by an internal cold finger. After photolysis, the solution was saturated with NaCl and extracted with 2 × 100 mL ether. Both $^1$H NMR and IR of the photolysate are consistent with nearly quantitative conversion to the methyl ether of 1. The $^1$H NMR ($CDCl_3$) showed a methoxy ether singlet at $\delta$ 2.9, with the aromatic signals remaining essentially unchanged. The IR showed no OH absorption band. TLC (1:1 $CH_2Cl_2$/pentane) showed complete conversion to the methyl ether ($R_f$ 0.3).

**Acknowledgment.** The support of this research through operating grants and the award of a University Research Fellowship (to P.W.) from the Natural Sciences and Engineering Research Council (NSERC) of Canada is gratefully acknowledged.

**Registry No.** 1, 596-38-3; 1 (methyl ester), 96865-79-1; 2, 20460-07-5; $H_2O$, 7732-18-5; MeOH, 67-56-1.

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# Electrostatic Control of Regioselectivity in Competing Biomolecular Eliminations

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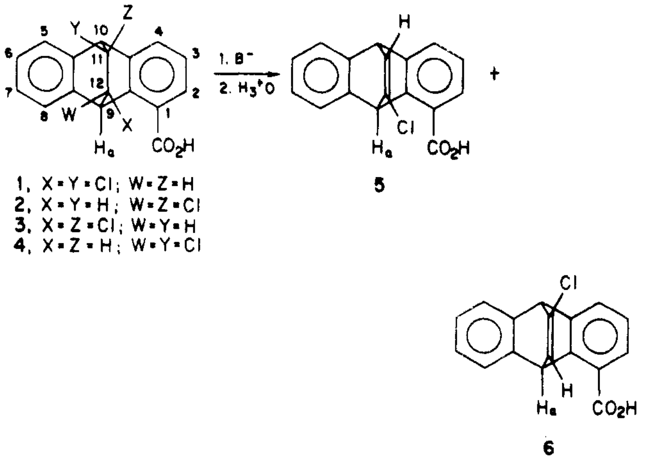
The isomeric *trans*-11,12-dichloro-9,10-dihydro-9,10-ethano-1-anthroic acids (1 and 2) have been prepared and characterized. Base-induced dehydrochlorinations of these and the corresponding *cis*-dichloroethano derivatives 3 and 4 were conducted under several sets of base/solvent conditions. Preparations and dehydrochlorinations of 2-[*trans*-11,12-dichloro-9,10-dihydro-9,10-ethano-9-anthryl]ethanoic acid (15) and the corresponding *cis*-dichloro isomer 16 are also reported. Regioselectivities in vinyl halide formations are highest with $K^+O^-$-*t*-Bu/*t*-BuOH/18-crown-6, conditions under which ion aggregation is minimized. The results of these studies indicate that both the syn and quasi-anti eliminations possess some carbanionic character but with most of the charge remaining on the attacking base in the transition states.

A variety of experimental techniques has been used to probe charge distributions in base-induced 1,2-eliminations. They include deuterium and heavy-atom isotope effects, Hammett $\rho$ values, leaving group rate effects, and base, solvent, and ion-pairing effects.[4–6]

Previously we demonstrated substituent electrostatic field effects on various reactions of carboxylate groups at the 1 and 2 postions of geometrically isomeric 11,12-dichloro-9,10-dihydro-9,10-ethanoanthracenes.[7,8] The results were discussed in terms of the Kirkwood–Westheimer electrostatic field model.[9] More recently we reported preliminary results of a study of base-induced eliminations of HCl from the anions of the four isomeric 11,12-dichloro-9,10-dichloro-9,10-ethano-1-anthroic acids 1–4.[10] The present paper extends these observations to include studies of the effects of changes in the base/solvent system on regioselectivity in these eliminations. Also included are results from dehydrochlorinations of the *cis*- and *trans*-dichloroethene cycloadducts of 9-anthrylacetic acid.



1, X=Y=Cl; W=Z=H
2, X=Y=H; W=Z=Cl
3, X=Z=Cl; W=Y=H
4, X=Z=H; W=Y=Cl

5

6

The dichloroethano-bridged anthracenes offer several advantages for a study of charge–charge and charge–dipole interactions in elimination reaction transition states not found in some alternate systems.[11] The rigidity of structures such as 1–4 facilitates reasonable estimates of through-space distances between sites of potential charge development. Choice of appropriate geometric isomer allows for the selective study of syn or quasi-anti eliminations without simultaneous dual pathways complicating interpretations of results. High yields of elimination products are observed. Steric and resonance interactions between developing partial charges and the substituents are minimal. Finally, the pivotal role played by Cristol's investigations[12,13] of the "unsubstituted" *cis*- and *trans-*

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[2] On leave from the Faculty of Science, Ain Shams University, Cairo.

[3] ACS-PRF Undergraduate Research Fellow, Summers of 1982, 1983.

[4] Saunders, W. H., Jr.; Cockerill, A. F. "Mechanisms of Elimination Reactions"; Wiley-Interscience: New York, 1973.

[5] (a) Bartsch, R. A.; Zavåda, J. *Chem. Rev.* **1980**, *80*, 453. (b) Hasan, T.; Sims, L. B.; Fry, A. *J. Am. Chem. Soc.* **1983**, *105*, 3967 and references therein. (c) Kwart, H.; Gaffney, A. H.; Kazimiera, A. W. *J. Chem. Soc., Perkin Trans. 2* **1984**, 565.

[6] Koch, H. F.; McLennan, D. J.; Koch, J. G.; Tumas, W.; Dobson, B.; Koch, N. H. *J. Am. Chem. Soc.* **1983**, *105*, 1930.

[7] Grubbs, E. J.; Fitzgerald, R; Phillips, R. E.; Petty, R. *Tetrahedron* **1971**, *27*, 935.

[8] Wang, C. T.; Grubbs, E. J. *J. Org. Chem.* **1977**, *42*, 534.

[9] For more recent studies of this type, see: (a) Bowden, K.; Hojatti, M. *J. Chem. Soc., Chem. Commun.* **1982**, 273 and (b) Siegel, M. G.; Liotta, C. L.; Cram, D. J. *J. Am. Chem. Soc.* **1982**, *104*, 1387 and references therein.

[10] Grubbs, E. J.; Schmidt, S. P.; Wang, C. T.; Goodrow, M. H.; Lewis, R. M.; Deardurff, L. A.; Coffey, D., Jr. *J. Am. Chem. Soc.* **1983**, *105*, 4115.

