nitric acid (15 ml) was shaken in the dark (48 hr). The mixture was poured over water and filtered. The solid residue was unaltered radical. The per cent recoveries of PTM, PPTM, PDTM, and PPTM were 98.8, 97.4, 98.9, and 99.2, respectively, as ascertained by combining weight and absorptivity at 500 nm.

Reaction of the PDMs with Sodium Hydroxide in DMSO. In the dark, under argon, and at room temperature, a mixture of radical (0.100 g), powdered sodium hydroxide ($\sim$0.5 g), ethyl ether (30–50 ml), and DMSO (7–12 ml) was shaken (2–5 hr). The resulting blue mixture was poured over diluted aqueous hydrochloric acid and the ethereal layer separated. By evaporation a solid was obtained which was purified (recrystallization, chromatography). The product was identified by infrared and mixture melting point with the corresponding αH-quasi-perchloro compound. The yields of II, III, and IV were 70, 57, and 78%, respectively.

Reaction of the PTMs with Sodium Hydroxide in DMSO. The reaction was performed as in the preceding case. However, on account of the low solubility of the radicals—except for PTBT—THF was replaced for ethyl ether, and the contact extended (up to 2 days) after having refluxed the mixture for a time (2 hr). The corresponding αH-quasi-perchloro compounds were obtained. They were characterized by infrared and CH analysis. The yields of V, VI, VII, and X were 94, 86, 84, and 70%, respectively.

Reaction of PDM with Potassium. A mixture of PDM (0.302 g), anhydrous ethyl ether (100 ml), and one chunk of potassium metal ($\sim$0.5 g) was shaken vigorously (1 hr) at room temperature and under argon. The remaining potassium was separated and the resulting violet solution poured over water. The ethereal layer gave a solid mixture (0.303 g) which was chromatographed with alumina grade 1 (hexane) giving a mixture of αH-undecachlorodiphenylmethane (II, 0.253 g, 83.5%) and $\alpha H,\alpha H$-decachlorodiphenylmethane (0.016 g, 5.6%), which were identified by mixture melting point and infrared spectra.

Reaction of PTM with Potassium. A mixture of PTM (0.085 g), anhydrous ethyl ether (50 ml), and chunks of potassium, metal was shaken vigorously (8 hr) at room temperature, under argon, and in the dark. The potassium was filtered off, the red solution was poured over diluted aqueous hydrochloric acid, and the ethereal layer was decanted, washed with water, and dried. Elimination of the solvent gave a solid (0.078 g) that was dissolved in hexane–carbon tetrachloride (1:1) and passed through silica gel. The white residue obtained consisted of αH-pentadecachlorotriphenylmethane (V, 0.067 g, 79%) which was identified by infrared and carbon–hydrogen analysis.

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Electrophilic Substitution at Saturated Carbon. XLV. Dissection of Mechanisms of Base-Catalyzed Hydrogen–Deuterium Exchange of Carbon Acids into Inversion, Isoinversion, and Racemization Pathways[1]

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Abstract: The stereochemical course of base-catalyzed hydrogen–deuterium exchange between carbon acids and hydroxylic solvents has been studied by the technique of reresolution of partially racemized mixtures. Partial racemization of (+)-2-methyl-2,3-dihydrobenzo[*b*]thiophene 1,1-dioxide ((+)-I-*h*) in methanol-*O-d* containing potassium methoxide at 75° gave material that was reresolved and analyzed for deuterium. The data provided the following second-order rate constants: net inversion with exchange, $6.1 \pm 1 \times 10^{-5}$ l. mol^{-1} sec^{-1}; isoinversion (inversion without exchange), $1.4 \pm 0.2 \times 10^{-5}$ l. mol^{-1} sec^{-1}; racemization with exchange, $11.7 \pm 1 \times 10^{-5}$ l. mol^{-1} sec.$^{-1}$ A parallel experiment with (+)-2-deuterio-2-methyl-2,3-dihydrobenzo[*b*]thiophene 1,1-dioxide ((+)-I-*d*) in methanol-*O-h* containing potassium methoxide at 75° gave rate constants: net inversion with exchange, $3.5 \pm 0.3 \times 10^{-5}$ l. mol^{-1} sec^{-1}; isoinversion, $3.1 \pm 0.4 \times 10^{-6}$ l. mol^{-1} sec^{-1}; racemization with exchange, $3.9 \pm 0.3 \times 10^{-5}$ l. mol^{-1} sec^{-1}. These data provided substrate and solvent isotope effects for racemization that agreed well with independently measured values. Mechanisms are proposed which rationalize the simultaneous occurrence of simple inversion and isoinversion in which solvation of the sulfone's oxygens plays a key role. Similar experiments with (−)-4-biphenylylphenylmethoxydeuteriomethane ((−)-II-*d*) at 150° in methanol-*O-h* containing potassium methoxide gave only racemization. The methoxyl group of (−)-II-*d* appeared unable to play the solvent organizational role assumed by the sulfone group in (+)-I-*d*.

In the early work on base-catalyzed hydrogen–deuterium exchange between optically active carbon acids and hydroxylic solvents,[3] k_e/k_α values (k_e is the rate constant for isotopic exchange and k_α that for racemization) were employed as criteria of the stereochemical pathway for reaction. This method identified reactions that occurred with high retention, complete racemization, or with high isoinversion, but failed to separate these from one another and from inversion with isotopic exchange when the rates of the possible

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[1] The authors thank the U. S. Army Research Office, Durham, North Carolina, for support of this work.

[2] To whom correspondence should be addressed.

[3] D. J. Cram, "Fundamentals of Carbanion Chemistry," Academic Press, New York, N. Y., 1965, pp 105–113.

