line spectra appeared which indicated faster motion of the label. Rotational correlation times, τ, calculated from the EPR spectra observed for **5a** in all of the hydrogen-bonding solvents studied, varied from 0.5 × 10^{-9} to 2.2 × 10^{-9} sec (Table I). One possible explanation which would account for the large difference between the two classes of solvents is that the covalently bound nitroxide is hydrogen-bonding to a neighboring silanol moiety (Si–OH).[19] Solvents added to **5a** which compete with this bonding could free the rotational motion of the spin label. Evidence in support of this theory was obtained by treating **5a** in dry pyridine with bis(trimethylsilyl)trifluoroacetamide yielding **5b**.[20] The room-temperature EPR spectra of **5a** and **5b** in the dry state were similar. By using either hydrogen- or nonhydrogen-bonding solvents to wet the surface of **5b**, the estimated rotational correlation times varied only from 0.8 × 10^{-9} to 3.6 × 10^{-9} sec.

In an effort to obtain direct evidence for a hydrogen-bond interaction, we have measured the parallel component of the nitroxide ^{14}N hyperfine splitting, A_N, at 77 K in **5a**, **5b**, and in the polystyryl nitroxide **3**. Our results are summarized in Table III. The A_N value of a nitroxide free radical is sensitive to hydrogen-bond formation.[19] Hoffman has recently demonstrated that di-*tert*-butyl nitroxide (DTBN)
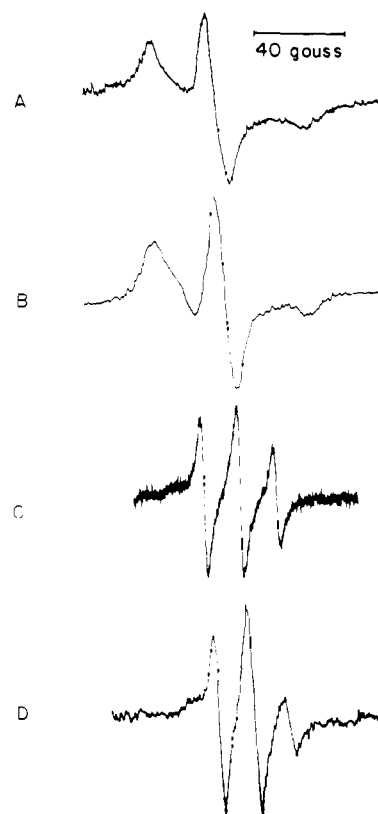

Figure 2. EPR spectra of: (A) **5a** in the dry state, (B) **5a** plus carbon tetrachloride, (C) **5a** plus ethanol, (D) **5b** plus carbon tetrachloride.

adsorbed on silica has a hyperfine splitting of 38.6 G, whereas a frozen toluene solution of the same spin-label has a splitting of 34.6 G.[21] The difference in the splitting has been attributed to DTBN hydrogen-bonding to surface silanol groups. Although we have found A_N(**5a**) > A_N(**3**), the difference in the hyperfine splitting is significantly less than that observed in Hoffman's system. In addition, it is not presently clear why A_N(**5b**) > A_N(**5a**).

Although we cannot quantitatively assess the importance of hydrogen bonding in influencing the mobility of the silica-bound nitroxide, the results cited here, nonetheless, provide strong evidence that the physical nature of substrates "immobilized" on trimethylsilylated glass surfaces will be considerably less solvent dependent than that of substrates bound to polystyrene matrices.

Experimental Section

General Methods. Tetrahydrofuran, *N,N*-dimethylformamide, and pyridine were purified by distillation from calcium hydride under a nitrogen atmosphere. All other solvents used were spectrophotometric grade (Aldrich Chemical Co.) and were dried over "Linde Type" 4A molecular sieves (Matheson Coleman and Bell) and distilled under nitrogen prior to use. The nitroxide 2,2,6,6-tetramethyl-4-piperidinol-1-oxyl (**1**) was obtained commercially (Aldrich Chemical Co.) and was used without further purification. Chloromethylated (1.0 mmol of chlorine/g of polymer) and non-chloromethylated cross-linked polystyrene beads (2% divinylbenzene, 200–400 mesh) were obtained from Bio-Rad Laboratories and were used without further purification. 4-Bromomethylphenylsilica was commercially available (Chemical Dynamics Corp.); the pore size was 2500 Å.