[11] See: (a) Badet, B.; Julia, M.; Mallet, J. M.; Schmitz, C. *Tetrahedron Lett.* **1983**, 4331. (b) Gevorkyan, A. A.; Arekelyan, A. S.; Kosyan, S. M. *Arm. Khim. Zh.* **1982**, *35* (6), 407. (c) Zavåda, J.; Pankova, M. *Collect. Czech. Chem. Commun.* **1979**, *44*, 1273. (d) Borowiecki, I.; Wodzki, W. *Rocz. Chem.* **1975**, *49*, 899. (e) Jarvis, B. B.; Govoni, J. P. *J. Org. Chem.* **1972**, *37*, 1568 and references therein.

[12] Cristol, S. J.; Hause, N. L. *J. Am. Chem. Soc.* **1952**, *74*, 2193.

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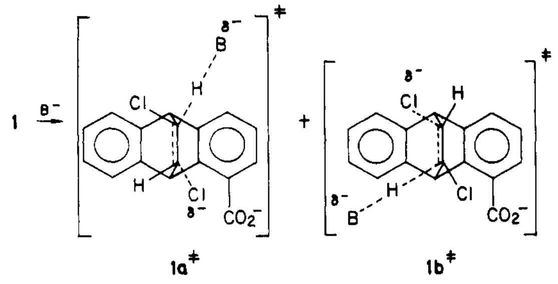
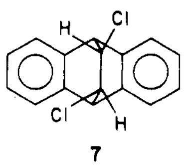
Scheme I



dichloro analogues of 1–4 in revealing preferred stereochemistries for base-induced eliminations as well as in suggesting the occurrence of carbanionic transitions states lends added significance to the present study.

Investigations of base-induced dehydrohalogenations of haloethano-bridged anthracenes and geometrically related norbornyl halides have focused attention on the question as to whether bimolecular eliminations in these systems should be characterized as relatively central $E_2$ or carbanionic processes.[14] Kinetic comparisons of eliminations for substances such as 7 and 8[13] suggest substantial carbanion character for the latter. But the structural differences between the two raise questions regarding a possible alteration in mechanism attending such a molecular modification.[15]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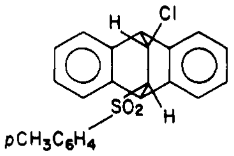
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A potentially sensitive probe of transition-state charge distribution in such rigidly constructed systems would be an assessment of the effects of the introduction of a remote charged group on regioselectivities. Unlike the potential consequence of replacing a chlorine atom in 7 by an arylsulfonyl group, the introduction of a remote carboxylate anion is unlikely to cause a fundamental change in the reaction mechanism. As employed in substrates 1–4, the carboxylate charge could be expected to interact with developing charges in two competing transition states in different and at least qualitatively predictable ways. For example, two limiting cases may be considered. First, central $E_2$ processes (1a‡ and 1b‡ from substrate 1 in Scheme I) and second, transition states with moderate carbanion character (corresponding to 1a‡ and 1b‡ but devoid of significant C–Cl bond breaking). Corresponding transition states derived from 3 and 4 can be envisioned. In a central $E_2$ process represented by Scheme I, the degree of regioselectivity observed in dehydrochlorinations of 1 would be expected to be influenced by charge–charge repulsions between Cl and $CO_2$ in 1a‡ more than in 1b‡. This would of course depend upon the magnitude of charge development on Cl. By contrast, in a similar mechanism but one in which little or no C–Cl bond breaking occurred, the regioselectivity would be primarily controlled by repulsion interactions between $CO_2$ and the base if entropic differences were minimal. The regioselectivities could also be influenced by repulsive interactions between the carboxylate anion and partial charges developing on the carbons from which the protons are removed.

Scheme II

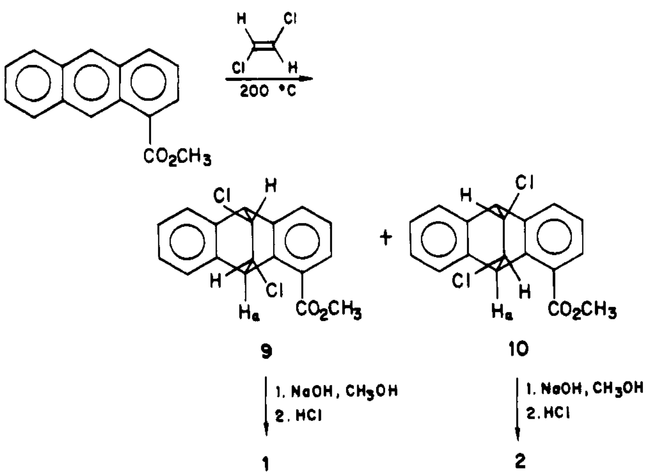


**Table I. Apparent p$K_a$'s of Several Bridged Anthracene-1-carboxylic Acids in 50% Aqueous Ethanol at 25 °C**

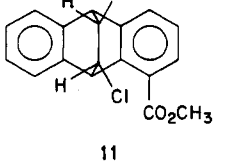
| acid | p$K_a$ |
|---|---|
| 1 | 5.86 ± 0.01 |
| 2 | 5.55 ± 0.01 |
| 3 | 5.94 ± 0.01 |
| 4 | 5.49 ± 0.01 |
| 9,10-ethano-9,10-dihydro-1-anthroic acid | 5.96 ± 0.01 |

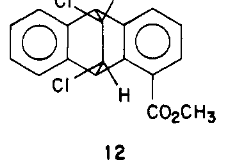
## Results

The syntheses and geometric characterizations of isomers 3 and 4 have been previously described.[8] Isomers 1 and 2 were similarly prepared as outlined in Scheme II. Separations of 9 and 10 could be accomplished using either fractional crystallization or chomatography. Isomer 10 was found to hydrolyze approximately four times faster than 9. This indicates that partial kinetic resolution of these diastereomers is feasible. Some success was in fact achieved in obtaining acids enriched in 2 and esters enriched in 9 by effecting partial hydrolysis in methanolic sodium hydroxide.

Apparent p$K_a$'s were determined for 1 and 2 in 50% by weight ethanol–water solutions. The results are listed in Table I. Included for comparison is the value for the nonhalogenated analogue reported by Golden and Stock[16] and the values for 3 and 4 also previously reported.[8]

Geometric assignments for 9 and 10 were initially made on the basis of the above p$K_a$'s and correlations of the C-9 proton chemical shifts between isomers 9 and 11 and between 10 and 12. The structure of 10 was subsequently established unequivocally by single crystal X-ray analysis.[17] Consequently structural assignments for the acids 1 and 2, obtained by hydrolyses of the separated esters, are unambiguous.


11


12

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[13] Cristol, S. J.; Arganbright, R. P. J. Am. Chem. Soc. 1957, 79, 3441 and references therein.