Table I. Kinetics of Racemization of (+)-2-Methyl-2,3-dihydrobenzo[*b*]thiophene 1,1-Dioxide ((+)-I) and of (−)-4-Biphenylylphenylmethoxymethane ((−)-II) Catalyzed by Potassium Methoxide

Run no.	Carbon acid Nature	Carbon acid Concn, *M*	Base concn, *M*	Solvent	Temp, °C	$k_\alpha^1 \times 10^5$ sec$^{-1\,a}$	$k_\alpha^2 \times 10^4$ l. M^{-1} sec$^{-1\,a,f}$
1	(+)-I-*h*[b]	0.069	0.172	CH_3OH	75.1	2.22 ± 0.015	1.29 ± 0.0085
2	(+)-I-*d*[c]	0.069	0.172	CH_3OH	75.1	2.06 ± 0.013	1.20 ± 0.0075
3	(+)-I-*d*[c]	0.115	0.176	CH_3OD[d]	75.1	4.58 ± 0.023	2.60 ± 0.013
4	(−)-II-*h*[e]	0.036	0.470	CH_3OH	150.5	2.64 ± 0.012	0.562 ± 0.003

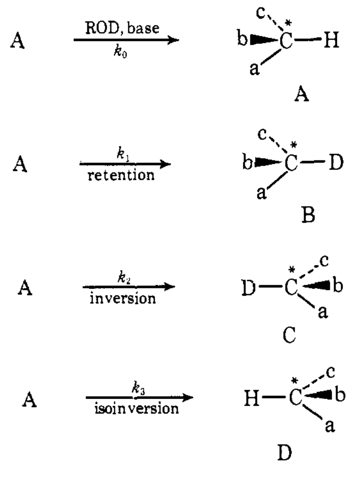
[a] Standard deviation of least-squares slope. [b] $[\alpha]^{25}_{546}$ +23.9° (*c* 4.2, chloroform). [c] 99% atom excess deuterium, $[\alpha]^{25}_{546}$ +24.2° (*c* 4.2, chloroform). [d] >99% atom excess deuterium. [e] $[\alpha]^{25}_{546}$ −6.3° (*c* 3.7, chloroform). [f] $k_4 \equiv 0.5k_\alpha^2$ when solvent and substrate isotopes are identical.

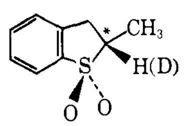
processes were of comparable magnitude. Accordingly,[4] a kinetic model was developed that provided a means for dissecting the rate data into its components. As a result, there emerged a more detailed picture of the proton transfer processes that composed the racemization and exchange reactions.

If an optically active carbon acid is treated with base in a medium that contains exchangeable protons of a different isotopic variety than that of the carbon acid, three possible products in addition to regenerated starting material can be formed. Each of the four materials is formally associated with a distinct stereospecific process, each with its own rate constant. If carbon acid A ionizes but is regenerated without isotopic exchange and with retention of configuration, the process occurs by an invisible reaction with rate constant k_0, and can be only inferred. If isotopically exchanged product of retained configuration (B) is formed, the process is identified by k_1. If inverted and exchanged product is formed (C), k_2 identifies the process. If inverted and nonexchanged product (D) is produced, k_3 is the rate constant and the process is termed *isoinversion*. Equation 1 relates k_e and k_α to k_1, k_2, and k_3.[4]

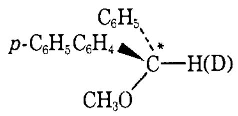
$$k_e/k_\alpha = (k_1 + k_2)/[2(k_2 + k_3)] \qquad (1)$$

Values for k_1, k_2, and k_3 can be obtained in a particular system by the following device. A carbon acid is submitted to partial racemization, and recovered material is fractionally crystallized into racemate and optically pure material. Isotopic analyses of these fractions coupled with an independently measured rate constant (k_4 = $k_\alpha/2$, for racemization of carbon acid containing the opposite isotopic label in the same medium) provide values of k_1, k_2, and k_3 at zero time.[4] With this technique, system (+)-IV-*h* in methanol-*O*-*d*-potassium methoxide was found to undergo isoinversion in competition with racemization (k_1 = k_2).[4] Application[5] of the technique to cyclic sulfone (−)-I-*d* in *tert*-butyl alcohol–potassium *tert*-butoxide revealed a blend of small isoinversion and net inversion-with-exchange components. Cyclic sulfone I also had been found[5] to give values of k_e/k_α slightly less than 1 in all media (0.64–0.73) unlike its open-chain counterpart (III). Sulfone III gave k_e/k_α values that ranged from 10 to about 2000, depending on medium.[6] Ether (−)-II-*h* in *tert*-butyl alcohol-*O*-*d*-potassium *tert*-butoxide gave a k_e/k_α value of 33 (high retention),[7a] whereas in methanol-*O*-*d*-dimethyl sulfoxide (75:25 by volume)-potassium methoxide, (−)-II-*d*, it gave k_e/k_α = 1.[7b]

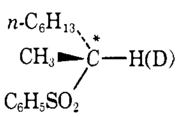




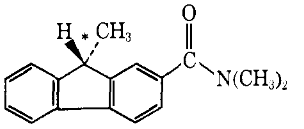
I-*h*(*d*)



II-*h*(*d*)



III-*h*(*d*)



IV-*h*

Particularly striking is the contrast provided by the predominance of a retention mechanism in *tert*-butyl alcohol for ether II and open-chain sulfone III and a racemization–isoinversion–inversion mechanistic blend for cyclic sulfone I in the same medium. The present work was undertaken to probe further by the reresolution method the mechanistic details of isotopic exchange of systems I and II in methanol–potassium methoxide, so that the behavior of all four systems could be compared in this medium.

