siderably greater than that for the high-spin ferric complex (0 Dq).[21] Thus, the Co(III)-substituted complex of MA should be kinetically inert. The present result of ^{59}Fe-uptake and chlorophyll synthesis clearly shows that MA is a typical phytosiderophore. In gramineous plants, the mechanism for absorption and transport of iron appears to involve the excretion of MA from the roots which aids Fe(III) solubilization and reduction of Fe(III) to Fe(II).

Acknowledgment. This study was supported in part by a grant from the Ministry of Education, Science, and Culture, Japan.

Registry No. MA-Fe(III), 85956-49-6; MA-Co(III), 85994-19-0; MA, 69199-37-7; ^{59}Fe, 14596-12-4; Fe^{III}, 20074-52-6; Fe(OH)$_3$, 1309-33-7; nicotianamine iron(III), 82678-55-5.

Supplementary Material Available: Crystal structure data for the mugineic acid–Co(III) complex; fractional atomic coordinates (Table S-I), thermal parameters with estimated standard deviations (Table S-II), fractional atomic coordinates and thermal parameters for hydrogen atoms (Table S-III), deviations of atoms from the least-squares plane (Table S-IV), endocyclic torsion angles calculated for various chelate rings (Table S-V), and a listing of observed and calculated structure factors (23 pages). Ordering information is given on any current masthead page.

---

[21] Schlafer, H. L.; Gliemann, G. In "Basic Principles of Ligand Field Theory"; Wiley-Interscience: London, 1969; pp 142–163.

Protonation and Alkylation of Ambident (9-Anthryl)arylmethyl Anions

Masato Takagi, Masatomo Nojima,* and Shigekazu Kusabayashi

Contribution from the Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan.

Received September 13, 1982. Revised Manuscript Received March 8, 1983

Abstract: We have investigated the protonation of ambident (9-anthryl)arylmethylsodiums (Na-**2**) and -lithiums (Li-**2**) (substituent = *p*-OMe, *p*-Me, H, *m*-F) with various oxygen and carbon acids in tetrahydrofuran to give a mixture of the anthracene derivatives **3a–d** and the 9,10-dihydroanthracenes **4a–d**. Product compositions were dramatically influenced by the substituent electronic effects of the carbanions **2** and the acidities of the proton donors. In the protonation with the oxygen proton donors the change of the countercation **2** and addition of hexamethylphosphoramide also exerted remarkable effects on the **3**:**4** ratio, whereas these two factors were not important in the case of the carbon acids. This fact would be interpreted as the extent of coordination of oxygen acids to metal cations being important in determining protonation regiochemistry. The reaction of (9-anthryl)arylmethyl anions (**2a–d**) with a series of aliphatic and benzylic halides gave a mixture of two cross-coupling products, **7** (coupling at C-α) and **8** (coupling at C-10), and/or dimers, **5** (C_α–C_{10} coupling) and **6** (C_{10}–C_{10} coupling), the composition being influenced by the substituent electronic effects of the carbanions **2** and the structure of the alkyl groups of the halides. The leaving group effects also have a significant influence on the product composition. Using dependence (or independence) of the product composition on the electronic effects of the substituent of **2** as a tool to differentiate the reaction mechanisms, we have attempted to rationalize the apparently complicated alkylation of the carbanions **2**.

With the realization that the allyl moiety is an integral feature of many natural products and biosynthetic intermediates,[1] it has become important to develop methods that would lead to controlled C–C bond formation at either the α- or γ-position of an allyl substrate. For this purpose the use of allylic organometallics seems to be promising,[2] but the regiochemistry of the products has been found to be a function of various factors[3] including substituents (electronic[4] and steric[5] effects), electrophiles,[6] countercations,[7] solvents,[8] and the presence of strongly coordinating additives toward metal cations (e.g., tetramethylethylenediamine, hexamethylphosphoramide, crown ether, etc.).[8] To develop more sophisticated methods, it must be, therefore, important to understand the detailed mechanism of the reaction. When stereochemistry and CIDNP are used as the most definitive indicators of the mechanisms, it has been confirmed that in the case of allylic alkali and alkaline-earth metallics, at least two different mechanisms, i.e., single electron transfer (SET) (eq 1) and nucleophilic substitution (eq 2), are possible. However, a delicate balance

$$R^1X + R^2M \xrightarrow[\text{transfer}]{\text{electron}} [R^1X^{-}\cdot, R^2M^{+}\cdot] \rightarrow R^1\text{–}R^2 \qquad (1)$$

$$R^1X + R^2M \xrightarrow[\text{substitution}]{\text{nucleophilic}} R^1\text{–}R^2 \qquad (2)$$

must exist between these mechanistic alternatives, and a minor

---

[1] Poulter C. D.; Rilling, H. C. *Acc. Chem. Res.* **1978**, *11*, 307.

[2] (a) Seebach, D.; Geiss, K.-H. *J. Organomet. Chem. Libr.* **1976**, *1*, 1. (b) Gröbel, B. T.; Seebach, D. *Synthesis* **1977**, 357. (c) Lever, O. W., Jr. *Tetrahedron* **1976**, *32*, 1943. (d) Gompper, R.; Wagner, H.-U. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 321. (e) Katzenellenbogen, J. A.; Crumrine, A. L. *J. Am. Chem. Soc.* **1976**, *98*, 4925. (f) Biellman, J. F.; Ducep, J. B. *Tetrahedron* **1971**, *27*, 5861. (g) Coates, R. M.; Ley, D. A.; Cavender, P. L. *J. Org. Chem.* **1978**, *43*, 4915. (h) Oshima, K.; Yamamoto, H.; Nozaki, H. *J. Am. Chem. Soc.* **1973**, *95*, 7926. (i) Yamamoto, Y.; Maruyama, K. *Ibid.* **1978**, *100*, 6282. (j) Yamamoto, Y.; Yatagai, H.; Maruyama, K. *Ibid.* **1981**, *103*, 1969.

[3] (a) Guthrie, R. D. "Comprephensive Carbanion Chemistry", Buncel, E., Durst, T., Eds.; Elsevier: Amsterdam, 1980; Part A, Chapter 5. (b) Negishi, E. "Organometallics in Organic Synthesis"; Wiley: New York, 1980; Vol. 1, Chapter 4. (c) Bank, S.; Bank, J. F. "Organic Free Radicals", Pryor, W. A., Ed.; American Chemical Society: Washington DC, 1978; ACS Symp. Ser. No. 69, p 343. (d) Magid, R. M. *Tetrahedron* **1980**, *36*, 1901. (e) Evans, D. A.; Takacs, J. M.; Hurst, K. M. *J. Am. Chem. Soc.* **1979**, *101*, 371. (f) Ehlinger, E.; Magnus, P. *Ibid.* **1980**, *102*, 5004.

[4] Bushby, R. J.; Ferber, G. S. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1688, 1695.

[5] Evans, D. A.; Andrews, G. C. *Acc. Chem. Res.* **1974**, *7*, 147.

[6] (a) Seyferth, D.; Murphy, G. J.; Mauze, B. *J. Am. Chem. Soc.* **1977**, *99*, 5317. (b) Murphy, W. S.; Wattanasin, S. *Tetrahedron Lett.* **1979**, 1827. (c) Oppolzer, W.; Snowden, R. L. *Ibid.* **1976**, 4187.

[7] (a) Hartmann, J.; Muthukrishnan, R.; Schlosser, M. *Helv. Chim. Acta* **1974**, *57*, 2261. (b) Schlosser, M. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 701. (c) Derguini-Boumechal, F.; Lorne, R.; Linstrumelle, G. *Tetrahedron Lett.* **1974**, 2665.

[8] Atlani, P. M.; Bielmann, J. F.; Dube, S.; Vicens, J. J. *Tetrahedron Lett.* **1974**, 2665.

Table I. Reaction of Chlorides 1a–d with 2 mol equiv of Metal Naphthalenide[a]

$M^+Naph^{-}\cdot$ M	chloride	product yield,[c] % [3:4][b]	[5:6][b]
Li	1a	94 [57:43]	
Li	1b	98 [79:21]	
Li	1c	96 [94:6]	
Li	1d	90 [~100:0]	
Na	1a	70 [81:29]	22 [27:73]
Na	1b	77 [~100:0]	16 [30:70]
Na	1c	71 [~100:0]	20 [32:68]
Na	1d	75 [~100:0]	19 [57:43]

[a] The reaction was carried out in THF at −70 °C under a nitrogen atmosphere, followed by workup with D_2O. [b] The product composition was determined by ^1H NMR spectroscopy after separation of crude products by column chromatography on silica gel. [c] The isolated yield.

change of reaction conditions may alter the extent of each process; this would be the origin of the effects of variables on the alkylation regiochemistry.