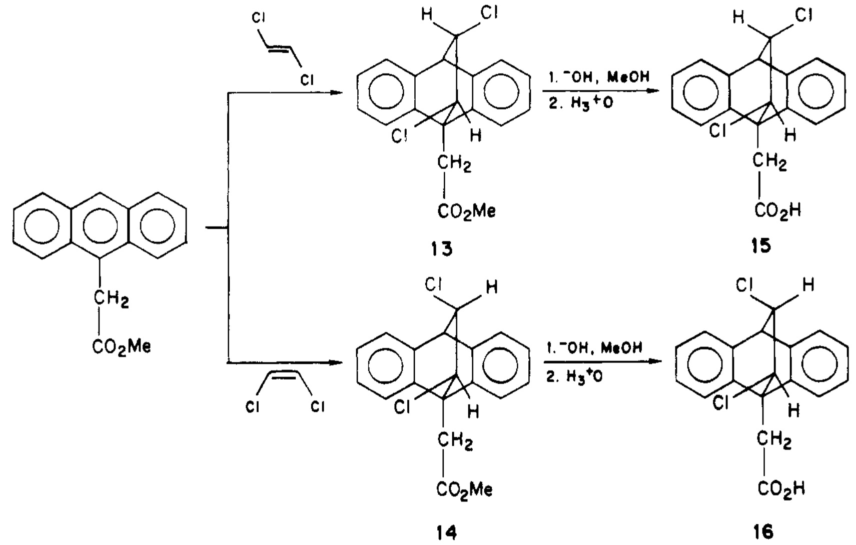
[14] See ref 4, pp 124–128 and references cited therein.

[15] McLennan, D. J. Q. Rev., Chem. Soc. 1967, 21, 490.

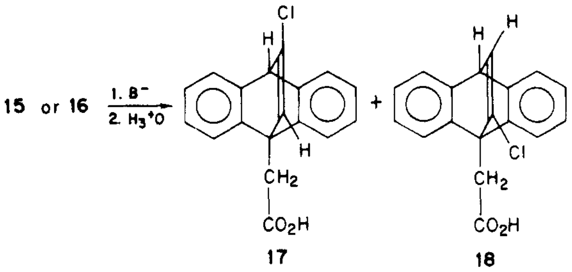
[16] Golden, R.; Stock, L. M. J. Am. Chem. Soc. 1972, 94, 3080.

[17] Full details of the crystal structure determination have been reported by Noordick (Noordick, J. Acta. Crystallogr., Sect. C: Cryst. Struct. Commun. 1984, 40, 123). We thank Dr. Noordick for his assistance with the X-ray crystallography. Questions regarding this aspect of the present study should be addressed to him at the University of Nijmegen, The Netherlands.

**Scheme III**



The isomeric acetic acid derivatives **15** and **16** were prepared as outlined in Scheme III. Dehydrohalogenations led to mixtures of **17** and **18** in high yield. The major isomer **17** was isolated from a preparative dehydrohalogenation of **16**. The mixtures of **17** and **18** (in some cases converted to methyl esters with diazomethane) were analyzed by using capillary GC, mass spectrometry, and $^1$H NMR.



Eliminations were conducted under several sets of conditions. Preliminary experiments were performed with acids **3** and **4** using sealed tubes containing degassed methanolic solutions of sodium or potassium hydroxide and the substrate. Runs were made with and without added crown ether (18-crown-6). Isolated yields of **5** and **6** were usually greater than 90%. Ratios of **6**/**5** were initially determined by area integrations for the C-9 proton ($H_a$) and confirmed by using capillary GC. Control experiments demonstrated that the products were stable to the reaction and workup conditions. The starting anions were shown to be configurationally stable to the elimination conditions by interruption of the reactions prior to completion, acidification, and examination of the starting substrates. Separations and full characterizations of **5** and **6** have been recently described.[18] Results of these eliminations are shown in Table II.

Dehydrochlorinations were also performed in degassed solutions of substrates **1**–**4**, **15**, and **16** in either *tert*-butyl alcohol (containing crown ether) or tetrahydrofuran using potassium *tert*-butoxide as base. Combined yields of the vinyl chloride products again exceeded 90% in each case. The results of these studies are summarized in Table III.

Attempts were made to induce dehydrochlorinations of the esters **9** and **10** with 1,5-diazabicyclo[4.3.0]nonen-5 (DBN). With 2/1 ratios of amine/substrate (in THF), no elimination was detected for reaction times up to 1 week at 80 °C.

**Table II. Dehydrochlorinations[a] of 3 and 4 in Methanolic Solutions of NaOH or KOH**

| substrate[b] | base[c] | temp, °C | crown ether[d] | prod ratio[e] (6/5) |
|---|---|---|---|---|
| 3 | NaOH | 113 | no | 0.96 |
| | NaOH | 144 | no | 1.0 |
| | NaOH | 144 | yes | 1.0 |
| | NaOH | 170 | no | 1.2 |
| | NaOH | 186 | no | 1.0 |
| | KOH | 123 | yes | 1.2 |
| | KOH | 144 | yes | 1.2 |
| | KOH | 144 | no | 0.81 |
| | KOH | 170 | yes | 1.1 |
| 4 | NaOH | 113 | no | 0.92 |
| | NaOH | 144 | no | 0.79 |
| | NaOH | 144 | yes | 2.3 |
| | NaOH | 170 | no | 0.82 |
| | NaOH | 186 | no | 0.92 |
| | KOH | 123 | yes | 3.5 |
| | KOH | 144 | yes | 3.8 |
| | KOH | 144 | no | 1.2 |
| | KOH | 170 | yes | 3.5 |

[a] Reaction time was 48 h. [b] Substrate concentration approximately 0.31 M. [c] Base concentration appproximately 1 N. [d] A 6% molar excess of 18-crown-6 over the total metal ion concentration was employed. [e] Estimated uncertainity is ±3%.

## Discussion

**Syntheses and Geometric Assignments for 1 and 2.** The synthesis of **1** and **2** followed the procedure previously described for **3** and **4**. However, in the case of the *trans*-dichloro compounds, resolution of the two diastereomeric esters **9** and **10** was facilitated by manual separations of the two isomers possessing markedly different macrocrystalline shapes. The observation of a substantial difference in rates of hydrolysis between **9** and **10** suggested that comparable effects in the dissociation constants of the corresponding acids **1** and **2** might be found. Further, it was hoped that these kinetic and thermodynamic differences might provide the basis for geometric assignments. Indeed, the similarities between p$K_a$'s for **1** and **3** and for **2** and **4** added support to the geometric assignments tentatively proposed (and later confirmed on the basis of single-crystal X-ray analysis of **10**) based on the kinetic behavior of the esters. It is clear from the p$K_a$ comparisons that the angular orientation of the C-12/Cl dipole plays the dominating role in determining the ap-

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[18] Grubbs, E. J.; Wang, C.; Deardurff, L. A. *J. Org. Chem.* **1984**, *49*, 4080.