Methods and Results

Starting materials were prepared according to earlier studies[5,7a] in an optically pure state, both deuterated (98%) and undeuterated. Previously,[5] an isotopic dilution experiment established that (±)-I could be fractionally crystallized from either enantiomer without isotope selection to give optically pure material and racemate. In the present work, (−)-II and (±)-II

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(4) (a) W. T. Ford, E. W. Graham, and D. J. Cram, *J. Amer. Chem. Soc.*, **89**, 689 (1967); (b) *ibid.*, **89**, 690 (1967); (c) *ibid.*, **89**, 4661 (1967).

(5) D. J. Cram and T. A. Whitney, *ibid.*, **89**, 4651 (1967).

( ) D. J. Cram, D. A. Scott, and W. D. Nielsen, *ibid.*, **83**, 3696 (19 1).

( ) (a) W. D. Kollmeyer and D. J. Cram, *ibid.*, **90**, 1779 (1968); (b) W. D. Kollmeyer and D. J. Cram, *ibid.*, **90**, 1784 (1968).

Table II. Results of Isotopic Exchange, Racemization, and Reresolution Experiments of (+)-2-Methyl-2,3-dihydrobenzo[*b*]thiophene 1,1-Dioxide ((+)-I) and of (−)-4-Biphenylylphenylmethoxydeuteriomethane ((−)-II-*d*)

	Carbon acid		Base									
Run no.	Nature	Concn, *M*	Nature	Concn, *M*	Solvent	Temp, °C	Time, min	% rac	$k_1{}^a$	$k_2{}^b$	$k_3{}^c$	$k_4{}^d$
5	(+)-I-*d*[e]	0.33	CH_3OK	0.172	CH_3OH	75.1	489.5	43.9	1.94 ± 0.18	5.48 ± 0.18	0.311 ± 0.042	6.45 ± 0.07
6	(+)-I-*h*[f]	0.33	CH_3OK	0.172	CH_3OD[g]	75.1	215	45.8	5.87 ± 0.53	12.0 ± 0.53	1.45 ± 0.20	13.0 ± 0.07
7	(−)-I-*d*[h]	0.33	*tert*-BuOK	0.028	*tert*-BuOH[i]	25.0	67.5	59.8	233	337	38.7	518
8	(−)-II-*d*[j]	0.052	CH_3OK	0.470	CH_3OH	150.5	963	51.6	1.46 ± 0.2	1.37 ± 0.1	0.00 ± 0.03	2.81 ± 0.02

[a] Units l. mol^{-1} sec^{-1} × 10^5: k_1, retention with exchange. [b] k_2, inversion with exchange. [c] k_3, isoinversion. [d] $k_4 = 0.5k_\alpha{}^2$ when solvent and carbon acid isotopes are the same. [e] 99% atom excess of deuterium, $[\alpha]_{546}{}^{25}$ +24.2° (*c* 4.2, chloroform). [f] $[\alpha]^{25}{}_{546}$ +23.9° (*c* 4.2, chloroform). [g] >99% atom excess deuterium. [h] 98% atom excess of deuterium, $[\alpha]^{25}{}_{546}$ −24.1° (*c* 4.0, chloroform). [i] *tert*-BuOH–$(CH_2)_4O$, 70:30 by volume. [j] 98% atom excess of deuterium, $[\alpha]^{25}{}_{546}$ −6.23° (*c* 4.2, chloroform).

were found easily separable by fractional crystallization from pentane to give optically pure (−)-II. It is assumed for system II that no isotopic selection accompanied this fractional crystallization.

Table I reports the results of kinetic runs (1–3) in which the rates of racemization of (+)-I-*h* and (+)-I-*d* in methanol-*O*-*h* and of (+)-I-*d* in methanol-*O*-*d* at 75° were followed polarimetrically with eight points through 2 half-lives. A similar run (4) with nine points carried through 2 half-lives was made at 150° with (−)-II-*h* in methanol-*O*-*h*. Good pseudo-first-order rate constants were obtained, from which were calculated second-order rate constants (k_4's) by dividing the first-order rate constants by twice the base concentration ($k_\alpha = 2k_4$).

Table II reports the results of the reresolution experiments. In run 5, (+)-I-*d* in methanol-*O*-*h* and in run 6, (−)-I-*h* in methanol-*O*-*d* were employed. Run 7 made at 25° involved (−)-I-*d* in 70% *tert*-butyl alcohol–30% tetrahydrofuran (by volume) that was 0.028 *M* in potassium *tert*-butoxide at 25°, and the data were taken from a previous paper.[5] Run 8 employed (−)-II-*d* in methanol-*O*-*h* at 150°. In measuring the extent of racemization in these runs, care was taken not to crystallize fractionally the products of these runs before rotations were taken. A computer program was written and used to extract the rate constants from the data.[8]

From eq 1 and the data of Table II, k_e/k_α values were calculated for sulfone system I for the isotopic label in both methanol and carbon acid (runs 5 and 6). Similar k_e/k_α values were calculated for deuterated sulfone system I in *tert*-butyl alcohol (run 7).[5] Chart I records the results. The values agree remarkably well with k_e/k_α values calculated earlier[5] from one-point rate constants without taking account of carbon acid isotope effects. These latter values are included in parentheses in Chart I. Similarly, from eq 1 and the *k*'s of run 8 (Table II), a k_e/k_α value was calculated for methoxide system II in methanol. The value obtained compares well with that calculated directly from kinetic rate constants obtained[7a] for potassium methoxide catalyzed racemization and exchange of methoxide system (−)-II-*h* at 126° in methanol-*O*-*d*–dimethyl sulfoxide (75:25% by volume). This value is included in parentheses.