In the light of these results, we have investigated the reactions of ambident (9-anthryl)arylmethyl anions (**2a–d**) with a series of alkyl halides and tosylates in a systematic fashion, and have determined the ratios of two cross-coupling products **7** (coupling at C-α) and **8** (coupling at C-10). If the para and meta substituents of the carbanions **2a–d** affect the composition of **7** and **8** in a significantly different fashion depending on the mechanism, then this approach would serve to elucidate the reaction paths participating in these reactions and the factors affecting the extent of each path. Of particular importance for this approach are the facts that (a) Bushby and Ferber[4] have revealed that "charge control" accounts for the course of protonation of a series of ambident 1,3-diarylpropenide ions, i.e., both the charge densities determined by the NMR spectroscopy of the carbanions and the ratios of two protonated products correlate well with substituent constants σ. We also report in this paper that the protonation of the carbanions **2a–d** gives the corresponding mixture of two protonated products, the composition being a marked function of the substituent electronic effects. As a reasonable extrapolation, one would expect that the reaction of **2a–d** with alkyl halides, if it proceeds by an S_N2 mechanism, affords a substituent-dependent mixture of **7** and **8**. In contrast, (b) the reaction of (9-anthryl)arylmethyl chlorides (**1a–c**) with *tert*-butylmagnesium bromide, which is reasonably considered to proceed by a mechanism involving SET,[3a] was found to give a substituent-independent mixture of two *tert*-butylated products.[9] This result would suggest that alkyl radicals attack both the C-α and C-10 of the (9-anthryl)arylmethyl radical (**9**), the proportion not being affected by the substituent of **9**.[10,11]

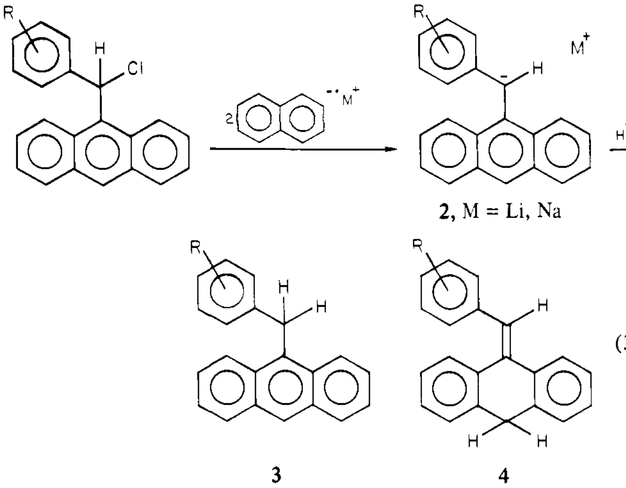
Results and Discussion

Preparation and Visible Spectra of (9-Anthryl)arylmethyl Anions (2a–d). Resonance-stabilized lithium compounds are usually prepared by treatment of the corresponding hydrocarbons with strong bases. The reaction of 9-benzylanthracene (**3c**) with *n*-butyllithium was, however, found not to give (9-anthryl)benzyllithium (Li-**2c**) in a satisfactory yield. Thus, we attempted to prepare the lithium compound Li-**2** by treating the corresponding chloride **1** with 2 mol equiv of lithium naphthalenide in tetrahydrofuran (THF) at −70 °C;[12] a green solution was

Table II. Visible Spectra of (9-Anthryl)arylmethyl Anions at Room Temperature

carbanion	λ_{max}, nm THF	THF-HMPA
Li-2a	724	727
Li-2c	736	738
Li-2d	739	742
Na-2a	722	728
Na-2c	734	738
Na-2d	739	741

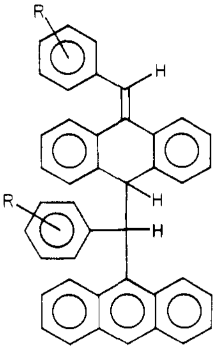
quenched by D_2O to afford a mixture of 9-(arylmethyl)anthracene-α-*d* (**3**) and 9-(arylmethylidene)-9,10-dihydroanthracene-**10**-*d* (**4**) in a yield of more than 90% (eq 3 and Table



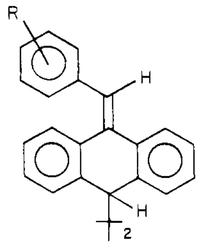
(3)

a, R = *p*-OMe; b, R = *p*-Me; c, R = H; d, R = *m*-F

I), indicating quantitative formation of the desired lithium compound Li-**2**. Treatment of the chloride **1** with sodium naphthalenide produced the corresponding sodium compound Na-**2**. This reduction was, however, accompanied by the formation of about 20% yield of the dimeric products **5** and **6** (Table I).



5



6

a, R = *p*-OMe; b, R = *p*-Me; c, R = H; d, R = *m*-F

The visible spectra of carbanions **2a–d** gave some valuable information for the structures (Table II). First, the absorption maximum showed a bathochromic shift on changing the substituent from *p*-OMe to *m*-F, suggesting that an electron-withdrawing group enhances the delocalization of the negative charge on the carbanion **2**. Probably, in the case of the carbanion **2** with an electron-withdrawing substituent, the aryl ring also bears a considerable amount of the negative charge. Second, the position of the peak of a lithium compound Li-**2** was much the same as that of the corresponding sodium compound Na-**2**, suggesting that these carbanions would exist mainly as the solvent-separated ion pairs. If the contribution of the contact ion pairs was significant, the position of the peak should have been a marked function of the countercation.[13] In solutions containing strongly coordinating

---

(9) Takagi, M.; Nojima, M.; Kusabayashi, S. *J. Am. Chem. Soc.* **1982**, *104*, 1636.

(10) The following facts would support this hypothesis. (a) The distribution of odd electrons in para-substituted benzyl radicals is perturbed by the para substituent only to a small extent,[11a] and (b) addition of CCl_3Br to substituted stilbenes does not show significant para-substituent effects on orientation.[11b]

(11) (a) Gey, E. *Z. Chem.* **1974**, *14*, 279. (b) Gadogan, J. I. G.; Duell, E. G.; Inwald, P. W. *J. Chem. Soc.* **1962**, 4164.

(12) (a) Zieger, H. E.; Angres, I. *J. Am. Chem. Soc.* **1973**, *95*, 8201. (b) Zieger, H. E.; Angres, I.; Mathisen, D. J. *Ibid.* **1976**, *98*, 2580.

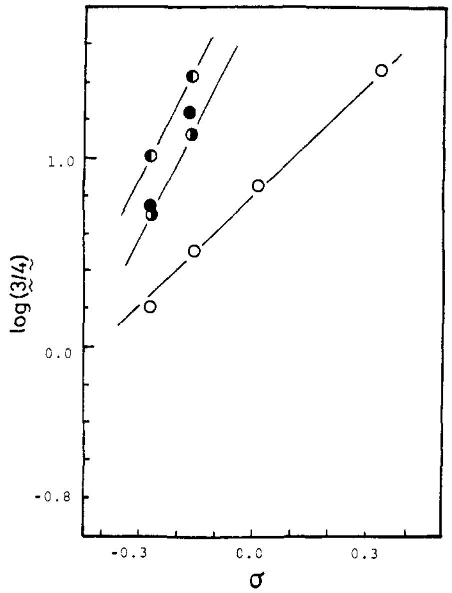


Figure 1. Plot of log ([**3**]/[**4**]) vs. σ constant for the reaction of Na-**2** with CH_3COOH (○), CF_3CH_2OH (●), *t*-BuOH (◐), and cyclopentadiene (◑) in THF at -70 °C.

Table III. Percent Yield of **3** Found on Protonation of Na-**2** in THF[a,b]

	Na			
proton donor	2a	2b	2c	2d
CF_3COOH	67	83	90	96
CH_3COOH	63	78	89	97
$4\text{-}NO_2C_6H_4OH$	62	79	87	97
C_6H_5OH	64	77	87	97
CF_3CH_2OH	86	95	~100	~100
H_2O	92	97	~100	~100
CH_3CH_2OH	92	99	~100	~100
t-BuOH	92	96	~100	~100
cyclopentadiene	85	94	~100	~100
indene	88	94	~100	

[a] The numbers show the relative yield of **3** determined by ^1H NMR spectroscopy. [b] The isolated yield of a mixture of hydrocarbons was about 75% in each case.

HMPA, the sodium and lithium salts had the same absorption, demonstrating that the cation was only loosely associated with the carbanion, if at all, in this solvent system. It should be noted that the effects of the addition of HMPA on the absorption maximum were, however, quite small. This would be taken as additional evidence to support the idea that in THF, Li-**2** and Na-**2** exist mainly as the solvent-separated ion pairs rather than the contact ion pairs.[13] These conclusions are in harmony with the present understanding for the ion-pair states of triphenylmethyl and diphenylmethyl anions.[13]

Protonation of the Carbanions. In Table III and Figure 1, the results obtained from the kinetically controlled protonation[14,15] of sodium compounds Na-**2** with various proton donors are summarized. The anthracene derivatives **3a–d** were the exclusive or major products, suggesting that the local charges on the more hindered C-α were considerably higher than those at C-10. The yield of the anthracene derivative **3** was a marked function of the substituent of the carbanion Na-**2**. There appears to be a linear relationship between the **3**:**4** ratio and a substituent constant σ (Figure 1), an electron-donating substituent resulting in an enhancement of the relative yield of the 9,10-dihydroanthracene **4**. These results would be interpreted as the electron-donating substituent increasing the charge on the 10-position in a relatively larger amount, and as a result increasing the proportion of attack at this position. Consistent with this, Bushby and Ferber[4] also have found that the site far from the substituent is more susceptible to the substituent electronic effects for 1,3-diarylpropenide ions.