**Table III. Dehydrochlorinations of 1–4, 15, and 16 at 80 °C Using Potassium *tert*-Butoxide**[a]

| substrate | solvent[b] | react, time, h | prod ratio[c,d] | |
|---|---|---|---|---|
| 1 | *t*-BuOH + CE | 30 | 1.70 (63/37) | = 6/5 |
| | THF | 60 | 13.3 (93/7) | |
| 2 | *t*-BuOH + CE | 30 | 24 (96/4) | |
| | THF | 60 | 19 (95/5) | |
| 3 | *t*-BUOH + CE | 30 | 2.4 (71/29) | |
| | THF | 60 | 1.33 (57/43) | |
| 4 | *t*-BuOH + CE | 30 | 13.3 (93/7) | |
| | THF | 60 | 4.6 (82/18) | |
| 15 | *t*-BuOH + CE | 72 | 19 (95/5) | =17/18 |
| | THF | 72 | 9.0 (90/10) | |
| 16 | *t*-BuOH + CE | 72 | 49 (98/2) | |
| | THF | 72 | 49 (98/2) | |

[a] A 0.50 M solution of *t*-BuOK in *t*-BuOH or 0.10 M *t*-BuOK in THF was employed. The substrate concentration in the basic solution was 0.095 M. Where crown ether was employed, a 1:1 mole ratio of 18-crown-6/total $K^+$ was used. [b] THF = tetrahydrofuran. [c] Average of two runs. Estimated uncertainty is ±3%. [d] Results of eliminations at 50 °C showed no significant differences from those measured at 80 °C.

parent p$K_a$'s. This illustrates a limitation in using resultant dipoles to predict p$K_a$'s. Were the vector sum of the two C/Cl dopoles employed in a K–W calculation and if one assumes $C_2$ symmetry for the dichloroethanoanthracene moiety (i.e., minus the carboxylate group), the p$K_a$'s for **1** and **2** would be identical. This vector sum approximation did account well for a vanished substituent effect for the *cis*-dichloro acid **3** (for which the K–W angle $\theta$ is approximately 89°).[8] In retrospect this is not surprising since the K–W angle $\theta$ employed if considering only the C-12/Cl dipole does not differ greatly from that value (approximately 100°). This combined with small differences in effective dielectric constant values ($D_E$) for the $CO_2^-\cdots Cl^{\delta-}$ and the $CO_2^-\cdots C^{\delta+}$ regions could account for the degree of agreement of calculated and measured $\Delta$p$K_a$'s.

**Elimination Studies.** Dehydrochlorinations of **3** and **4** using methanolic KOH and NaOH (Table II) show little regioselectivity in the absence of crown ether. And in the presence of crown ether, only **4** shows appreciable selectivity generating preferentially **6**. The difference between the behavior of **3** and **4** is understandable if little or no charge is developing on the Cl in the transition states. Thus the dominating electrostatic interaction would be between the carboxylate anion and the incoming base (with some charge perhaps located on the $\beta$ carbon in each case). And only when ion aggregation is limited by the addition of crown ether can these differing charge–charge repulsions impose significant differences on the two transition-state free energies. Potassium ion is more effectively complexed by 18-crown-6 than is sodium ion. This may account for the greater regioselectivity (**6**/**5**) using KOH. The assumption that product ratios are not primarily determined by differences in entropy of activation for the competing eliminations is supported by insensitivity of product ratios to temperature changes under a given set of conditions (Table II).[19]

The eliminations were next studied in *tert*-butyl alcohol/KO-*t*-Bu media containing 18-crown-6 to circumvent the uncertainty regarding the identity of the attacking base ($OH^-$ or $OCH_3^-$) in this solvent/base system and to lower the dielectric constant of the medium (and thus hopefully the effective dielectric constants mediating the charge–charge repulsions). Eliminations were repeated in tetrahydrofuran in the absence of crown ether to probe ion-aggregation effects. The results are shown in Table III. In most cases, eliminations were less selective in THF. The one notable exception (from **1**) is considered later in this discussion.

**Table IV. Observed and Calculated Ratios of 6/5 from Dehydrochlorinations Using $K^+O^-$-*t*-Bu/*t*-BuOH/Crown Ether**

| compd | obsd | calcd |
|---|---|---|
| 1 | 1.70 (63/37) | 1.53 (61/40) |
| 2 | 24 (96/4) | 19 (95/5) |
| 3 | 2.4 (71/29) | 3.0 (75/25) |
| 4 | 13.3 (93/7) | 9.7 (91.9) |

A reasonable interpretation of the results in Table III involving eliminations with the crown ether is the proposal that the ratio of products from each elimination is chiefly determined by repulsive interactions between the charge on the carboxylate group and the charge on the incoming base in the competing transition states.[10] Initial calculations dealt with the results from substrates **1–4**. A number of constant features for the transition states were assumed (refer to transition states **1a**$^\ddagger$ and **1b**$^\ddagger$ in Scheme I) in order to estimate these repulsive energies. Direct through-space distances separating the carboxylate anionic center and either $C_\beta$, Cl, or the oxygen of the attacking base were estimated by using Dreiding models (with necessary bond extensions to locate carboxylate and base charge centers). The charge on the carboxylate anion was taken as centered at the point between the two oxygen atoms and 2.1 Å from C-1. The distance between $C_\beta$ and the alkoxide oxygen was estimated at 2.7 Å[20] ($—C_\beta\cdots H\cdots O—$ assumed linear). Differences in the total repulsive potential energies for each pair of competing transition states were computed from Coulomb's law with variables being the effective dielectric constant[21] and the fractions of charge on the oxygen of the attacking base and on $C_\beta$. Differences in repulsive potential energies were converted to rate ratios by using the Arrhenius equation. An iterative least-squares computer program was used for these calculations.[24] The calculations lead to a best fit with an effective dielectric constant of 13.7 D ± 1.6 and the fraction of charge on the *tert*-butoxy oxygen ($f_0$) equal to 0.85 ± 0.13 (with the remainder on $C_\beta$). The calculations converge to the same values within the range 0–1.0 for $f_0$ and 5–50 for $D_E$. Calculations in which a significant charge is allowed to develop on the departing chlorine are not consistent with the experimental values of **6**/**5**. For example with as little as 0.3 fraction of a unit charge on chlorine, calculations fail to converge. With 0.1 charge on chlorine (0.53 on the base and 0.37 on $C_\beta$) convergence leads to a value of 10.2 ± 1.2 for $D_E$, but the fit to experimental data is poorer. Lack of agreement between calculated and experimental **6**/**5** ratios when the departing chloride assumes charge is particularly noticeable where the chloride would depart in the direction of the carboxylate anion. For example, in the elimination

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(19) A similar insensitivity of product ratio to reaction temperature (50 °C and 80 °C) for eliminations using $K^+O^-$-*t*-Bu/*t*-BuOH with crown ether was observed.