Chart I

$$^{75°}(k_e/k_\alpha)_{\text{I-}d}{}^{CH_3OH} = 0.64\ (0.64)$$

$$^{75°}(k_e/k_\alpha)_{\text{I-}h}{}^{CH_3OD} = 0.66\ (0.65)$$

$$^{25°}(k_e/k_\alpha)_{\text{I-}d}{}^{tert\text{-BuOH}} = 0.76\ (0.66)$$

$$^{150°}(k_e/k_\alpha)_{\text{II-}d}{}^{CH_3OH} = 1.0\ (1.1)$$

From eq 2–5 and the rate constants of Table II,

$$(k_{CH}/k_{CD})_{OH(D)}{}^\alpha = 2k_4/[2(k_2 + k_3)] \qquad (2)$$

$$(k_{CH}/k_{CD})_{OD}{}^\alpha = 2(k_2 + k_3)/2k_4 \qquad (3)$$

$$(k_{OH}/k_{OD})_{CH}{}^\alpha = 2k_4/[2(k_2 + k_3)] \qquad (4)$$

$$(k_{OH}/k_{OD})_{CD}{}^\alpha = [2(k_2 + k_3)]/2k_4 \qquad (5)$$

the hydrogen–deuterium carbon acid and solvent isotope effects were calculated for sulfone system I–methanol. Chart II records the results. The carbon acid isotope effect for I-*d* in *tert*-butyl alcohol–potassium *tert*-butoxide was also available from earlier work,[5] and is included. The values in parentheses in Chart II are those calculated directly from the rate constants of Table I, or comparable data obtained earlier.[5] In all cases the agreement between the values of the isotope effects obtained by direct measurement, and those calculated from the reresolution data are in good agreement. This internal consistency strengthens the case for the general validity of the reresolution approach.

Chart II

$$^{75°}(k_{\text{I-}h}/k_{\text{I-}d})_{CH_3OH}{}^\alpha = 1.12\ (1.08)$$

$$^{75°}(k_{\text{I-}h}/k_{\text{I-}d})_{CH_3OD}{}^\alpha = 1.03$$

$$^{75°}(k_{CH_3OH}/k_{CH_3OD})_{\text{I-}d}{}^\alpha = 0.45$$

$$^{75°}(k_{CH_3OH}/k_{CH_3OD})_{\text{I-}h}{}^\alpha = 0.48\ (0.46)$$

$$^{25°}(k_{\text{I-}h}/k_{\text{I-}d})_{tert\text{-BuOH}}{}^\alpha = 1.25\ (1.29)$$

$$^{150°}(k_{\text{II-}h}/k_{\text{II-}d})_{CH_3OH}{}^\alpha = 2.1$$

Unsuccessful attempts were made to racemize or isotopically exchange sulfone (+)-I-*d* with amine bases in a variety of solvents. These included triethylenediamine at 135° in dimethyl sulfoxide–*tert*-butyl alcohol and in tetrahydrofuran–*tert*-butyl alcohol; Δ^5-1,5-diazabicyclo[4.3.0]nonene (DBN) at 100° with no solvent; pentamethylguanidine at 200° in tetrahydrofuran–*tert*-butyl alcohol and at 100° in dimethyl sulfoxide–*tert*-butyl alcohol; cyclohexylamine at 200° in pyridine.

Discussion

In the first section, the mechanistic components observed in the isotopic exchange–racemization of the

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(8) The authors wish to thank Mr. K. C. Chu for his assistance with the program.

Table III. Rate Factors for Mechanistic Components in Isotopic Exchange–Racemization of Cyclic Sulfone I

Run no.[a]	Carbon acid	Temp, °C	Solvent	Rate factors relative to isoinversion				
				Ret	Inv	Isoinv	Net inv[c]	Rac[c]
5	(+)-I-*d*	75	CH_3OH	6.3	17.6	1.0	11.3	12.5
6	(+)-I-*h*	75	CH_3OD	4.1	8.3	1.0	4.2	8.1
7	(−)-I-*d*	25	*tert*-BuOH[b]	6.0	8.7	1.0	2.7	12

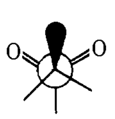
[a] Table II. [b] *tert*-BuOH–$(CH_2)_4O$, 70:30 by volume. [c] With exchange.

cyclic sulfone I are discussed. The difference in behavior of the cyclic sulfone I and its open-chain counterpart (sulfone III) is taken up in the second section. The third section is concerned with a comparison between the isotopic exchange–racemization mechanisms in methanol–potassium methoxide of carbon acids whose anions are stabilized by different means. Isotope effects are discussed in the fourth section.

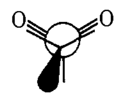
Mechanistic Components for Isotopic Exchange–Racemization of Cyclic Sulfone I. The results of the reresolution experiments indicate the presence of three mechanistic components in the isotopic exchange–racemization of cyclic sulfone I in methanol. These components can be discussed most conveniently in terms of the values of their relative rate constants, k_1 (exchange with retention), k_2 (exchange with inversion), and k_3 (inversion without exchange, or isoinversion). In all experiments in this system, $k_2 > k_1$, and therefore $k_2 - k_1$ is the rate constant for *net inversion* with exchange and $2k_1$ that for racemization with exchange of the system. The rate constant factors relative to the isoinversion rate constant (set equal to one) are listed in Table III.

The rate factors for the mechanistic components provide a number of interesting conclusions. (1) Inversion, retention, and isoinversion components are found irrespective of whether the solvent is methanol or *tert*-butyl alcohol. (2) Inversion exceeds retention by factors of 3, 2, and 1.3 in passing from methanol-*O-d* to methanol-*O-h* to *tert*-butyl alcohol-*O-h*, respectively. Retention exceeds isoinversion by factors of 6, 4, and 6 as solvent is changed in the same sequence. (3) Net inversion as compared to racemization decreases as solvent is changed in the same sequence. (4) The change in rate factors is almost as great in passing from methanol to deuterated methanol as from deuterated methanol to *tert*-butyl alcohol.