EPR spectra were recorded at ambient temperature using a Varian E-3 (X-band) spectrometer. No power saturation or modulation amplitude effects were noted at the 1.0-mW and 1.0-G levels used in this investigation. Each polymer or silica sample was allowed to remain in contact with an excess of solvent for 24 hr in an EPR tube, sealed with a No-Air stopper. The tube was purged with

nitrogen for 10 min prior to spectral analysis. Rotational correlation times, τ, were estimated from line-width analyses of the EPR spectra employing equations developed previously.[11,12] It should be noted that the estimation of slow-motion rotational correlation times ($\tau > 10^{-8}$ sec) depends significantly on the diffusional model adopted, e.g., Brownian, moderate jump, or large jump diffusion. We have arbitrarily assumed Brownian diffusion.

Nitroxide–Polystyrene 3. 2,2,6,6-Tetramethyl-4-piperidinol-1-oxyl (**1**) (0.006 g, 0.03 mmol) and sodium hydride (0.048 g, 2.0 mmol) were placed in a 25-ml round-bottomed flask equipped with a No-Air stopper and a Teflon-coated magnetic stirring bar. The flask was thoroughly degassed under a stream of nitrogen, and 8 ml of freshly distilled N,N-dimethylformamide (DMF) was added via syringe. The solution was stirred for 2 hr at room temperature, transferred by forced siphon through a stainless steel cannula under a nitrogen atmosphere into a 250-ml round-bottomed flask capped with a No-Air stopper which contained a degassed mixture of 2% cross-linked chloromethylated polystyrene (10.0 g, 1.0 mmol of chlorine/g of polymer), preswelled in 75 ml of DMF. The resulting mixture was stirred under a nitrogen atmosphere for 24 hr, filtered, and washed successively with water, ethanol, benzene, and ether and was dried under vacuum [24 hr, 65° (0.05 mm)]. Using the above proportions of spin label and polymer, the resulting nitroxide–polymer **3** must contain less than 4×10^{-3} mmol of nitroxide/g of polymer.[22]

Nitroxide–Polystyrene Ion-Exchange Resin 4. The 2% cross-linked polystyrene (20 g) was placed in a 500-ml round-bottomed flask equipped with a No-Air stopper and Teflon-coated magnetic stirring bar. The polymer was swelled with 90 ml of chloromethyl methyl ether (Aldrich Chemical Co.) and stirred for 1 hr at room temperature. (*Caution: chloromethyl methyl ether is carcinogenic!*) A cold solution of 6 ml of anhydrous $SnCl_4$ in 40 ml of chloromethyl methyl ether was added, and the mixture was stirred at room temperature for an additional 48 hr. The polymer was filtered, washed successively with 3:1 dioxane–water, 3:1 dioxane–3 N HCl, water, dioxane, and anhydrous ether. The beads were then dried under vacuum [48 hr, 65° (0.05 mm)]. The product contained 6.4 mmol of chlorine/g of polymer (96% ring substitution).[24]

Nitroxide **1** was covalently attached to this matrix using a procedure similar to that described in the preparation of **3**. A portion (3.0 g) of the resulting nitroxide–polymer was converted into **4** by treatment with pyridine (50 ml) for 3 hr at 100°. The resin was then filtered, washed with anhydrous ether, and dried under vacuum [10 hr, 65° (0.05 mm)]. Chloride ion analysis indicated complete quaternization of the resin.