(20) This is about the distance between oxygen atoms in hydrogen-bonded alcohols (Pimentel, G. C.; McClelland, A. L. "The Hydrogen Bond", Pauling, L., Ed.; W. H. Freeman: San Francisco, 1960).

(21) This is an "empirical effective dielectric constant" as defined earlier[22,23] (a number which allows one to fit an observed substituent effect to an equation such as the Bjerrum or Eucken equation, representing coulombic interactions).

(22) Hoefnagel, A. J.; Wepster, B. M. *J. Org. Chem.* **1982**, *47*, 2318.

(23) King, E. J. "Acid-Base Equilibria"; Pergamon Press: Oxford, 1965; p 160.

(24) Johnson, J. K. "Numerical Methods in Chemistry"; Marcel Dekker Inc.: New York, 1980; 279–294.

from 1, using the best fit $D_E$ of 13.7 and assuming 0.2 charge on chlorine (0.8 on the oxygen of the base), the calculated ratio **6**/**5** is 0.62. That is, the predicted regioselectivity is actually reversed. The best fit calculated values for **6**/**5** along with the experimental values from eliminations on **1**–**4** in the $K^+O^-$-*t*-Bu/*t*-BuOH/18-crown-6 system are give in Table IV.

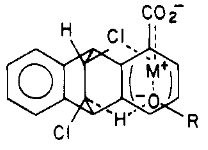
There exists a substantial body of chemical[25a] and computational[25b] evidence which indicates that bimolecular syn-periplanar eliminations involve transition states with carbanion character. Our results for both **1** and **2** (for which syn elimination is required) and as well as for **3** and **4** (which proceed from an anti-clinal conformation) suggest that some carbanion character is obtained (with little charge on chlorine) but with most of the charge remaining on the attacking base. Maximum regiospecificity requires the crown ether conditions, presumably to limit ion aggregation in both the base and substrate. Zavâda and co-workers[26] have shown that in 0.03–0.8 molal solutions potassium *tert*-butoxide in *tert*-butyl alcohol has its monomeric ion pairs quantitatively complexed with 18-crown-6.

The question can be raised as to whether the effective dielectric constant convergence value (13.7) is reasonable. The dielectric constant for our solvent (*t*-BuOH) is approximately 6.5 at 80 °C.[27] Although the dielectric constant of the pure crown ether does not appear to have been reported, the added crown ether in our solvent system probably does not alter this value appreciably.[28] The effects of dissolved ions in our solvent system, however, should be appreciable. Wepster[29] has shown with studies of ionizations of polar substituted aromatic carboxylic acids that increasing the ionic strength of the solvent mimics the effect of an increase in the dielectric constant. Considering the ionic strength in our system, effects comparable to those observed by Wepster in water could reasonably be expected to lead to the elevated effective dielectric constant obtained from our calculations.

The success observed in using a single effective dielectric constant in the above-described calculations is at first sight somewhat surprising and deserves comment. Remarkably good correlations involving a total of eight transition states were obtained by using this oversimplification. Apparently under these conditions of reasonably high ionic strength the individual effective dielectric constant values are fairly constant. In this regard it is interesting to note that Kirkwood–Westheimer calculations of $\log K_X/K_H$ for acids **3** and **4** in 50% aqueous ethanol previously reported[8] led to $D_E$ values which differed only slightly (4.24 and 4.50, respectively, using the Tanford sphere approximation).

In the analysis of the present dehydrohalogenation data, for lack of evidence to the contrary, the eliminations have been assumed to be single-step processes. Kinetic isotope effect studies may help to delineate the possible occurrence of a short-lived carbanionic intermediate. However, in the current work, starting dichlorides reisolated after partial dehydrohalogenation show no geometric isomerization. Thus free carbanions with significant half-lives are unlikely intermediates.

Returning to Table III, a noteworthy exception to the usually greater regioselectivity of eliminations employing the *t*-BuOH/crown ether conditions is the result of the dehydrochlorination of **1** in THF without crown ether. Bartsch and Zavâda[5a] have reviewed evidence supporting the proposal[30,31] that syn eliminations are facilitated by ion-paired bases leading to transition states in which an associated alkali-metal cation simultaneously coordinates with the anion of the base and the leaving group. The syn transition state leading to **6** from **1** (namely, **19**) is the only one that could also possibly derive additional stabilization from charge–charge interaction between the metal ion and the carboxylate anion. This may be the source of the unusual regioselectivity in this reaction. Nonetheless it leaves unanswered the question as to why the **6**/**5** from **2** remains unchanged under the differing solvent/base conditions.



**19**

One implication of the degree of agreement between the experimental and calculated values shown in Table IV is that the extent of β C–H bond breaking in these syn- and anti-clinal transition states (and thus the charge distribution) is very similar. To the extent that this is true, regioselectivities in syn- and anti-clinal eliminations from related systems where the probe charge extends symmetrically from the bridgehead (C-9) position should be comparable. With this in mind, the dehydrochlorinations of **15** and **16** were explored. A high degree of regioselectivity was observed in eliminations from **15** and from **16** under both sets of conditions (Table III). Steric effects appear to play a minimal role in controlling these selectivities. For example, the two vinyl chlorides obtained in the dehydrochlorination of the *cis*-dichloroethene adduct of 9-methylanthracene are formed in nearly equal amounts.[32] Calculations similar to those already applied[10] to transition states for eliminations from **1**–**4** can be made for **15** and **16**. However such an analysis is complicated by charge–charge distance uncertainties arising from rotations about the bond linking the bridgehead carbon (C-9) to the α-carbon of the acetic acid moiety. The most favorable transition state conformation would appear to be one in which the C-9 to C-12 bond is oriented approximately anti to the $CH_2$–$CO_2$ carbon–carbon bond.[33] If the value of $D_E$ is again taken to be 13.7,[10] transition-state comparative electrostatic calculations lead to a predicted product ratio, **17**/**18** of 83/17.[34] For the more improbable

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(25) See: (a) Baciocchi, E.; Ruzziconi, R.; Sebastiani, G. V. *J. Am. Chem. Soc.* **1983**, *105*, 6114. (b) Bach, R. D.; Badger, R. C.; Lang, T. J. *J. Am. Chem. Soc.* **1979**, *101*, 2845 and references cited therein.

(26) Pechanec, V.; Kocian, O.; Halaska, V.; Pankova, M.; Zavâda, J. *Collect Czech. Chem. Commun.* **1981**, *46* (9), 2166.