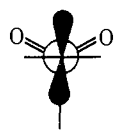
Comparison of Mechanistic Components for Isotopic Exchange–Racemization for Cyclic Sulfone I and Open-Chain Sulfone III. In methanol or *tert*-butyl alcohol, 2-phenylsulfonyloctane (III) underwent base-catalyzed isotopic exchange with high retention of configuration,[6] III-*d* in methanol giving k_e/k_α = 10 (at 100°) and III-*d* in *tert*-butyl alcohol giving values $k_e/k_\alpha > 100$. With III, the high retention was shown to be independent of the presence of a metal cation, and was attributed to an intrinsically *asymmetric carbanion*. Since the original report[9a] that open-chain α-sulfonyl carbanions are capable of intrinsic asymmetry, many confirmations have appeared,[9b–h] experiments devised,[9b–k] and calculations made[9l,m] in attempts to identify the character of the asymmetry. The most refined calculations[9m] indicate for the species $\bar{C}H_2SO_2H$ a pyramidal carbanion of lowest energy whose electron pair occupies an sp^3 orbital oriented directly between the two oxygens of the sulfonyl group as in E. This conformation and configuration is more stable by 5 kcal/mol than its inverted form (F), and by 2.5 kcal/mol than its most stable sp^2 hybridized carbanion (G). The authors[9m] conclude "the asymmetry of α-sulfinyl and α-sulfonyl carbanions need not be related to a possible existence of 3d orbital conjugation. Rather, we now believe that the two species adopt an asymmetric structure as a consequence of the stereochemical requirements of two adjacent electron pairs or an electron pair and an adjacent dipole." The bulk of the experimental work[9f,g,i,j] is most compatible with the view that in open-chain systems, α-sulfonyl carbanions are formed and captured from a conformation that involves E on the reaction coordinate, and that its asymmetry is more associated with restricted rotation than with a barrier to inversion to form F. Aside from the calculations,[9m] no evidence bears on the question of whether G is a transition state separating E and F as intermediates, or E is a transition state and G an intermediate.[10]



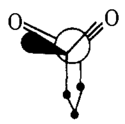
E



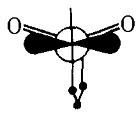
F



G



H



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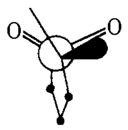

K

For the cyclic sulfone, only structures H, J, and K are available because of the constraints imposed by the five-membered ring. Calculations[9m] indicate that H and K are more stable than J by 1.5 kcal/mol which

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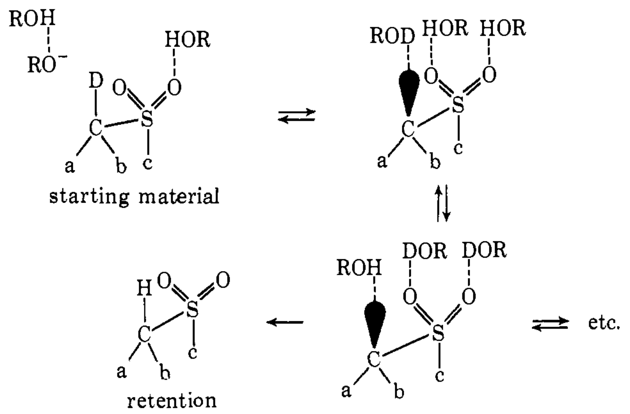
[9] (a) D. J. Cram, W. D. Nielsen, and B. Rickborn, *J. Amer. Chem. Soc.*, **82**, 6415 (1960); (b) E. J. Corey and E. T. Kaiser, *ibid.*, **83**, 490 (1961); (c) E. J. Corey, H. Konig, and T. H. Lowry, *Tetrahedron Lett.*, 515 (1962); (d) H. L. Goering, D. L. Towns, and B. Dittmer, *J. Org. Chem.*, **27**, 736 (1962); (e) D. J. Cram and A. S. Wingrove, *J. Amer. Chem. Soc.*, **84**, 1496 (1962); (f) E. J. Corey and T. H. Lowry, *Tetrahedron Lett.*, 793, 803 (1965); (g) D. J. Cram, R. D. Trepka, and P. St. Janiak, *J. Amer. Chem. Soc.*, **88**, 2749 (1966); (h) F. G. Bordwell, D. D. Philips, and J. M. Williams, *ibid.*, **90**, 426 (1968); (i) F. G. Bordwell, B. B. Jarvis, and P. W. R. Corfield, *ibid.*, **90**, 5298 (1968); (j) L. A. Paquette, *Accounts Chem. Res.*, **1**, 209 (1968); (k) T. Jordan, H. W. Smith, L. L. Lohr, and W. H. Lipscomb, *J. Amer. Chem. Soc.*, **85**, 846 (1963); (l) S. Wolfe, A. Rauk, and I. G. Csizmadia, *ibid.*, **89**, 5710 (1967); (m) S. Wolfe, A. Rauk, and I. G. Csizmadia, *ibid.*, **91**, 1567 (1969).

[10] In this first article on asymmetric α-sulfonyl carbanions (ref 9a), we stated,"...the carbanion formed as intermediate is probably asymmetric...The carbanion might exist either as a d-orbital stabilized sp^3 hybrid with exchange occurring faster than inversion, or as a rehybridized but still asymmetric species in which carbon is "doubly bonded" to sulfur by p–d orbital overlap. In the latter case, formation and disposal of the carbanion might occur preferentially from the same side due to steric and (or) dipole–dipole interactions. Under such circumstances, substitution could occur with retention of configuration." However, later (ref 9g) we indicated a preference on electrostatic grounds for carbanion F as the more stable conformation and configuration. The calculations of ref 9m suggest the basis of this preference is groundless.

suggests that J is a transition state for interconversion of H and K, and that the activation energy is extremely small.