Table IV. Percent Yield of **3** Found on Protonation of Li-**2** in THF[a,b]

	Li			
proton donor	2a	2b	2c	2d
CF_3COOH	54	64	67	89
CH_3COOH	57	63	70	89
C_6H_5OH	53	63	66	88
CF_3CH_2OH	46	57	68	90
H_2O	66	80	92	98
CH_3CH_2OH	42	57	73	93
i-PrOH	38	52	70	97
t-BuOH	26	53	79	~100
cyclopentadiene	91	96	98	~100
indene	91	93	95	98

[a] See footnotes in Table III. [b] The isolated yield of a mixture of hydrocarbons was >90% in each case.

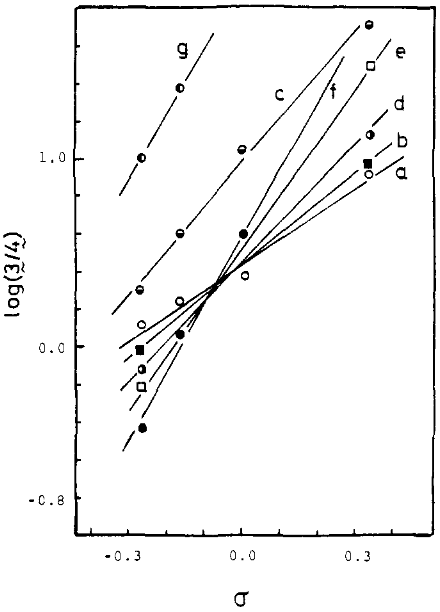


Figure 2. Plot of log ([**3**]/[**4**]) vs. σ constant for the reaction of Li-**2** with proton donors in THF at -70 °C: (a) CH_3COOH, (b) CF_3CH_2OH, (c) H_2O, (d) CH_3CH_2OH, (e) *i*-PrOH, (f) *t*-BuOH, (g) cyclopentadiene.

The nature of proton donors also seems to be important in determining the protonation regiochemistry (Figure 1). The proton donors used represent a wide range of pK_a's (0.2–20). They can also be classed as those that can coordinate to metal cations (the oxygen proton donors) and those that are not likely to coordinate to metal cations (the carbon proton donors). Protonation of Na-**2** with "strong" oxygen acids, trifluoroacetic acid, acetic acid, and phenol (pK_a 0.2, 4.7, and 10.0, respectively), yielded less **3a–d** than did protonation with "weak" oxygen acids, trifluoroethanol, water, ethanol, and 2-methyl-2-propanol (pK_a 12, 14, 16, and 19, respectively). The **3**:**4** ratio obtained from the protonation with cyclopentadiene (pK_a 16) was much the same as that obtained from the reaction with ethanol, having a similar pK_a, suggesting that in the case of sodium compound Na-**2**, coordination of the metal to the proton donors has a negligible influence on the protonation regiochemistry.

The change of the countercation of the carbanion **2** from sodium to lithium exerts a remarkable influence on the protonation regiochemistry (Table IV). Product composition was a marked

---

(13) (a) Sewarc, M., Ed. "Ion and Ion Pairs in Organic Reactions"; Wiley: New York, 1972; Vol. 1. (b) Buncel, E. "Comprehensive Carbanion Chemistry"; Buncel, E., Durst, T., Eds.; Elsevier: Amsterdam, 1980; Part A. (c) O'Brien, D. H.; Russell, C. R.; Hart, A. *J. Am. Chem. Soc.* **1979**, *101*, 633.

(14) The formation of the thermodynamically less stable isomer **4** in a significant proportion is taken to support that the protonation occurs under the kinetically controlled conditions.[15]

(15) Ogata, F.; Takagi, M.; Nojima, M.; Kusabayashi, S. *J. Am. Chem. Soc.* **1981**, *103*, 1145.

Table V. Percent Yield of 3 Found on Protonation of Li-2 and Na-2 in the Presence of 15 mol equiv of HMPA[a]

proton donor	Li[c]				Na[b]			
	2a	2b	2c	2d	2a	2b	2c	2d
H_2O	91	~100	~100	~100				
CF_3CH_2OH	97	~100	~100	~100	95	~100	~100	~100
t-BuOH	92	~100	~100	~100				
cyclopentadiene	93	98	~100	~100	88	92	93	

[a,b] See footnotes in Table III. [c] The isolated yield of a mixture of hydrocarbons was about >90% in each case.

function of the substituent electronic effects, the **3**:**4** ratio being correlated well with σ (Figure 2). The proportion of the anthracene **3** obtained from the reaction of Li-**2** with the oxygen acids was, however, much smaller than that obtained from the corresponding reaction of the sodium compound Na-**2**. This trend was significantly pronounced in the case of "weak" oxygen acids, 2-methyl-2-propanol, ethanol, water, and trifluoroethanol. The most dramatic case was the protonation of *p*-methoxy compounds Li-**2a** and Na-**2a** with 2-methyl-2-propanol. The anthracene derivative **3a** was obtained from Na-**2a** in a yield of 92%, and in direct contrast, the thermodynamically less stable 9,10-dihydroanthracene **4a** was obtained from Li-**2a** in a yield of 74%. The acidities of the oxygen proton donors affected the product compositions in a dramatic fashion. The slopes of the correlation lines between the **3**:**4** ratio and σ were increased with the decrease of the acidities; trifluoroacetic acid, acetic acid, phenol (1.5) < trifluoroethanol (1.7) < ethanol (2.1) < 2-propanol (2.9) < 2-methyl-2-propanol (3.9) (Figure 2). As a result, in the protonation of the *p*-methoxy compound Li-**2a** the proportion of the anthracene **3a** increased as the proton donor became increasingly acidic, whereas the opposite trend was observed in the case of the *m*-fluoro compound Li-**2d**. In the case of the carbon acids, cyclopentadiene or indene, the **3**:**4** ratio observed in the reaction of Li-**2** was much the same as that obtained from the corresponding reaction of Na-**2**. These facts lead us to deduce that coordination of oxygen acids toward lithium cation is a probable reason for the appearance of the countercation effects on the protonation regiochemistry, observed specifically in the reaction of **2** with the oxygen acids.[16,17] For coordination by oxygen acids, sodium cation having a relatively larger radius is expected to be significantly more disadvantageous than lithium cation.[18]

To obtain further insight into the effects of the coordination on the protonation regiochemistry, we undertook the reaction of Li-**2** in the presence of HMPA (Table V). Plots of the **3**:**4** ratio vs. the HMPA to Li-**2** ratio showed that the increase in proportion of HMPA leads to the increased formation of the anthracene **3** (Figure 3). The "break" point in the plots was the HMPA to Li-**2** ratio of ca. 12. If the facts that (a) in the system there exist equal amounts of Li-**2** and LiCl and (b) a typical coordination number for lithium cation is four[19] are taken into consideration, this value of 12 would be understandable.[20,21] Examination of the data in Tables III–V revealed certain trends. (a) The yield of the anthracene **3** observed in the reaction of Li-**2** with "weak" oxygen acids, water, trifluoroethanol, and 2-methyl-2-propanol, in the presence of 15 mol equiv of HMPA was significantly larger than that observed in the corresponding reaction of Li-**2** in the absence of HMPA. In contrast, the reaction of Na-**2** with trifluoroethanol was influenced by the addition of HMPA but to a small extent.[22] These results would be interpreted as follows. By the addition of HMPA, coordination of lithium cation to the oxygen acids is significantly decreased and, as a result, the **3**:**4** ratio obtained from the reaction of Li-**2** in the presence of this additive becomes very similar to that from the reaction of Na-**2** in the absence of HMPA. (b) In the case of the carbon acids, the addition of HMPA or the change of the countercation of **2** has only a small influence on the product composition, as expected. Thus, all the data seem to indicate that lithium cation directs protonation at C-10 and that coordination of the proton donors is probably responsible. We are, however, not able to offer an appropriate explanation as to why the coordination of the proton source has this effect.

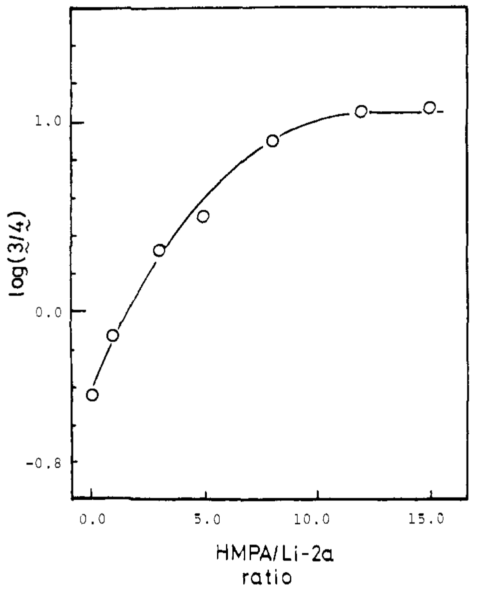


Figure 3. The influence of added HMPA on the **3**:**4** ratio on reaction of Li-**2a** with 2-methyl-2-propanol in THF at −70 °C.