(27) Extrapolated from data at 30 °C, 50 °C, and 70 °C: "Handbook of Chemistry and Physics", 63rd ed.; CRC Press, Inc.: Boca Raton, FL, p E-52.

(28) Additions of 18-crown-6 (at a molarity comparable to that in our solvent system) to either 1,2-dimethoxyethane ($\epsilon_0$ = 7.05 @ 25 °C) or to 1,3-dioxolane ($\epsilon_0$ = 6.95 @ 25 °C) result in no significant (±1%) changes in the dielectric constant of these mixtures. See: Farber, H.; Petrucci, S. *J. Phys. Chem.* **1981**, *85*, 1396.

(29) Hoefnagel, A. J.; Hoefnagel, M. A.; Wepster, B. M. *J. Org. Chem.* **1978**, *43*, 4720.

(30) Zavâda, J.; Svoboda, M.; Pânkovâ, M. *Tetrahedron Lett.* **1972**, 711.

(31) Zavâda, J.; Svoboda, M.; Sicher, J. *Collect. Czech. Chem. Commun.* **1968**, *33*, 4027.

(32) Chow, K. H.; Grubbs, E. J., unpublished study.

(33) This would minimize usual nonbonded repulsions. However, a small angular rotation (from this conformation) differing in magnitude and direction (depending upon which proton was being removed) would presumably be required to minimize charge–charge repulsion.

(34) Charge distributions of 0.85 unit charge on the alkoxide oxygen and 0.15 unit charge on $C_\beta$ were again employed. For the "anti" conformation, the distances separating the carboxylate anion from charges on *t*-BuO and $C_\beta$ in the transition states are estimated to be as follows: $CO_2^- \cdots RO_{11}$ = 7.3 Å; $CO_2^- \cdots C_{11}$ = 5.7 Å; $CO_2^- \cdots RO_{12}$ = 5.5 Å; $CO_2^- \cdots C_{12}$ = 4.5 Å where again $RO_{11}$ is the alkoxide oxygen atom removing the proton from $C_{11}$ etc.

conformation in which C-12 and the $CO_2$ group are eclipsed, the calculations predict a ratio, **17**/**18** of >99/1. The calculated and experimental results are again in at least qualitative agreement. If indeed the acids **15** and **16** are reacting in anti conformation (with reference to $CH_2$–C-9 rotation), a possible source of the greater than anticipated regioselectivity may be a lower value for $D_E$ than obtained from correlative calculations involving acids **1**–**4**. For example, for eliminations involving **15** and **16**, a value of $D_E = 7$ (using the same distances and charge distributions as employed above[34]) leads to a predicted ratio **17**/**18** of 95/5 in close agreement with experimental values.

The nearly identical product ratios **17**/**18** from **15** and **16** under crown ether conditions support the postulate (based upon data and calculations for eliminations from **1**–**4**) that in these related systems the charge distributions in both the syn- and anti-clinal transition states are similar.

The possibility was considered that a reversal of the regioselectivity observed above might be induced by using different conditions. An intramolecular action of the carboxylate anion as the base in **15** or **16** would necesasarily lead to proton transfer from C-12 generating isomer **18**. With this in mind, a dilute solution of **15** in *tert*-butyl alcohol containing crown ether was treated with slightly less than an equivalent of KO-*t*-Bu. After a 72-h reaction period at 80 °C, the usual workup yielded no evidence of dehydrochlorinated product. A high recovery (87%) of unreacted **15** was obtained. The absence of any product formed via an intramolecular elimination is apparently a result of the combination of the weakness of the carboxylate anion as a base and the inability of the transition state to accommodate the preferred linear C···H···O arrangement.[35]

## Experimental Section

Melting points are uncorrected and were determined in open capillary tubes with a Thomas-Hoover melting point apparatus. Infrared spectra were obtained on a Perkin-Elmer Model 621 spectrophotometer. $^1$H NMR spectra were determined on a Varian EM-390 spectrometer. Mass spectra were obtained on a Hitachi Perkin-Elmer Model RMU mass spectrometer. The apparent $pK_a$'s were obtained by potentiometric titration. A Beckman research pH meter equipped with a Beckman No. 39000 glass electrode and a Beckman No. 39071-A3U calomel electrode was used. Gas chromatography was performed with a Carlo Erba Series 4160 chromatograph using SE-52 and SE-54 fused silica capillary columns. Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, TN.

All reagents and solvents were reagent grade and used without further purification unless otherwise specified. The potassium *tert*-butoxide/*tert*-butyl alcohol and potassium *tert*-butoxide/THF solutions were prepared by the method of Bailey and Saunders.[36] Solution preparations and the charging of the reaction tubes (subsequently degassed and sealed) were conducted in a drybox under an atmosphere of argon. The preparations and characterizations of *syn*- and *anti*-*cis*-11,12-dichloro-9,10-dihydro-9,10-ethano-1-anthroic acids (**3** and **4**) have been previously reported.[8]

**Methyl *trans*-11,12-Dichloro-9,10-dihydro-9,10-ethano-1-anthroates (9 and 10).** A 5.00-g (0.0212 mol) sample of methyl 1-anthroate, 0.1 g of 2,6-di-*tert*-butylphenol, 6.8 mL of *trans*-1,2-dichloroethene, and 20 mL of toluene were placed in a heavy-walled 25 mm × 200 mm reaction tube. The mixture was degassed on a vacuum line and the tube sealed. The tube was heated in a steel bomb at 205 ± 5 °C for 77 h. The contents of the tube including two 10-mL ether washes were concentrated under reduced pressure to a dark brown oil. This was passed through a short column of Florisil using chloroform and further decolorized using activated charcoal. The solution was concentrated again under reduced pressure and the resulting oil crystallized from hexane afforded 6.6 g (94%) of a nearly white crystalline mixture of mainly **9** and **10**. NMR analysis based upon subsequent geometric assignments showed the presence of **9** and **10** in a ratio of approximately 60/40.

Separations of **9** and **10** could be accomplished chromatographically (partial resolutions using neutral silicic acid and eluting with hexane) followed by repeated recrystallizations. Separations were also achieved by direct fractional crystallization from hexane. Manual separations of different crystal types were employed during this procedure. Progress in the separations could be monitored by measurement of the relative intensities of the C-9 bridgehead proton absorptions. This bridgehead proton for the less soluble, higher melting isomer **9** absorbs at 5.84 ppm (in $CDCl_3$). The corresponding proton for the lower melting isomer **10** absorbs at 5.65 ppm.