Superposition of solvation effects on this calculated model provides a mechanism compatible with both our results and those of others.[9] This mechanism involves the following assumptions. (1) The starting carbon acids are already solvated in their ground states by hydrogen bonds between the hydroxyl groups of the medium and the sulfone groups. (2) Once ionization occurs, much of the isotopic exchange occurs by simple exchange in position between those solvent molecules originally hydrogen bonded to oxygen, and the differently labeled alcohol molecule hydrogen bonded to the carbanion generated by ionization.

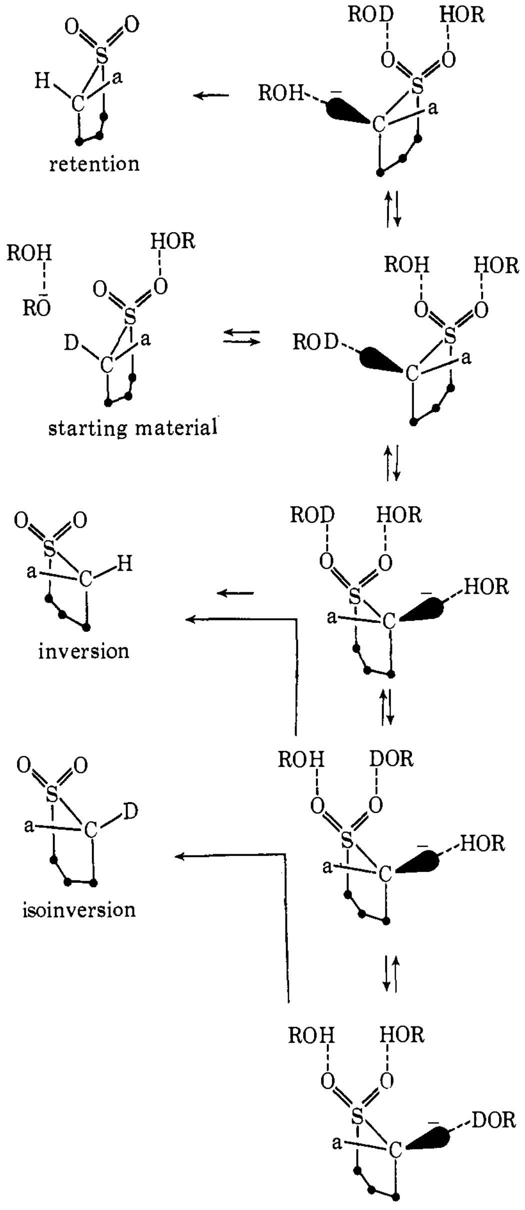
Chart III. Retention Mechanism



These simple notions are applied to the open-chain sulfone system I in Chart III, and to the cyclic sulfone system in Chart IV. One additional feature characterizes the inversion and isoinversion mechanisms envisioned in Chart IV. Pyramidal inversion of the cyclic carbanion without loss in solvation energy, and with a minimum dislocation of solvent structure is accompanied by a circular threefold movement of the three solvating alcohol molecules from their hydrogen bonding sites to adjacent sites. This movement of solvent molecules among hydrogen bonding sites resembles the movement of people in the game of musical chairs.

This mechanism provides the following rationale for the stereochemical results. (1) In the open-chain sulfonyl carbanion, the three hydrogen bonding sites are closer together than in the cyclic sulfonyl carbanion. Solvent molecule rotations between sites and collapse to the covalent state provide only retention. Retention dominates over other paths by a factor of 10 in methanol. (2) In the cyclic sulfonyl carbanion, the three sites are not equally spaced, and pyramidal inversion accompanying a *three-solvent molecule rotation* among sites in effect brings the sites closer together. After one such rotation and collapse to product, inversion is predicted. Inversion (k_2) occurs two to three times as fast as other processes. A three-solvent molecule rotation with pyramidal inversion, followed by a second three-solvent molecule rotation *without* pyramidal inversion and collapse to the covalent state predicts isoinversion. Isoinversion (k_3) is the least used path by the system. (3) This mechanism does not depend on the presence or absence of a cation nor on the dielectric properties of the solvent. Qualitatively, the selection of predominant reaction pathways for the two sulfones does not depend on the presence or absence of cation, nor on the solvent character employed.

Chart IV. Inversion–Isoinversion–Retention Mechanism



Comparison between Isotopic Exchange Racemization Mechanisms of Carbon Acids Whose Anions Are Stabilized by Different Means. Systems I–IV now have all been examined in methanol and *tert*-butyl alcohol, and show widely different behavior. Unlike sulfone systems I and III which exhibit intrinsic carbanion asymmetry, diarylmethoxymethane system II and amidofluorene system IV probably generate symmetrical carbanions. Thus with II and IV, stereospecificity depends on asymmetric ion pairing or solvation, and is therefore much more sensitive to solvent dielectric constant and the nature of the base. For example, application of the reresolution method to (−)-II-*d* in methanol-*O-h* (run 8, Table II) gives $k_1 = k_2$ and $k_3 = 0$ within experimental error. Thus the reaction was nonstereospecific and contained no isoinversion component. The lack of stereospecificity suggests that the starting material in methanol does not ionize in a form in which the methoxyl group of the carbon acid is hydrogen bonded to a solvent molecule, since such a path would probably produce net inversion as with cyclic sulfone I. The absence of an isoinversion component in run 8 indicates that the methoxyl group does not provide a path for transferring a deuterium from the front to the back face of the carbanion that can compete with isotopic drowning. The sulfonyl group in cyclic sulfone I provides such a path, as does the amido group in fluorene system IV, in either methanol or *tert*-butyl alcohol.[4c] The difference between the methoxyl and these other two groups (sulfone and amide) is that the latter distribute negative charge by conjugation whereas the former does not. Apparently the unshared electron pairs on oxygen of the methoxyl group of II do not provide a pathway for a conducted tour (by alkoxide) of deuterium from the front to the back face of the carbanion.