In summary, protonation at C-10 would be favored under the following conditions: (a) the protonation of the carbanion **2** having an electron-donating substituent, (b) protonation with "strong" oxygen acids, and (c) protonation of Li-**2** with "weak" oxygen acids. In contrast, the following factors would direct the protonation to occur at C-α: (a) the introduction of an electron-withdrawing group on the phenyl ring of **2**, (b) the change of the countercation of **2** from lithium to sodium, (c) protonation with carbon acids, and (d) addition of HMPA.

Reaction of Carbanions with Aliphatic Halides. The reaction of lithium compounds Li-**2** with methyl, ethyl, and isopropyl halides afforded a mixture of the corresponding cross-coupling products **7** (coupling at C-α) and **8** (coupling at C-10) almost quantitatively (eq 4 and Table VI).

Examination of the data in Table VI reveals the following. First, the formation of the thermodynamically less stable isomer **8**[23,24]

---

[16] The importance of coordination of lithium cation to oxygen acids has been confirmed by the fact that protonation of α-lithio sulfoxides is prone to occur syn to the metal cation.[17]

[17] (a) Durst, T.; Viau, R.; McClory, M. R. *J. Am. Chem. Soc.* **1971**, *93*, 3077. (b) Nishihata, K.; Nishio, M. *J. Chem. Soc., Perkins Trans. 2* **1972**, 1730. (c) Biellmann, J. F.; Vicens, J. J. *Tetrahedron Lett.* **1978**, 467. (d) Chassaing, G.; Lett, R.; Marquet, A. *Ibid.* **1978**, 471. (e) Cere, V.; Pollicino, S.; Sandi, E.; Fava, A. *Ibid.* **1978**, 5239. (f) Yamamoto, Y.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1980**, 239.

[18] (a) Hogen Esch, T. E.; Smid, J. *J. Am. Chem. Soc.* **1966**, *88*, 307. (b) Zaugg, H. E.; Schaefer, A. D. *Ibid.* **1965**, *87*, 1857.

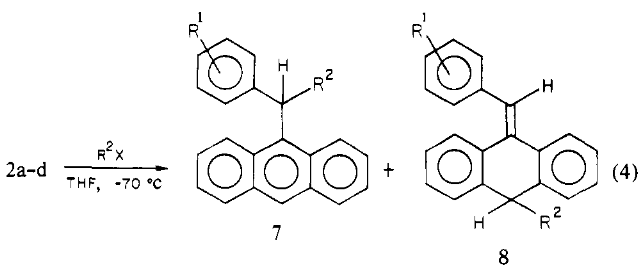
[19] Chan, L. L.; Smid, J. *J. Am. Chem. Soc.* **1967**, *89*, 4547.

[20] In the reaction of the lithium salt, formed from 10-*tert*-butyl-9-methyl-9,10-dihydroanthracene by proton abstraction, with ethanol in diethyl ether, addition of HMPA has been found to change the protonation stereochemistry from cis to trans, 6.5 mol equiv of HMPA being required for the exclusive formation of trans hydrocarbon.[21]

[21] Panek, E. J.; Rodgers, T. J. *J. Am. Chem. Soc.* **1974**, *96*, 6921.

[22] In the protonation of the carbanion, formed from 10-*tert*-butyl-9-methyl-9,10-dihydroanthracene by proton abstraction, the nature of the countercation (Li, Na) has been found to exert a negligible influence on the product composition.[21]

[23] Treatment of 9-(*p*-methoxybenzylidene)- or 9-(*m*-fluorobenzylidene)-10-benzhydryl-9,10-dihydroanthracene (**8w** or **8z**) with excess diphenylmethyllithium in THF at room temperature gave exclusively the corresponding anthracene derivative **7w** or **7z**, suggesting that the anthracene **7w** or **7z** is the thermodynamically more stable isomer. Although such a rearrangement is not observed in other 10-alkylated 9-(arylmethylidene)-9,10-dihydroanthracenes, the above result would suggest that the anthracene derivatives **7** are more stable than the corresponding 9,10-dihydroanthracenes.[24]



a, $R^1 = p$-OMe; R^2 = Me; b, $R^1 = p$-Me, R^2 = Me; c, R^1 = H, R^2 = Me; d, $R^1 = m$-F, R^2 = Me; e, $R^1 = p$-OMe, R^2 = Et; f, $R^1 = p$-Me, R^1 = Et; g, R^1 = H, R^2 = Et; h, $R^1 = m$-F, R^2 = Et; i, $R^1 = p$-OMe, $R^2 = i$-Pr; j, $R^1 = p$-Me, $R^2 = i$-Pr; k, R^1 = H, $R^2 = i$-Pr; l, $R^1 = m$-F, $R^2 = i$-Pr; m, $R^1 = p$-OMe, R^2 = $PhCH_2$; n, $R^1 = p$-Me, R^2 = $PhCH_2$; o, R^1 = H, R^2 = $PhCH_2$; p, $R^1 = m$-F, R^2 = $PhCH_2$; q, R^1 = p-MeO, $R^2 = p$-$CH_3OC_6H_4CH_2$, r, $R^1 = p$-Me, $R^2 = p$-$CH_3OC_6H_4$-CH_2; s, $R^1 = m$-F, $R^2 = p$-$CH_3OC_6H_4CH_2$; t, $R^1 = p$-OMe, R^2 = m-$ClC_6H_4CH_2$; u, R^1 = H, $R^2 = m$-$ClC_6H_4CH_2$, v, $R^1 = m$-F, R^2 = m-$ClC_6H_4CH_2$; w, $R^1 = p$-OMe, R^2 = Ph_2CH; x, $R^1 = p$-Me, R^2 = Ph_2CH; y, R^1 = H, R^2 = Ph_2CH; z, $R^1 = m$-F, R^2 = Ph_2CH

in a significant proportion suggests that the alkylation occurs under the kinetically controlled conditions. Second, the product composition is a marked function of the substituent electronic effects, the **7**:**8** ratio being increased as the substituent becomes increasingly electron withdrawing. The fact that the reactions of (9-anthryl)arylmethyl chlorides (**1a–c**) with methyllithium give substituent-independent mixtures of **7a–c** and **8a–c** (the **7**:**8** ratio = ca. 1:1)[9] suggests that lithium–halogen exchange is not important in both the reaction of Li-**2** with methyl halides and that of **1** with methyllithium. The **7**:**8** ratio obtained from the reaction of **2a–d** with aliphatic halides correlates well with σ. The slope decreases with the increase of steric bulk of the alkyl group; methyl bromide (3.3) > ethyl bromide (2.5) > isopropyl iodide (2.3) (Figure 4). Third, the **7**:**8** ratio decreases with the increase in steric bulk of the alkyl moieties of the halides, suggesting that the bulky alkyl halides are prone to attack the less hindered[25] but less charge developed C-10 of **2a–d**. The decrease of the slope and the increase of the proportion of the 9,10-dihydroanthracene **8** with the increase of steric bulk of the alkyl group may suggest that in the case of the bulky halides, the steric effects of the alkyl group of the halides rather than the electronic effects of the substituent of **2** become a major factor in determining the product composition. Reflecting the accumulated effects of the substituent of **2** and the steric bulk of the isopropyl group, the reactions of Li-**2a,b** with isopropyl iodide give exclusively the 9,10-dihydroanthracenes **8i,j**. This trend is noted to be different from that observed in the reactions of the chlorides **1a–c** with isopropylmagnesium bromide,[9] in which the anthracenes **7i–k** are obtained in considerable amounts (the substituent-independent **7**:**8** ratio is ca. 1:2). Fourth, the reactivity order of the alkyl halides, judged qualitatively by the rate of disappearance of the characteristic color of the carbanion Li-**2**, follows the sequence: primary > secondary, and I > Br > Cl.[26,27] Fifth, the reaction with a series of MeX (X = I, Br, OTs) and EtX (X = I, Br) reveals that the change of the leaving group does not affect the composition of the alkylation products **7** and **8**.[28] Finally, the change of the countercation of the carbanion **2** does not seem to be important in determining the **7**/**8** ratio, as the reaction with methyl bromide indicates.[29] Addition of HMPA also does not exert a meaningful