By repeated fractional crystallizations, **9** was obtained as colorless crystals: mp 144–145 °C; IR (cm$^{-1}$, KBr) 1712; $^1$H NMR ($CDCl_3$) $\delta$ 3.84 (3 H, s, OMe), 4.12 (2 H, m, $C_{11}$- and $C_{12}$-H), 4.33 (1 H, d, $C_{10}$-H), 5.84 (1 H, d, $C_9$-H), 7.0–7.8 (7 H, m, 7 × Ar H); mass spectrum, *m*/*z* 333 and 335 ($M^+$). Anal. Calcd for $C_{18}H_{14}Cl_2O_2$: C, 64.88; H, 4.24; Cl, 21.28. Found: C, 65.04; H, 4.26; Cl, 21.37.

Similarly pure **10** was obtained as colorless crystals: mp 121–122 °C; IR (cm$^{-1}$, KBr) 1716; $^1$H NMR ($CDCl_3$) $\delta$ 3.90 (3 H, s, OMe), 4.13 (2 H, m, $C_{11}$- and $C_{12}$-H), 4.36 (1 H, d, $C_{10}$-H), 5.65 (1 H, d, $C_9$-H), 7.0–7.8 (7 H, m, 7 × Ar H); mass spectrum, *m*/*z* 333 and 335 ($M^+$). Anal. Calcd for $C_{18}H_{14}Cl_2O_2$: C, 64.88; H, 4.24; Cl, 21.28. Found: C, 64.69; H, 4.09; Cl, 21.58.

In repeated separations, combined yields of the two pure isomers ranged from 30% to 50%.

***anti*-11,*syn*-12-*trans*-11,12-Dichloro-9,10-dihydro-9,10-ethano-1-anthroic Acid (1).** A solution of 1.00 g (3.00 mmol) of **9**, 0.561 g (14.0 mmol) of NaOH, and 50 mL of methanol was boiled under reflux for 24 h. It was cooled and poured into 200 mL of water. the resulting mixture was filtered (5% of **9** recovered) and the filtrate acidified with 3 mL of 6 N HCl. The precipitate was collected and dried, affording 0.896 g (94%) of **1** as a white microcrystalline powder, mp 237–238 °C. Recrystallization from benzene raised the melting point to 239–240.5 °C: IR (cm$^{-1}$, KBr) 1690; $^1$H NMR ($Me_2SO$-$d_6$) $\delta$ 4.29 (2 H, m, $C_{11}$- and $C_{12}$-H), 4.61 (1 H, d, $C_{10}$-H), 5.81 (1 H, d, $C_9$-H), 7.0–7.9 (7 H, m, 7 × Ar H); mass spectrum, *m*/*z* 318 and 320 ($M^+$–H). Anal. Calcd for $C_{17}H_{12}Cl_2O_2$: C, 63.97; H, 3.79. Found: C, 63.82; H, 3.69.

In a preliminary run, a mixture of 1.00 g (3.00 mmol) of **9**, 0.554 g (13.9 mmol) of NaOH, and 50 mL of methanol was boiled under reflux for 4 h. The usual workup afforded 0.492 g of unreacted **9** (mp 144.5–145.5 °C) and 0.457 g (47.7%) of **1**, mp 238–239.5 °C.

***syn*-11,anti-12-*trans*-11,12-Dichloro-9,10-dihydro-9,10-ethano-1-anthroic Acid (2).** A 1.05-g (3.15 mmol) sample of **10** was similarly hydrolyzed by boiling the basic methanol solution for 4 h. Final acidification afforded 0.965 g (96%) of the isomeric acid **2** as a white powder; mp 247.0–248.5 °C. Recrystallization twice from benzene/hexane (90/10) followed by drying the sample under vacuum raised the melting point to 252–254 °C: IR (cm$^{-1}$, KBr) 1685; $^1$H NMR ($Me_2SO$-$d_6$) $\delta$ 4.27 (2 H, m, $C_{11}$- and $C_{12}$-H), 4.62 (1 H, d, $C_{10}$-H), 5.64 (1 H, d, $C_9$-H), 6.9–7.8 (7 H, m, 7 × Ar H); mass spectrum, *m*/*z* 318 and 320 ($M^+$–H). Anal. Calcd for $C_{17}H_{12}Cl_2O_2$: C, 63.97; H, 3.79. Found: C, 64.08; H, 3.75.

**9-Anthrylacetic Acid.** This acid was prepared by the method of Acton and Berliner.[37] Starting from 9-hydroxymethylanthracene (Aldrich Chemical Co.), the desired acid was obtained as yellow crystals; mp 226–228 °C (lit.[37]/mp 229–231.4 °C). The overall yield for the three-step sequence was 52%.

**Methyl 9-Anthrylethanoate.** A 10.6-g (45 mmol) sample of 9-anthrylacetic acid was esterified with diazomethane generated from *N*,*N*′-dinitroso-*N*,*N*′-dimethylterephthalamide (Dupont EXR-101). The ester was obtained in 90% yield as yellow crystals;

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[35] (a) Cort, A. D.; Mandolini, L.; Masci, B. *J. Org. Chem.* **1983**, *48*, 3979. (b) Gandour, R. D. *Tetrahedron Lett.* **1974**, 295.

[36] Bailey, D. S.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1970**, *92*, 6904.

[37] Acton, N.; Berliner, E. *J. Am. Chem. Soc.* **1964**, *86*, 3312.

mp 88–90 °C (lit.[37] mp 87–88 °C).

**Methyl 2-[*trans*-11,12-Dichloro-9,10-dihydro-9,10-ethano-9-anthryl]ethanoate (13).** A mixture of 1.56 g (6.23 mmol) of methyl 9-anthrylethanoate, 6.0 mL (78.0 mmol) of *trans*-1,2-dichloroethene, 0.110 g of 2,6-di-*tert*-butylphenol and 6.5 mL of benzene was degassed, sealed in a glass tube under vacuum, and heated at 175 °C for 48 h. The tube was cooled and opened, and the contents were filtered and washed with cold ether, affording 1.33 g of pure **13**; mp 176.5–177.5 °C. Concentration of the filtrate afforded 0.5 g of the crude adduct. This was recrystallized from a mixture of benzene and petroleum ether (90–120 °C), giving an additional 0.30 g (total yield 75%) of the pure adduct: mp 176–177 °C; IR (cm$^{-1}$, KBr) 1730; $^1$H NMR (CDCl$_3$) $\delta$ 3.52 (2 H, dd $J$ = 18 Hz, –CH$_2$CO$_2$R), 3.7 (3 H, s, CO$_2$CH$_3$), 4.2 (2 H, m, –CHClCHCl–), 4.75 (1 H, d, C$_{10}$-H), 6.9–7.25 (8 H, m, 8 × Ar H). Anal. Calcd for $C_{19}H_{16}Cl_2O_2$: C, 65.70; H, 4.64; Cl, 20.44. Found: C, 65.87; H, 4.65; Cl, 20.36.