2,2,5,5-Tetramethylpyrrolidin-1-oxyl-3-carboxylic Acid Ionically Bound to an Ion-Exchange Resin. A solution of 2,2,5,5-tetramethylpyrrolidin-1-oxyl-3-carboxylic acid (0.001 g, 0.006 mmol) in 8 ml of water was added to a dry form of the anion exchange resin AG 1-X2 (1.0 g) and was stirred at room temperature for 10 hr.[25] The polymer was then filtered, washed with anhydrous ether, and dried under vacuum [5 hr, 65° (0.05 mm)].

Nitroxide–Silica 5a. 2,2,6,6-Tetramethyl-4-piperidinol-1-oxyl (**1**) (0.017 g, 0.10 mmol) and sodium hydride (0.048 g, 2.0 mmol) were placed in a 25-ml round-bottomed flask equipped with a No-Air stopper and a Teflon-coated magnetic stirring bar. The flask was thoroughly degassed under a stream of nitrogen, and 5 ml of freshly distilled DMF was added via syringe. The solution was stirred for 2 hr at room temperature, and 4-bromomethylphenylsilica (0.2 g, 0.025 mmol of bromine/g of silica) was added. The mixture was stirred at room temperature for 48 hr under a nitrogen atmosphere, filtered and washed with water, ethanol, and anhydrous ether successively, and then dried under vacuum [10 hr, 65° (0.05 mm)]. Comparison of the EPR signal intensity generated from **5a** with that of **3** indicated that the concentration of the label on the silica was less than 4×10^{-3} mmol/g.

Nitroxide–Silica 5b. Nitroxide–silica **5a** (0.1 g) was placed in a 10-ml round-bottomed flask equipped with a No-Air stopper and Teflon-coated magnetic stirring bar. A solution of 0.5 ml of bis(trimethylsilyl)trifluoroacetamide in 2 ml of freshly distilled pyridine containing 0.025 ml of trifluoroacetic acid was added to the flask via syringe.[26] The suspension was stirred for 24 hr at room temperature, filtered, washed with anhydrous ether, and dried under vacuum [10 hr, 100° (0.05 mm)]. Comparison of the EPR signal intensity from **5b** with that of **5a** indicated that the concentration of

the spin label on both silica supports was approximately the same.

Swelling Measurements. Swelling was measured using a procedure identical with that described by Gregor.[27] The polymer beads were equilibrated with solvent for 24 hr, rapidly filtered under suction, and weighed.[14]

References and Notes

(1) Supported by the Research Corporation, the donors of the Petroleum Research Fund, administered by the American Chemical Society, and the Marquette University Committee on Research.

(2) G. Baum, F. B. Ward, and H. H. Weetall, *Biochim. Biophys. Acta*, **268**, 411 (1972); R. D. Mason and H. H. Weetall, *Biotechnol. Bioeng.*, **14**, 637 (1972); H. H. Weetall, *Nature (London)*, **232**, 473 (1971); *Science*, **166**, 615 (1969); H. H. Weetall and G. Baum, *Biotechnol. Bioeng.*, **12**, 399 (1970); T. L. Newirth, M. A. Diegelman, E. K. Pye, and R. G. Kallen, *ibid.*, **15**, 1089 (1973).

(3) R. B. Merrifield, *J. Am. Chem. Soc.*, **85**, 2149 (1963); R. L. Letsinger, M. J. Kornet, V. Mahadevan, and D. M. Jerina, *ibid.*, **86**, 5163 (1964); I. T. Harrison and S. Harrison, *ibid.*, **89**, 5723 (1967); J. I. Crowley and H. Rapoport, *ibid.*, **92**, 6363 (1970); A. Patchornik and M. A. Kraus, *ibid.*, **92**, 7587 (1970); M. A. Kraus and A. Patchornik, *ibid.*, **93**, 7325 (1971).