Table VI. Reaction of 2a-d with Aliphatic Halides[a]

carbanion	electrophile	reaction time, min	product yield,[b] % [7:8][c]
Li-**2a**	MeBr	5	83 [20:80]
Li-2b	MeBr	5	84 [42:58]
Li-2c	MeBr	5	86 [74:26]
Li-2d	MeBr	5	80 [100:0]
Na-2a	MeBr	5	71[d] [23:77]
Na-2b	MeBr	5	75[d] [51:49]
Na-2c	MeBr	5	72[d] [74:26]
Na-2d	MeBr	5	70[d] [100:0]
Li-2a (HMPA)[e]	MeBr	5	82 [18:82]
Li-2b (HMPA)[e]	MeBr	5	87 [50:50]
Li-2c (HMPA)[e]	MeBr	5	90 [74:26]
Li-2d (HMPA)[e]	MeBr	5	88 [97:3]
Li-2a	MeI	2	85 [23:77]
Li-2b	MeI	2	86 [47:53]
Li-2c	MeI	2	83 [67:33]
Li-2d	MeI	2	80 [96:4]
Li-2a	MeOTs	40	83 [20:80]
Li-2b	MeOTs	40	56[f] [47:53]
Li-2c	MeOTs	40	60[f] [72:28]
Li-2d	MeOTs	40	56[f] [96:4]
Li-2a	EtBr	5	83 [12:88]
Li-**2b**	EtBr	5	85 [23:77]
Li-2c	EtBr	5	83 [47:53]
Li-2d	EtBr	5	90 [83:17]
Li-2a	EtI	5	82 [11:89]
Li-2c	EtI	5	88 [51:49]
Li-2d	EtI	5	83 [86:14]
Li-2b	*i*-PrBr	30	17[f] [0:100]
Li-2a	*i*-PrI	5	88 [0:100]
Li-2b	*i*-PrI	5	90 [0:100]
Li-2c	*i*-PrI	5	87 [5:95]
Li-2d	*i*-PrI	20	40[f] [22:78]

[a] The reaction with 3 mol equiv of alkyl halide in THF at −70 °C under a nitrogen atmosphere. [b] The isolated yield. [c] The product composition was determined by ^{1}H NMR spectroscopy. [d] Accompanied by a mixture of 5 and 6. [e] The reaction in the presence of 15 mol equiv of HMPA. [f] Accompanied by a mixture of 3 and 4, which are believed to be formed from the unreacted carbanion by protonation.

Table VII. Reaction of 2a-d with Benzyl Derivatives[a]

carbanion	electrophile	reaction time, min	product yield,[b] % [7:8][c]
Li-2a	$PhCH_2Cl$	5	92 [16:84]
Li-**2b**	$PhCH_2Cl$	5	80 [29:71]
Li-2c	$PhCH_2Cl$	5	88 [46:54]
Li-2d	$PhCH_2Cl$	5	90 [87:13]
Na-1a	$PhCH_2Cl$	5	75[d] [17:83]
Li-2a	$PhCH_2Br$	5	90 [23:77]
Li-2b	$PhCH_2Br$	5	88 [37:63]
Li-2c	$PhCH_2Br$	5	87 [53:47]
Li-2d	$PhCH_2Br$	5	85 [89:11]
Li-2a (HMPA)[e]	$PhCH_2Br$	5	88 [20:80]
Li-2b (HMPA)[e]	$PhCH_2Br$	5	91 [41:69]
Li-2c (HMPA)[e]	$PhCH_2Br$	5	87 [62:38]
Li-2d (HMPA)[e]	$PhCH_2Br$	5	88 [85:15]
Li-2a	$PhCH_2OTs$	5	92 [14:86]
Li-2b	$PhCH_2OTs$	5	80 [25:75]
Li-2c	$PhCH_2OTs$	5	92 [51:49]
Li-2d	$PhCH_2Ots$	5	80 [85:15]
Li-2a	p-$MeOC_6H_4CH_2Cl$	5	80 [10:90]
Li-2b	p-$MeOC_6H_4CH_2Cl$	15	86 [37:63]
Li-2d	p-$MeOC_6H_4CH_2Cl$	15	86 [86:14]
Li-2a	m-$ClC_6H_4CH_2Cl$	5	78 [17:83]
Li-2c	m-$ClC_6H_4CH_2Cl$	5	82 [46:54]
Li-2d	m-$ClC_6H_4CH_2Cl$	5	75 [86:14]

[a-e] See footnotes in Table VI.

---

(24) Jager, C. W.; Kornblum, N. *J. Am. Chem. Soc.* **1972**, *94*, 2545.

(25) Takagi, M.; Nojima, M.; Kusabayashi, S. *J. Chem. Soc., Perkin Trans. 1* **1979**, 2941.

(26) This order is in good agreement with that observed in typical S_N2 reactions.

(27) Collman, J. P.; Finke, R. G.; Cawse, J. N.; Brauman, J. I. *J. Am. Chem. Soc.* **1977**, *99*, 2515 and the references therein.

(28) These results are in marked contrast to the fact that in the alkylation of ambident lithium ketene thioacetal, the proportion of attack at the *S*-substituted site has been found to increase with increasing hardness of the leaving group I < Br < Cl < OTs < SO_4.[6b] A similar leaving group effect has also been observed in the reaction of (3-(triethylsiloxy)pentadienyl)lithium with alkyl halides.[6c]

Table VIII. Reaction of 2a-d with Benzhydryl Halides[a]

			product yield,[b] %			
carbanion	Ph_2CHX X	reaction time, min	alkylation [7:8][c]	dimerization [5:6][c]	$Ph_2CHCHPh_2$[d]	unreacted[e]
Li-2a	Cl	120	75 [0:100]			
Li-2b	Cl	120	75 [0:100]			
Li-2c	Cl	120	65 [0:100]			20
Li-2d	Cl	120	10 [0:100]			77
Na-2a	Cl	120	62 [0:100]	11 [55:45]		
Na-2d	Cl	120	25 [28:72]	23 [55:45]		32
Li-2a (HMPA)[f]	Cl	120	93 [0:100]			
Li-2b (HMPA)[f]	Cl	120	75 [0:100]			
Li-2c (HMPA)[f]	Cl	120	74 [0:100]			21
Li-2d (HMPA)[f]	Cl	120	17 [23:77]	11 [57:43]		70
Li-2a	Br	5	55 [25:75]	23 [50:50]	39	
Li-2b	Br	5	50 [26:74]	20 [50:50]	30	
Li-2c	Br	5	57 [25:75]	16 [38:62]	33	
Li-2d	Br	5	42 [35:65]	28 [71:29]	30	
Na-2a	Br	5	40 [23:77]	38 [50:50]	25	
Na-2d	Br	5	34 [31:69]	33 [57:43]	27	
Li-2a (HMPA)[f]	Br	5	56 [18:82]	21 [52:48]	20	
Li-2b (HMPA)[f]	Br	5	45 [14:86]	32 [44:56]	48	
Li-2c (HMPA)[f]	Br	5	48 [12:88]	26 [33:67]	46	
Li-2d (HMPA)[f]	Br	5	54 [28:72]	25 [47:53]	25	

[a-c] See footnotes in Table VI. [d] The yield was calculated as follows; moles per the moles which should be obtained under the complete electron-transfer condition. [e] The yield of a mixture of **3** and **4**, which are believed to be formed from the unreacted carbanion by protonation. [f] The reaction in the presence of 15 mol equiv of HMPA.

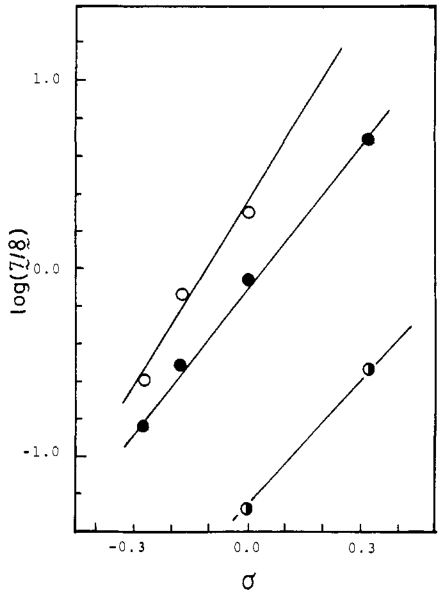


Figure 4. Plot of log ([**7**]/[**8**]) vs. σ constant for the reaction of Li-**2** with methyl bromide (○), ethyl bromide (●), and isopropyl iodide (◑) in THF at -70 °C.

influence on the product composition.[30] These trends are in marked contrast to those observed in the protonation of Li-**2** with the oxygen acids, and would suggest that coordination of lithium cation to the leaving group of the alkyl halide would be small.[17,31]

If the reaction of the well-delocalized carbanions **2a-d** with the aliphatic halides is considered to proceed by an S_N2 mechanism, with the difference in the charge densities between C-α and C-10, together with the steric bulk of the alkyl group of the electrophiles, being important in the determination of the **7**:**8** ratio, then these results would be understandable. This mechanistic interpretation

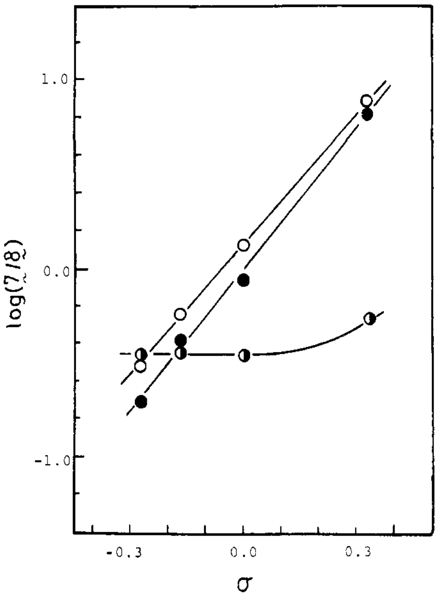


Figure 5. Plot of log ([**7**]/[**8**]) vs. σ constant for the reaction of Li-**2** with benzyl chloride (●), benzyl bromide (○), and benzhydryl bromide (◑) in THF at -70 °C.