The striking change from high retention[7a] to total racemization for methoxy system II when methanol–potassium methoxide was substituted for *tert*-butyl alcohol–potassium *tert*-butoxide is clearly a consequence of asymmetric ion pairing in the latter solvent, and lack of it in the former.[11]

Isotope Effects. The kinetic isotope effects for racemization (Chart II) of cyclic sulfone I in methanol (k_H/k_D) at 75° were about 1.1, irrespective of whether deuterated or ordinary methanol was employed. The value in *tert*-butyl alcohol[5] at 25° was about 1.3. These low isotope effects suggest that the transition states of highest free energy in the overall free energy–reaction coordinate diagram for the racemization process involve a carbanion–solvent reorganization rather than a breaking of the carbon–hydrogen bond.[6] That these observed low values are probably comprised of an equilibrium component ($\text{C–H} + {}^{-}\text{OR} \rightleftarrows \text{C}^{-}\cdots\text{HOR}$) and a kinetic component ($\text{C}^{-}\cdots\text{HOR} + \text{DOR} \rightarrow \text{C}^{-}\cdots\text{DOR} + \text{HOR}$) has been suggested in many other cases where low values were observed.[6,12] A much higher kinetic isotope effect of 2.1 was observed for the diarylmethoxymethane system (II) at 150° (Chart II), and this value would have been substantially larger at lower temperatures. This higher value suggests that the isotope effect is not composite, and probably does not involve an equilibrium component.

The observed solvent isotope effects $(k_{\text{CH}_3\text{OH}}/k_{\text{CH}_3\text{OD}})^{\alpha}$ were the same within error (0.46) for both the racemization of optically active I-*h* and I-*d* (Chart II). This value corresponds well to that of 0.43 observed for racemization of fluorene system IV-*h* and IV-*d* at 25° and appears to be a property of the solvent–base system for these carbon acids. A similar value has been obtained in another investigation where carbon acids were ionized by sodium hydroxide in methanol.[13]

Experimental Section

Starting Materials. Optically active and deuterated 2-methyl-2,3-dihydrobenzo[*b*]thiophene 1,1-dioxide (I) was prepared as before:[5] (+)-I-*h*, mp 73–74°, $[\alpha]^{25}_{546}$ +23.9° (*c* 4.2, chloroform); (+)-I-*d*, mp 73–74°, $[\alpha]^{25}_{546}$ +24.2° (*c* 4.2, chloroform), 98.8–99.1% atom excess of deuterium. Reported procedures[7] gave optically active and deuterated *p*-biphenylylphenylmethoxymethane (II): (−)-II-*h*, mp 102–103°, $[\alpha]^{25}_{546}$ −6.2° (*c* 4.4, chloroform); (−)-II-*d*, mp 102.4–103.3°, $[\alpha]^{25}_{546}$ −6.2° (*c* 4.2, chloroform), 98.0% atom excess deuterium (mass spectrometry).

Kinetics of Racemization of (+)-I-*h*, (+)-I-*d*, and (−)-II-*h*. The loss of optical activity of these compounds was followed polarimetrically. Table I records the conditions, and the number of points taken and the extent to which the reaction was followed are indicated under Results. The ampoules were loaded as described below under the reresolution experiments. After the ampoules were cooled and opened, the rotations were taken directly on the reaction mixtures in a 1-dm cell thermostated at 25°.

Reresolution Experiments. Run 5. To a small clean glass ampoule was added 0.250 g of (+)-I-*d*. After the ampoule had been flushed well with dry, oxygen-free nitrogen, 4.00 ml of 0.172 *N* potassium methoxide in methanol-*O-h* was added; the ampoule was capped quickly, degassed, and sealed under vacuum. The ampoule was placed in a thermostated oil bath at 75.10 ± 0.05° after shaking to ensure homogeneity. Time zero was taken after 1 min had elapsed. Since the zero time affects the subsequent calculations, and the ampoule has to warm from 25 to 75°, this extra minute made allowances for the temperature rise. The half-life of racemization was about 500 min (about 250 min in run 6 and 960 min in run 8). Thus the uncertainty in temperature equilibration introduces only a small error.

The ampoule was quenched at 0° after an estimated half-life of racemization had elapsed, and the time was accurately noted. The solution was shaken with 10 ml of dichloromethane and 10 ml of dilute hydrochloric acid. The aqueous layer was extracted with three additional portions of dichloromethane, and the combined organic layer was washed once with 5% aqueous sodium bicarbonate, once with water, and once with saturated sodium chloride solution, and was dried over sodium sulfate. Evaporation of the solvent from the filtered solution yielded a solid which was purified by *total* sublimation, yield 0.178 g, $[\alpha]^{25}_{546}$ +13.56° (*c* 3.99, chloroform).

The sublimed sulfone was fractionally crystallized from ether and 1:1 ether–pentane to yield pure (+)-I and pure (±)-I for deuterium analyses. Crystallization data are shown in Table IV. Crops 6 and 7 were combined and sublimed, $[\alpha]^{25}_{546}$ +24.03° (*c* 4.1, chloroform). Crops 1 and 2 were combined and recrystallized from 4.5 ml of ether to give 30.5 mg (crop A) and 24.2 mg (crop B). Crops A and B were combined and recrystallized from 1.5 ml of ether to yield 32.2 mg, $[\alpha]^{25}_{546}$ +0.10 ± 0.1° (*c* 2.6, chloroform), 99.6 ± 0.6% racemic. Analysis[5] for deuterium content of (+)-I gave 86.8 ± 0.5 and for (±)-I gave 45.8 ± 0.5% excess deuterium per

Table IV. Fractional Crystallization of (+)-I from (±)-I in the Product from Run 5

Crop	Wt, mg	% total wt	Crystallization solvent	
			Nature	Amt, ml
1	51.5	29	Ether	9.5
2	22.5	13	Ether	5.5
3	12.3	7	Ether–pentane[a]	13
4	10.6	6	Ether–pentane[a]	6
5	16.1	9	Ether–pentane[a]	3
6	38.0	21	Ether–pentane[a]	1
7	9.4	5	Ether–pentane[a]	0.5
A	30.5		Ether	4.5
B	24.2		Ether	1.0

[a] 1:1 by volume.