(4) A. J. Moffat, *J. Catal.*, **19**, 322 (1970); R. H. Grubbs and L. C. Kroll, *J. Am. Chem. Soc.*, **93**, 3062 (1971); R. H. Grubbs, C. Gibbons, L. C. Kroll, W. D. Bonds, Jr., and C. H. Brubaker, *ibid.*, **95**, 2373 (1973); J. P. Collman, L. S. Hegedus, M. P. Cooke, J. R. Norton, G. Dolcetti, and D. N. Marquardt, *ibid.*, **94**, 1789 (1972); J. P. Collman and C. A. Reed, *ibid.*, **95**, 2048 (1973); G. O. Evans, C. U. Pittman, Jr., R. McMillan, R. T. Beach, and R. Jones, *J. Organomet. Chem.*, **67**, 295 (1974).

(5) E. C. Blossey, D. C. Neckers, A. L. Thayer, and A. P. Schaap, *J. Am. Chem. Soc.*, **95**, 5820 (1973).

(6) Reviews: C. G. Overberger and K. N. Sannes, *Angew. Chem.*, *Int. Ed. Engl.*, **13**, 99 (1974); C. C. Leznoff, *Chem. Soc. Rev.*, **3**, 65 (1974).

(7) S. L. Regen, *J. Am. Chem. Soc.*, **96**, 5275 (1974).

(8) Swelling has been found to have a large effect on the rotational motion of 2,2,5,5-tetramethyl-3-pyrroline-1-oxyl attached to certain polyurethane networks: T. C. Ward and J. T. Books, *Macromolecules*, **7**, 207 (1974).

(9) W. Dumont, J. C. Poulin, T. P. Dang, and H. B. Kagan, *J. Am. Chem. Soc.*, **95**, 8295 (1973); C. U. Pittman, Jr., and R. F. Felis, *J. Organomet. Chem.*, **72**, 389 (1974).

(10) C. L. Hamilton and H. M. McConnell, "Structural Chemistry and Molecular Biology", A. Rich and N. Davidson, Ed., W. H. Freeman, San Francisco, Calif., 1968, p 115; O. H. Griffith and A. S. Waggoner, *Acc. Chem. Res.*, **2**, 17 (1969).

(11) D. Kivelson, *J. Chem. Phys.*, **27**, 1087 (1957); J. H. Freed and G. K. Fraenkel, *ibid.*, **39**, 326 (1963); S. A. Goldman, G. V. Bruno, and J. H. Freed, *J. Phys. Chem.*, **76**, 1858 (1972); R. P. Mason and J. H. Freed, *ibid.*, **78**, 1321 (1974); A. T. Bullock, G. G. Cameron, and P. M. Smith, *J. Polym. Sci., Part A-2*, **11**, 1263 (1973).

(12) The rigid-lattice value of the anisotropic ^{14}N hyperfine splitting used was 32.5 G; this was determined experimentally from **3** in the dry state at 77 K.

(13) Those spectra which appeared as three sharp lines were further analyzed and found to be well behaved; i.e., the quantity, (line width)^2 × (amplitude), was constant for all three lines (±3%): G. K. Fraenkel, *J. Phys. Chem.*, **71**, 139 (1967).

(14) The degree of swelling values, q, were determined from the measured density of the dry resin and the weight of imbibed solvent. Swelling measurements were made after the nitroxide polymers were equilibrated with a given solvent for at least 24 hr; equilibrium was usually attained within a 2-hr period. Reproducibility was ±5%.

(15) In this calculation, it was assumed that the volumes of the polymer and solvent are additive. The density of **3** was experimentally found to be 0.95 ± 0.03 g/cm^3.

(16) C. Lagercrantz and M. Setaka, *J. Am. Chem. Soc.*, **96**, 5652 (1974). For a related spin-label study, see: D. B. Chesnut and J. F. Hower, *J. Phys. Chem.*, **75**, 907 (1971).

(17) The rotational motion of certain amino acids ionically bound to cation exchange resins has previously been reported: H. Sternlicht, G. L. Kenyon, E. L. Packer, and J. Sinclair, *J. Am. Chem. Soc.*, **93**, 199 (1971).