is consistent with the present understanding for the reaction of benzylic and allylic carbanions with aliphatic halides.[3a]

Reaction of Carbanions with Benzylic Halides. The reactions of Li-**2** with $PhCH_2X$ (X = Br, Cl, OTs), 4-methoxybenzyl chloride, and 3-chlorobenzyl chloride gave the mixtures of alkylation products **7** and **8** (eq 4 and Table VII). The data revealed certain trends. First, the product compositions obtained from the reactions with benzyl bromide were significantly affected by the substituent electronic effects. The plots of log ([**7**]/[**8**]) against σ gave a straight line with a slope of 2.3. This value is noted to be much the same as that from the reaction with ethyl bromide (Figures 4 and 5), suggesting that the reaction with benzyl bromide also proceeds mainly by an S_N2 mechanism, the steric requirement of this bromide being similar to that of ethyl bromide. Second, the leaving group effects had only a small influence on the product composition. In all the benzyl derivatives the **7**:**8** ratios correlated well with σ, the slopes being 2.5 for the chloride and tosylate and 2.3 for the bromide (Figure 5). Third, the reaction with para- and meta-substituted benzyl chlorides indicated that the sub-

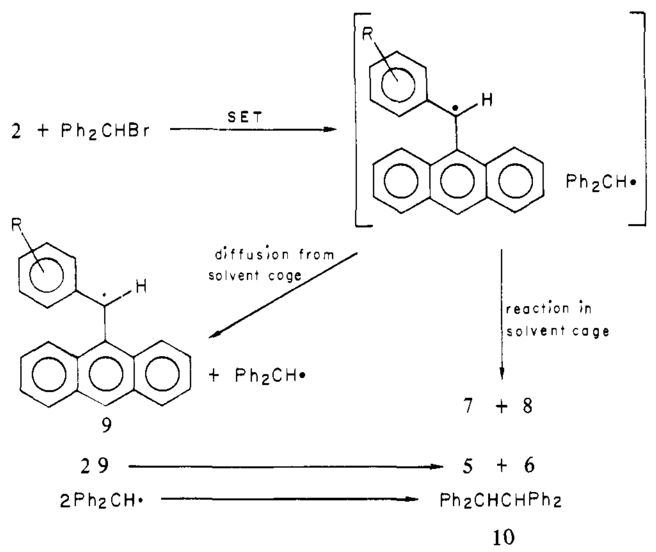
---

(29) In the reaction of methyl iodide with the carbanions, formed from allyl phenyl sulfide by proton abstraction, the nature of the countercation has been observed to affect the product composition, the lithium compound giving more α-product than the potassium compound.[7a]

(30) The α/σ ratio observed in the reaction of lithium derivatives of allylic sulfides with methyl iodide has been found to depend on solvent as well as strongly coordinating additives, the proportion of σ-attack increasing by the addition of HMPA or [2,2,2]cryptate.[8]

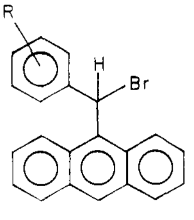
(31) The same conclusion has been derived from the fact that alkylation of α-lithio sulfoxide occurs anti to the metal cation.[17]

Scheme I



stituents of the benzyl chlorides exert a negligible influence on the product compositions. Finally, the change of the countercation and addition of HMPA did not affect the **7**:**8** ratio.

A remarkable leaving group effect was observed in the case of benzhydryl halides. The reaction of Li-**2** with benzhydryl bromide gave, along with the expected cross-coupling products **7** and **8**, the dimers of (9-anthryl)arylmethyl radicals (**9**), **5** and **6**, and tetraphenylethane (**10**) (Table VIII). Both the **7**:**8** ratio (ca. 1:3) and the **5**:**6** ratio (ca. 5:4) were not affected by the substituent of **2**.[32] The observed **5**:**6** ratio was noted to be exactly the same as that from the reaction of the halides **1a,e–g** with silver in THF,[9] suggesting that in both reactions (9-anthryl)arylmethyl radical (**9**) is the common intermediate leading to the dimers **5** and **6**. Diphenylmethyl radical was considered to be the precursor of tetraphenylethane (**10**). These considerations, together with the fact that the **7**:**8** ratio (ca. 1:3) is insensitive to the substituent of **2**, lead us to believe that the alkylation products **7** and **8** are formed by cross-coupling between (9-anthryl)arylmethyl radical (**9**) and diphenylmethyl radical.[9-11] Thus, the mechanism shown in Scheme I seems to rationalize the reaction of **2** with benzhydryl bromide most reasonably. The first step of the reaction involves SET to afford a radical pair, which couples in the cage to afford a mixture of **7** and **8**, while the radicals **9** escaped from the cage yield a mixture of **5** and **6**. The reaction of **2** with benzhydryl chloride proceeded very slowly. It took about 2 h for the characteristic color of **2** to disappear, this being in marked contrast to the rapid disappearance of the color in the case of benzhydryl bromide (5 min). The 9,10-dihydroanthracene **8** was the sole product, whereas a mixture of **5**–**8** was obtained in the case of benzyhdryl bromide (Table VIII). This fact suggests that for the reaction of **2** with benzhydryl chloride, an alternative mechanism must be taken into consideration. One would suspect that the reaction proceeds by an S_N2 mechanism, in which the approach of the bulky chloride to the C-α of **2** is subject to a large steric hindrance and, as a result, the reaction is forced to occur at the less hindered C-10.[33] Alternatively, an $S_{RN}1$ mechanism involving exclusive attack of benzhydryl radical on the carbanion **2** at C-10 would rationalize the reaction with benzhydryl chloride.[34,35] In harmony with the leaving group effects observed in the reaction of **2** with benzhydryl halides, the reaction of the bromdies **1e–g** with diphenylmethyllithium gave a mixture of **5** and **8**, whereas the 9,10-dihydroanthracene **8** was the sole product in the case of the chloride **1** (Table IX). The reaction of **1b–d** with benzylmagnesium chloride yielded, however, a mixture of **5** and **8**, both the **7**:**8** ratio (ca. 5:4)and the **5**:**6** ratio being insensitive to the substituents of the chlorides **1b–d** (Table IX).



1e, R = p-OMe
1f, R = H
1g, R = m-F

Table IX. Reaction of 1a-g with Diphenylmethyllithium[a] and Benzylmagnesium Chloride[b]

		product yield,[c,d] %		
reagent	RX	alkylation [7:8]	dimerization [5:6]	others
Ph$_2$CHLi	1a	88 [0:100]		
Ph$_2$CHLi	1b	81 [0:100]		
Ph$_2$CHLi	1c	85 [0:100]		
Ph$_2$CHLi	1d	83 [0:100]		
Ph$_2$CHLi	1e	37 [19:81]	58 [55:45]	57[e]
Ph$_2$CHLi	1f	30 [19:81]	55 [56:44]	52[e]
Ph$_2$CHLi	1g	28 [30:70]	66 [50:50]	58[e]
PhCH$_2$MgCl	1b	66 [58:42]	26 [59:41]	f
PhCH$_2$MgCl	1c	61 [51:49]	27 [51:49]	f
PhCH$_2$MgCl	1d	60 [54:46]	28 [53:47]	f

[a] The reaction with 1 mol equiv of a lithium compound in THF at 0 °C for 5 min. [b] The reaction with 5 mol equiv of the Grignard reagent in ether at 0 °C for 30 min. [c] The isolated yield. [d] The product composition was determined by ^{1}H NMR spectroscopy. [e] The yield of tetraphenylethane (10); moles per moles of diphenylmethyllithium taken. [f] Accompanied by 1,2-diphenylethane; the yield was not counted.

Table X. Reaction of 2a-d with the Corresponding Halides 1a-g[a]

carbanion	halide	product yield,[b] % [5:6][c]
Li-2a	1a	90 [25:75]
Li-2b	1b	85 [29:71]
Li-2c	1c	84 [34:66]
Li-2d	1d	85 [66:34]
Li-2b	1e	80 [53:47]
Li-2c	1f	90 [52:48]
Li-2d	1g	94 [57:43]

[a] The reaction with 1 mol equiv of the halide at −70 °C in THF for 10 min under a nitrogen atmosphere. [b] The isolated yield. [c] The product composition was determined by ^{1}H NMR spectroscopy.