Table V. Fractional Crystallization of (−)-II from (±)-II in the Product from Run 8

Crop	Wt, mg	% total wt	Pentane, ml
1	43	12.8	28
2	24	7.2	18
3	37	11.0	12
4	35	10.4	8
5	53	15.8	5

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molecule. Run 6 was modeled after run 5. The (±)-I isolated from run 6 contained 53.5 ± 0.5% excess deuterium per molecule; the (+)-I contained 16.3 ± 0.5% deuterium.

Run 8. The procedure for the reaction resembled that of run 5 except 350 mg of (−)-II-*d* was employed and temperature was 150.5 ± 0.1°. After being cooled the ampoule's content was washed into 100 ml of dilute hydrochloric acid. The product separated as a white solid, was collected, washed with water, dried, and totally sublimed, wt 336 mg, $[\alpha]^{25}_{546}$ −3.01° (*c* 4.7, chloroform). This material was fractionally crystallized from pentane, and Table V records the results. Crops 1, 2, and 3 were combined and recrystallized from 5 ml of pentane by cooling slowly to 6°. The product (65 mg) of long, fine needles was sublimed, mp 102.5–103.1°, $[\alpha]^{25}_{546}$ −6.2° (*c* 5.5, chloroform), 61.4% atom excess deuterium (mass spectrometry). Crops 9 and 10 were combined and sublimed, mp 76.3–77.7°, $[\alpha]^{25}_{546}$ 0.0° (*c* 3.3, chloroform), 30.6% atom excess deuterium.

Limits of Error. The limits of error given in Table II were obtained by recalculation of the rate constants k_1, k_2, and k_3 using reasonable error values for deuterium content (±0.5%), time (1% of total), rotation (0.2% of observed), and k_4 (standard deviation of $k_\alpha/2$).

Deuterium Analyses. Deuterium analyses of II were performed by mass spectrometry as previously described.[11] Analyses of I were similar except that 20 eV and the direct heated inlet system were used.

Electrophilic Substitution at Saturated Carbon. XLVI. Crown Ethers' Ability to Alter Role of Metal Cations in Control of Stereochemical Fate of Carbanions[1]

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Abstract: The effect of dicyclohexyl-18-crown-6 cyclic polyether (V) on rates and the stereochemical course of potassium alkoxide catalyzed carbanion-generating reactions in alcoholic solvents have been studied. When treated at 70° with 0.17 *M* potassium *tert*-butoxide in *tert*-butyl alcohol, 0.17 *M* in crown ether, (−)-4-biphenylylphenylmethoxydeuteriomethane ((−)-I-*d*) underwent deuterium–hydrogen exchange (k_e) and racemization (k_α) at essentially the same rates ($k_e/k_\alpha \sim 1$). In the absence of crown ether, $k_e/k_\alpha = 46$. The presence of crown ether increased dramatically the rates of both isotopic exchange and racemization, the former by a factor estimated to be between 30 and 1000, and the latter between 500 and 17,000. When treated at 101° with a solution of 0.13 *M* potassium *tert*-butoxide in *tert*-butyl alcohol, 0.13 *M* in crown ether V, (+)-4-phenyl-3,4-dimethyl-3-hexanol ((+)-II) cleaved to 2-phenylbutane ((+)-III) with 15% net *inversion* of configuration. In the absence of crown ether, the reaction occurred with 89–93% net *retention* of configuration. These results are interpreted in terms of the ability of crown ether to occupy the coordination sites of potassium ion, and forbid these sites to the leaving and entering groups on the front face of the carbanion intermediates in these electrophilic substitution reactions. Clearly the retention mechanism is dependent on the metal ions' organizing capacity. The rate constants for isotopic exchange and racemization of (+)-2-methyl-2,3-dihydro-2-deuteriobenzo[*b*]thiophene 1,1-dioxide ((+)-IV) in 0.148 *M* potassium methoxide–methanol that was 0.148 *M* in crown ether were found to be close to those obtained in the absence of crown ether. The k_e/k_α value of 0.66 was the same as that obtained without crown ether. In this more polar medium, the metal cation or the crown ether appears to play no role in determining the stereochemical course of exchange.

Earlier studies established that potassium *tert*-butoxide catalyzed hydrogen–deuterium exchange of carbon acid I[3a] and cleavage of tertiary alcohol II[3b,c] to 2-phenylbutane III in the same medium proceeded with high retention of configuration. Explanation of these results involved formation of potassium carbanide ion pairs in which the leaving and entering electrophile occupied coordination sites on the potassium ion, which played an organizing role on the front face of the carbanion.[3a,4] The preceding paper[5] reported that carbon acid III underwent isotopic exchange catalyzed by potassium methoxide in methanol in which racemization, inversion-with-exchange, and isoinversion components were blended. The explanation did not assign any role to the potassium ion in any of the mechanistic components.

Pedersen[6] reported that dicyclohexyl-18-crown-6 cyclic polyether V and many other cyclic ethers exhibited the ability to complex potassium ion in a variety of solvents that ranged from hexane to methanol. Smid and coworkers[7] have demonstrated that crown ethers and glyme ethers in ethereal solvents complex the metal ion

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