(18) W. Parr and K. Grohmann, *Tetrahedron Lett.*, 2633 (1971). 4-Bromomethylphenylsilica was commercially available (Chemical Dynamics Corp.); the pore size was 2500 Å.

(19) A. H. Cohen and B. M. Hoffman, *J. Am. Chem. Soc.*, **95**, 2061 (1973); G. P. Lozos and B. M. Hoffman, *J. Phys. Chem.*, **78**, 200 (1974); A. H. Cohen and B. M. Hoffman, *Inorg. Chem.*, **13**, 1484 (1974).

(20) N. E. Hoffman and K. A. Peteranetz, *Anal. Lett.*, **5**, 589 (1972).

(21) G. P. Lozos and B. M. Hoffman, *J. Phys. Chem.*, **78**, 2110 (1974). We thank Professor Hoffman for communicating these results to us prior to publication.

(22) We have found that, for similar preparations using 0.2 mmol of spin label/g of resin, the displacement reaction proceeds quantitatively; the molar amount of nitrogen bound was identical with the molar amount of chloride ion displaced.[23]

(23) Chloride ion was analyzed by Volhard titration using procedures described elsewhere: J. M. Stewart and J. D. Young, "Solid Phase Peptide Synthesis", W. H. Freeman, San Francisco, Calif. 1969, p 55. Nitrogen was determined by microanalysis (Midwest Microlab, Indianapolis, Ind.).

(24) The chloromethylation procedure used was similar to procedures described elsewhere: R. B. Merrifield, *J. Am. Chem. Soc.*, **85**, 2149 (1963); K. W. Pepper, H. M. Paisley, and M. A. Young, *J. Chem. Soc.*, 4097 (1953).

(25) The resin AG 1-X2 (Bio-Rad Laboratories) was purified by washing suc-

cessively with water, ethanol, and anhydrous ether and was dried under vacuum [10 hr, 65° (0.05 mm)]. The nitroxide 2,2,5,5-tetramethylpyrrolidin-1-oxyl-3-carboxylic acid was a gift of our colleague, Professor Jerry H. Smith.

(26) Bis(trimethylsilyl)trifluoroacetamide was obtained commercially (Regis Chemical Co.) and was used without further purification.
(27) H. P. Gregor, Guenther K. Hoeschele, J. Potenza, A. G. Tsuk, R. Feinland, M. Shida, and Ph. Teyssie, J. Am. Chem. Soc., 87, 5525 (1965).

# Ortho Neighboring-Group Participation of Amides in Photolytic Hydration of Triple Bonds[1a,b]

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Abstract: Photolysis of o-acetamidophenylacetylenes in hexane or acetonitrile gives 2-methyl-4-methylidene-1,3-4H-benzoxazines which add ^{18}O-labeled water to yield o-acetamidophenyl ketones with the label in the amide carbonyl. Proof of the site of the label lies in determination and analysis of the mass spectral fragmentation of the amido ketones. Irradiation of o-acetamidobenzonitrile in aqueous acetic acid yields o-acetamidobenzamide, 3-acetoanthranilonitrile, 5-acetoanthranilonitrile, and anthranilonitrile. If the photolysis is repeated with added benzophenone and a 366-nm source, only o-acetamidobenzamide results. Triplet states are proposed as precursors in photocyclizations of o-acetamidobenzonitriles and of o-acetamidophenylacetylenes. Irradiation of p-acetamidobenzonitrile does not cause photohydration but rather photo Fries-like fragmentation and rearrangement to p-aminobenzonitrile and 3-aceto-4-aminobenzonitrile.
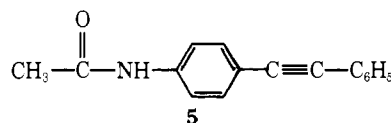
Previous reports of the photochemistry of diphenylacetylene have included reduction to stilbene,[1a] oxidation to benzoic acid,[2a] addition of protic solvents to give α-substituted stilbenes,[1a,b] self-cycloaddition to yield dimers, trimers, and tetramers,[2b] and cyclization of the acetylene moiety with o-nitro,[2c] o-ethylenyl,[2d] and o-ethynyl groups,[2e] respectively. A study is presently reported of photochemical hydration of phenylacetylenes and benzonitriles containing amido groups in ortho and para positions. The research investigation illustrates novel examples of photointeraction of amido functions with o-ethynyl and cyano groups and reveals the significance of neighboring-group participation in photolytic hydration of triple bonds.