The reaction of Li-**2** with (9-anthryl)arylmethyl halides (**1a–g**) afforded the dimers **5** and **6** (Table X). The substituent-independent **5**:**6** ratio obtained from the reaction of a lithium compound Li-**2** with the corresponding bromide **1e–g** is noticed to be the same as that observed in the reaction of **1e–g** with Ag in THF. In direct contrast, the **5**:**6** ratio observed in the reaction of a lithium compound Li-**2** with the corresponding chloride **1a–d** is a marked function of the substituent electronic effects, the ratio being increased as the substituent becomes increasingly electron withdrawing. These results suggest again that leaving group effects are important in determining the reaction processes. The observed product compositions would suggest that the reactions with the chlorides **1a–d** proceed mainly by an S_N2 process, while a SET process is important in the case of the bromides **1e–g**.

Treatment of Li-**2c** with triphenylmethyl chloride at −70 °C for 5 min, followed by exposure to air, gave bis(triphenylmethyl) peroxide (**11**) in a yield of 40%, along with a complex mixture containing **5** and **6**. The formation of **11** is readily rationalized

---

(32) The relatively higher **7**/**8** ratio (ca. 1:2) was observed in the reaction of Li-**2d** with benzhydryl bromide. The reason is obscure.

(33) A similar leaving group effect on the course of reaction has been observed in the reaction of diphenylmethyl- and triphenylmethyllithium with benzhydryl and triphenylmethyl halides (the leaving group = F, Cl).[12b]

(34) (a) Bunnett, J. F. *Acc. Chem. Res.* **1978**, *11*, 413. (b) Saveant, J. M. *Ibid.* **1980**, *13*, 323.

(35) This possibility was kindly suggested by a referee.

in terms of the dimerization of triphenylmethyl radicals followed by reaction with oxygen. Supporting this, this reaction is noted to be significantly faster than that of Li-**2** with the relatively less bulkier benzhydryl chloride. If both of these reactions proceed by S_N2 processes, a reverse trend should have been observed.

In summary the following factors would favor the alkylation at C-10: (a) the increase of steric bulk of the alkyl halides, (b) the introduction of the electron-donating group on the phenyl ring of **2** in the case of alkylation with aliphatic halides, and (c) alkylation with benzylic halides having a relatively poor leaving ability.

Experimental Section

General. ^{1}H NMR spectra were obtained with a JNM-PS-100 spectrometer in $CDCl_3$. Visible spectra were obtained with a Hitachi 220A spectrophotometer. All reactions involving organometallic compounds were carried out under a nitrogen atmosphere. Tetrahydrofuran was dried over lithium aluminum hydride and distilled from this reagent. Hexamethylphosphoramide was vacuum distilled from sodium immediately before use. Cyclopentadiene was prepared by the reported method.[36] Alcohols, phenol, and indene were used after distillation. Acetic acid, trifluoroacetic acid, and *p*-nitrophenol were commercial grade. Alkyl halides and tosylates were commercially available and were distilled prior to use. Benzyl tosylate[37] and triphenylmethyl chloride[38] were prepared by the reported method. Lithium and sodium naphthalenides were prepared by the reported method.[12b] 9-(α-Chloro-3-fluorobenzyl)anthracene (**1d**) was prepared by the reaction of the corresponding alcohol with thionyl chloride:[39] mp 108–110 °C (from benzene–hexane); NMR δ 7.63 (s, 1 H, α-position), 8.45 (s, 1 H, 10-position). Other chlorides **1a–c** and bromides **1e–g** were prepared by the previously reported method.[15]

Preparation of ((9-Anthryl)arylmethyl)lithiums and -sodiums. In a 100-mL flask, equipped with a magnetic stirrer and maintained under N_2, was added a THF solution of lithium naphthalenide (6.6 mmol) by a syringe. This flask was cooled to −70 °C and then a THF solution (20 mL) of **1c** (1.0 g, 3.3 mmol) was added in one portion. The color changed to bright green. The visible spectra were measured by diluting aliquots of this solution with dry THF in a quartz cell maintained under N_2 (Table II). This solution was quenched by adding 1.0 mL of D_2O under the same conditions (the characteristic color immediately disappeared), and the reaction mixture was extracted with ether. The crude products were chromatographed on silica gel to afford a colorless oil (0.88 g, 98%) shown by NMR analyses to contain 9-benzylanthracene-α-*d* (**3c**) [NMR δ 4.94 (s, 1 H)] and 9-benzylidene-9,10-dihydroanthracene-10-*d* (**4c**) [NMR δ 4.00 (s, 1 H)] in a molar ratio of 94:6.

The sodium compound Na-**2c** was obtained by reacting 6.6 mmol of sodium naphthalenide with **1c** (1.0 g, 3.3 mmol) in 20 mL of THF at −70 °C. The solution was quenched by adding 1.0 mL of D_2O and the reaction mixture was extracted with ether. Column chromatography on silica gel (elution with 1:5 benzene–hexane) gave 9-benzylanthracene-α-*d* (**3c**) in a yield of 71%. From the second fraction (elution with 1:1 benzene–hexane) was obtained a mixture of 32% 10-(α-(9′-anthryl)-benzyl)-9-benzylidene-9,10-dihydroanthracene (**5c**) (a mixture of two conformational isomers) [NMR δ 5.60 (d, 1 H, *J* = 12 Hz)] and 68% 9,9′-dibenzylidene-9,9′,10,10′-tetrahydro-10,10′-bianthracene (**6c**) (a mixture of two conformational isomers) [NMR δ 4.80 (s, 2 H) and 4.00 (s, 2 H), respectively] (0.18 g, 20%). Other sodium compounds also gave mixtures of **5** and **6** (Table I). Physical properties of **5d** and **6d** were as follows. **5d**: mp 115 °C dec (from benzene–hexane); NMR δ 5.57 (d, 1 H, *J* = 12 Hz). **5d′**: mp 201–203 °C (from benzene–hexane); NMR δ 5.57 (d, 1 H, *J* = 12 Hz). **6d**: mp 232–234 °C (from THF–hexane); NMR δ 4.24 (s, 2 H). **6d′**: mp 208–210 °C (from benzene–hexane); NMR δ 3.94 (s, 2 H). Physical data of other dimeric products **5a–c** and **6a–c** were previously reported.

Protonation Reactions. Protonation reactions were usually done by adding a THF solution (5 mL) of a proton donor (ca. 1.0 g) to the solution of the carbanion **2** (prepared from 1.0 g of **1**) at −70 °C. THF–HMPA mixture solutions of **2** were prepared by adding an appropriate amount of HMPA to a THF solution of **2** by a syringe. The crude products were separated by column chromatography on silica gel, the product composition being determined by ^{1}H NMR spectroscopy. Elaborate column chromatography and fractional recrystallizations of the hydrocarbon part gave **3** and **4** in pure states. The physical properties of **3d** and **4d** were as follows. Anthracene **3**:: mp 101–102 °C (from benzene–methanol); NMR δ 4.94 (s, 2 H). 9,10-Dihydroanthracene **4d**: mp 105–106 °C (from benzene–methanol); NMR δ 4.00 (s, 2 H). The physical properties of other hydrocarbons **3a–c** and **4a–c** were reported previously.

Competitive Protonation. To a THF solution (20 mL) of Li-**2a** (3.0 mmol) was added a mixture of cyclopentadiene (0.99 g, 15 mmol) and 2-methyl-2-propanol (1.11 g, 15 mmol) in 5 mL of THF at −70 °C. Column chromatography on silica gel (elution with 1:1 benzene–hexane) gave a mixture of **3a** and **4a** (0.81 g, 90%) in a molar ratio of 32:68.

Reaction with Methyl Bromide. To a THF solution (20 mL) of Li--**2c** prepared by the reaction of **1c** (1.0 g, 3.3 mmol) with 6.6 mmol of lithium naphthalenide was added methyl bromide (9.54 mL, 9.9 mmol) in one portion at −70 °C and the mixture was kept with stirring at this temperature. The characteristic color of the carbanion disappeared within 5 min. The reaction mixture was extracted with ether and the solvent was removed under vacuum. The crude products were chromatographed on silica gel to give a yellow oil (0.8 g, 2.84 mmol, 86%) shown by NMR analyses to contain 9-(α-methylbenzyl)anthracene (**7c**) [NMR δ 5.79 (q, 1 H, *J* = 7 Hz)] and 10-methyl-9-benzylidene-9,10-dihydroanthracene (**8c**) [NMR δ 4.09 (q, 1 H, *J* = 7 Hz)] in a molar ratio of 74:26.

Reaction with Benzyl Bromide. To a THF solution (20 mL) of Li-**2c** (6.6 mmol) was added benzyl bromide (1.2 mL, 9.9 mmol) at −7– °C. The color of the solution immediately disappeared. The reaction mixture was extracted with ether and separated by column chromatography on silica gel. The fraction eluted with 1:5 benzene–hexane (1.0 g, 2.87 mmol, 87%) was analyzed by ^{1}H NMR spectroscopy, which indicated that products consisted of 53% **7o** and 47% **8o**. Repeated column chromatography and fractional recrystallizations gave **7o** [mp 129–130 °C (from benzene–methanol); NMR δ 3.52–4.20 (m, 2 H), 5.90 (m, 1 H)] and **8o** [mp 129–130 °C (from benzene–methanol); NMR δ 2.98 (d, 2 H, *J* = 7 Hz), 4.00 (d, 1 H, *J* = 7 Hz)] in pure states.