**Methyl 2-[*cis*-11,12-Dichloro-9,10-dihydro-9,10-ethano-9-anthryl]ethanoate (14).** A degassed mixture of 2.00 g (7.99 mmol) of methyl 9-anthrylethanoate, 5.0 mL (65 mmol) of *cis*-1,2-dichloroethene, 0.05 g of 2,6-di-*tert*-butylphenol, and 5 mL of benzene was heated for 48 h at 175 °C. Chromatographic workup (Florisil) of product mixture followed by two recrystallizations of the crude adduct from petroleum ether (90–120 °C) afforded 1.73 g (62%) of colorless crystals of **14**: mp 177–178 °C; IR (cm$^{-1}$, KBr) 1735; $^1$H NMR $\delta$ 3.58 (2 H, dd $J$ = 18 Hz, –CH$_2$CO$_2$R), 3.63 (3 H, s, CO$_2$CH$_3$), 4.47 (2 H, m, –CHClCHCl–), 5.07 (1 H, d, C$_{10}$-H), 6.97–7.3 (8 H, m, 8 × Ar H). Anal. Calcd for $C_{19}H_{16}Cl_2O_2$: C, 65.70; H, 4.64; Cl, 20.44. Found: C, 65.86; H, 4.80; Cl, 20.61.

**2-[*trans*-11,12-Dichloro-9,10-dihydro-9,10-ethano-9-anthryl]ethanoic Acid (15).** A mixture of 1.74 g (5.01 mmol) of **13**, 8 g of NaOH, and 120 mL of methanol was stirred and boiled under reflux for 70 h. The methanol was removed under reduced pressure. Water (500 mL) was added. The mixture was filtered and the filtrate acidified with dilute HNO$_3$. The white precipitate was collected, washed thoroughly with water, and dried, affording 1.56 g of **15**: mp 197–199 °C. This was recrystallized from benzene–petroleum ether (90–120 °C), yielding 1.40 g (84%) of colorless crystals; mp 202–205 °C. An analytical sample melted at 205–207 °C; IR (cm$^{-1}$, KBr) 1710; $^1$H NMR (CD$_3$COCD$_3$) $\delta$ 3.6 (2 H, dd $J$ = 18 Hz, –CH$_2$CO$_2$–), 4.3 (1 H, t, C$_{11}$-H), 4.5 (1 H, d, C$_{12}$-H), 4.97 (1 H, d, C$_{10}$-H), 7.0–7.5 (8 H, m, 8 × Ar H). Anal. Calcd for $C_{18}H_{14}Cl_2O_2$: C, 64.88; H, 4.23; Cl, 21.28. Found: C, 64.82; H, 4.44; Cl, 21.12.

**2-[*cis*-11,12-Dichloro-9,10-dihydro-9,10-ethano-9-anthryl]ethanoic Acid (16).** The *cis*-dichloroethano-bridged ester (0.87 g, 2.5 mmol) was similarly hydrolyzed. The crude acid was recrystallized from a mixture of benzene and acetic acid affording **14** (0.67 g, 81%) as colorless crystals: mp 231–232.5 °C; IR (cm$^{-1}$, KBr) 1710 cm$^{-1}$; $^1$H NMR (CD$_3$COCD$_3$) $\delta$ 3.6 (2 H, dd $J$ = 18 Hz, –CH$_2$CO$_2$–), 4.4–4.7 (2 H, m, –CHClCHCl–), 5.12 (1 H, d, C$_{10}$-H), 6.87–7.33 (8 H, m, 8 × Ar H). Anal. Calcd for $C_{18}H_{14}Cl_2O_2$: C, 64.88; H, 4.23; Cl, 21.28. Found: C, 65.07; H, 4.36; Cl, 21.01.

This acid was also prepared in 27% yield by the direct cycloaddition of 9-anthrylacetic acid and *cis*-1,2-dichloroethene in benzene (at 175 °C).

**2-[11-Chloro-9,10-etheno-9,10-dihydro-9-anthryl]ethanoic Acid (17).** For preparative purposes a degassed mixture of 0.300 g (0.900 mmol) of **16**, 0.503 g (4.49 mmol) of KO-*t*-Bu, 9 mL of *t*-BuOH, and 1.18 g (4.47 mmol) of 18-crown-6 was heated at 80 °C for 96 h. Workup in the usual way followed by recrystallization of the dehydrochlorinated acid from an 80/20 mixture of hexane/benzene afforded 0.140 g (52%) of colorless crystals: mp 203–204 °C, IR (cm$^{-1}$, KBr) 1695, 1725; $^1$H NMR (CD$_3$COCD$_3$) $\delta$ 2.9 (1 H, s, CO$_2$H), 3.75 (2 H, s, CH$_2$), 5.15 (1 H, d, C$_{10}$-H), 6.9–7.5 (9 H, m, aromatic and vinyl H); mass spectrum, $m/z$ 296 (M$^+$–H). Anal. Calcd for $C_{18}H_{13}ClO_2$: C, 72.85; H, 4.41; Cl, 11.95. Found: C, 73.04; H, 4.45; Cl, 11.83.

**Potassium *tert*-Butoxide Induced Dehydrochlorinations.** To the 1.5 × 6 cm heavy-walled reaction tubes were added approximately 60 mg of the appropriate dichloroacid, 2.0 mL of the chosen base, and 0.31 g of 18-crown-6 (when employed). These reaction tube preparations were conducted in a drybox under an argon atmosphere. The tubes were then degassed, sealed, and placed in a constant temperature bath for 30–72 h at 80.0 ± 0.1 °C. The tubes were opened, rinsed repeatedly with water, and acidified with 6 N HNO$_3$. The resulting precipitates were collected, washed thoroughly with water, and dried under reduced pressure.

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**Registry No.** **1**, 85993-37-9; **2**, 85993-35-7; **3**, 60573-55-9; **4**, 60618-78-2; **5**, 91798-51-5; **6**, 91798-50-4; **9**, 85993-38-0; **10**, 85993-36-8; **13**, 96929-59-8; **14**, 96997-78-3; **15**, 96929-60-1; **16**, 96997-79-4; **17**, 96929-61-2; **18**, 96929-62-3; methyl 1-anthrylmethanoate, 25308-58-1; *trans*-1,2-dichloroethylene, 156-60-5; methyl 9-anthrylethanoate, 20139-92-8; 9-anthrylacetic acid, 6624-23-3; *cis*-1,2-dichloroethene, 156-59-2.

**Supplementary Material Available:** Estimates of distances separating the carboxylate anion charge center from charges on $C_\beta$, RO, and Cl in various transition states (Table V) (1 page). Ordering information is given on any current masthead page.