o-Acetamidophenyl(phenyl)acetylene (1) photolyzes rapidly (253.7 nm) in wet hexane in the absence of oxygen to give o-acetamidophenyl benzyl ketone (2, eq 1). The structure of ketone 2 is established by literature melting point comparison,[3] analysis of spectral properties, and acid-catalyzed hydrolysis to o-aminophenyl benzyl ketone (3, eq

$$(1)$$
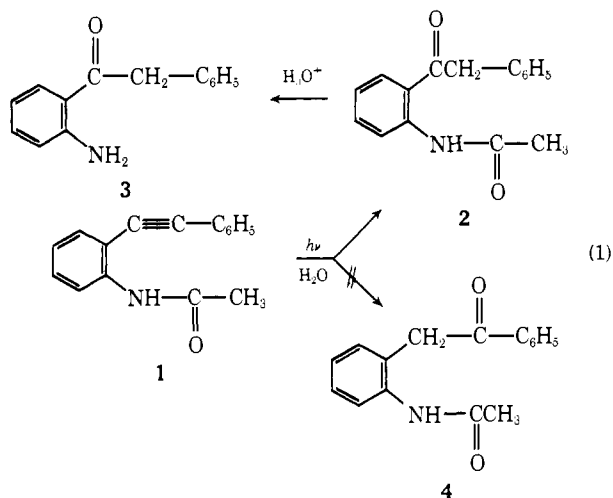
1). This experiment reveals that hydration of the triple bond of 1 occurs upon photolysis to produce only one of two possible benzyl ketones, that is 2 and not o-acetamidoben-

zyl phenyl ketone (4, eq 1). Ketone 4 might have been also expected as a product of direct photohydration of the triple bond of 1. The fact that p-acetamidophenyl(phenyl)acetylene (5) is inert under the above photolysis conditions indi-

cates that the o-acetamido group is playing much more than a simple electronic role in the photochemical hydration of 1 to 2 (eq 1). The collective results of this portion of the study suggest that there is some type of neighboring-group interaction involving the amide and ethynyl groups during photolysis of 1.

An investigation was then made of the products and mechanisms of photolysis of o-amidophenylacetylenes in anhydrous environments. Irradiation of o-acetamidophenyl(m-methoxyphenyl)acetylene[4] (6) in dry hexane yields a mixture of syn- and anti-4-(m-methoxybenzylidene)-2-methyl-1,3-4H-benzoxazines (7a and 7s, eq 2) as a yellow oil which then reacts readily upon addition of water to give o-acetamidophenyl m-methoxybenzyl ketone (8, eq 2). Assignments of structures of the mixture of 7s and 7a are based on spectral properties and reduction with sodium borohydride[5] and then hydrolysis to o-aminophenyl m-methoxybenzyl ketone (9, eq 2). Isomerization and the stereochemistry of 7s and 7a are indicated by the benzylidene proton absorptions at τ 3.9 and 4.1, respectively, and by the change in the proton magnetic resonance of the mixture of the benzoxazines upon exposure to ultraviolet light and upon storage in darkness. Upon photolysis of 7s–7a in chloroform at 254 nm, the absorption at τ 3.9 gradually decreases, whereas that at τ 4.1 increases. The proton magnetic resonance changes reverse when irradiated mixtures of 7s and 7a are stored in the dark, and thus 7a is the thermodynamically more stable isomer.[6]

Hydration of benzoxazines 7s and 7a could occur by attack of water on their exo carbon–carbon or their endo carbon–nitrogen double bonds to yield 8. The mechanism path