Reaction with Benzhydryl Bromide. To a THF solution (20 mL) of Li-**2a** (3.0 mmol) was added a THF solution (10 mL) of benzhydryl bromide (2.2 g, 9.0 mmol) in one portion at −70 °C. The color of the solution immediately disappeared. The reaction mixture was extracted with ether and the solvent was removed under vacuum. Then, the crude products were heated with aqueous KOH in dioxane to convert unreacted benzhydryl bromide to the corresponding alcohol. Column chromatography on silica gel (elution with 1:2 benzene–hexane) gave tetraphenylethane (**10**) (0.13 g). Elution with 1:1 benzene–hexane next gave a colorless solid (0.77 g, 1.65 mmol, 55%) containing **7w** and **8w** in a molar ratio of 1:3. The third fraction eluted with benzene (0.21 g, 0.69 mmol, 23%) was analyzed by NMR spectroscopy to contain 10-(α-(9-anthryl)-*p*-methoxybenzyl)-9-*p*-methoxybenzylidene-9,10-dihydroanthracene (**5a**) (a mixture of two conformational isomers) [NMR δ 5.57 (d, 1 H)] and 9,9′-bis(*p*-methoxybenzylidene)-9,9′,10,10′-tetrahydro-10,10′-bianthracene (**6a**) (a mixture of two conformational isomers) [NMR δ 4.00 (s, 2 H) and 4.08 (s, 2 H), respectively] in a molar ratio of ca. 1:1. Elaborate column chromatography on silica gel and fractional recrystallizations of the second fraction gave **7w** [mp 105 °C dec (from benzene–hexane); NMR δ 3.61 (s, 3 H), 5.54 (d, 1 H, *J* = 12 Hz)] and **8w** [mp 211–213 °C (from benzene–hexane); NMR δ 3.78 (s, 3 H), 4.29 (d, 1 H, *J* = 11 Hz), 4.64 (d, 1 H, *J* = 11 Hz)] in pure states.

Reaction of Li-2c with 1c. To 3.3 mmol of Li-**2c** in 20 mL of THF was added a THF solution (10 mL) of **1c** (1.0 g, 3.3 mmol) at −70 °C and the mixture was kept with stirring at this temperature for 10 min. Column chromatography on silica gel (elution with 1:1 benzene–hexane) afforded a mixture of **5c** and **6c** (0.74 g, 1.39 mmol, 84%) in a molar ratio of 34:66.

Reaction of Li-2c with Triphenylmethyl Chloride. To 3.3 mmol of Li-**2c** in 20 mL of THF was added a THF solution (10 mL) of triphenylmethyl chloride (2.8 g, 9.9 mmol) at −70 °C. The color changed from green to dark orange. The mixture was kept with stirring at −70 °C for 5 min, followed by exposure to air. After workup, the reaction mixture was heated with aqueous KOH in dioxane to convert the unreacted triphenylmethyl chloride to the corresponding alcohol. Bis(triphenylmethyl) peroxide (**11**) was isolated by triturating the crude products with benzene–hexane (0.3 g, 0.64 mmol, 39%). Column chromatography on silica gel of the mother liquor (elution with 1:1 benzene–hexane) gave a mixture of **5c** and **6c** (0.53 g, 0.99 mmol. 60%) in a molar ratio of ca. 1:1.

Reaction of 1 with (Diphenylmethyl)lithium. To a THF solution (20 mL) of **1a** (1.0 g, 3.0 mmol) cooled to 0 °C was slowly added dropwise a THF solution of (diphenylmethyl)lithium (3.0 mmol) by a syringe, and the mixture was kept with stirring at 0 °C for 5 min. Column chromatography on silica gel (elution with 1:1 benzene–hexane) gave **8w** in a yield of 88%.

Reaction of 1 with Benzylmagnesium Chloride. To 16.5 mmol of benzylmagnesium chloride in 30 mL of ether was added an ether solution

---

[36] "Organic Synthesis"; Wiley: New York, 1963; Collect. Vol. IV, p 238.

[37] Gillman, H.; Beaber, N. *J. Am. Chem. Soc.* **1925**, *47*, 518.

[38] "Organic Synthesis"; Wiley: New York, 1964; Collect. *Vol.* I, p 471.

[39] Gibson, S.; Mosnaim, A. D.; Nonhebel, D. C.; Russel, J. A. *Tetrahedron* **1969**, *25*, 5047.

of **1c** (1.0 g, 3.3 mmol) at 0 °C. After 30 min, the reaction mixture was decomposed by aqueous NH_4Cl solution and extracted with ether. The crude products were chromatographed on silica gel. Elution with 1:5 benzene–hexane gave a mixture of **7o** and **8o** (0.85 g, 2.01 mmol, 61%) in a molar ratio of 56:44. From the second fraction (elution with 1:1 benzene–hexane) was obtained a mixture of 51% **5c** and 49% **6c** (0.25 g, 0.46 mmol, 28%).

Reaction of 8 with (Diphenylmethyl)lithium. To a THF solution (20 mL) of **8w** (0.3 g, 0.65 mmol) was added 3.25 mmol of (diphenylmethyl)lithium in THF at 20 °C. The mixture was kept with stirring at 20 °C for 5 h. Column chromatography on silica gel (elution with 1:1 benzene–hexane) gave **7w** in a yield of 88%. Treatment of **8x–z** with (diphenylmethyl)lithium (5 mol equiv) also gave **7x–z** quantitatively.

Registry No. 1a, 77032-88-3; **1b**, 77032-89-4; **1c**, 72948-51-7; **1d**, 85865-12-9; **1e**, 85865-13-0; **1f**, 77032-93-0; **1g**, 85865-14-1; **2a**-Li, 85865-15-2; **2a**-Na, 85865-16-3; **2b**-Li, 85865-17-4; **2b**-Na, 85865-18-5; **2c**-Li, 85865-19-6; **2c**-Na, 85865-20-9; **2d-Li**, 85865-21-0; **2d**-Na, 85865-22-1; **3c**, 1498-71-1; **3c**-*d*, 85865-23-2; **3d**, 85865-24-3; **4c**-*d*, 85882-55-9; **4d**, 85882-56-0; **5a**, 85922-49-2; **5a′**, 85922-50-5; **5c**, 85922-51-6; **5c′**, 85922-52-7; **5d**, 85882-57-1; **5d′**, 85922-53-8; **6a**, 85922-54-9; **6a′**, 85922-55-0; **6c**, 85922-56-1; **6c′**, 85922-57-2; **6d**, 85882-58-2; **6d′**, 85922-58-3; **7c**, 80503-06-6; **7d**, 85865-25-4; **7h**, 85865-26-5; **7l**, 85865-27-6; **7m**, 85865-28-7; **7n**, 85865-29-8; **7o**, 85865-30-1; **7p**, 85865-31-2; **7r**, 85882-59-3; **7s**, 85865-32-3; **7t**, 85865-33-4; **7u**, 85865-34-5; **7v**, 85865-35-6; **7w**, 85865-36-7; **7x**, 85865-37-8; **7y**, 85865-38-9; **7z**, 85865-39-0; **8c**, 77033-38-6; **8h**, 85882-60-6; **8l**, 85882-61-7; **8m**, 85882-62-8; **8n**, 85882-63-9; **8o**, 85882-64-0; **8p**, 85882-65-1; **8q**, 85882-66-2; **8r**, 85882-67-3; **8s**, 85882-68-4; **8t**, 85882-69-5; **8u**, 85882-70-8; **8v**, 85882-71-9; **8w**, 85882-72-0; **8x**, 85882-73-1; **8y**, 85882-74-2; **8z**, 85882-75-3; $Li^+Naph^{-}\cdot$, 7308-67-0; $Na^+Naph^{-}\cdot$, 3481-12-7; CF_3COOH, 76-05-1; CH_3COOH, 64-19-7; 4-$NO_2C_6H_4OH$, 100-02-7; C_6H_5OH, 108-95-2; CF_3CH_2OH, 75-89-8; H_2O, 7732-18-5; CH_3CH_2OH, 64-17-5; *t*-BuOH, 75-65-0; HMPA, 680-31-9; MeBr, 74-83-9; MeI, 74-88-4; MeOTs, 80-48-8; EtBr, 74-96-4; EtI, 75-03-6; *i*-PrBr, 75-26-3; *i*-PrI, 75-30-9; $PhCH_2Cl$, 100-44-7; $PhCH_2Br$, 100-39-0; $PhCH_2OTs$, 1024-41-5; *p*-$MeOC_6H_4CH_2Cl$, 824-94-2; *m*-$ClC_6H_4CH_2Cl$, 620-20-2; Ph_2CHCl, 90-99-3; Ph_2CHBr, 776-74-9; Ph_2CHLi, 881-42-5; $PhCH_2MgCl$, 6921-34-2; *i*-PrOH, 67-63-0; cyclopentadiene, 542-92-7; indene, 95-13-6.

Supplementary Material Available: Table of physical properties of compounds **7** and **8** (3 pages). Ordering information is given on any current masthead page.

Synergistic Effect of Iodine and Neighboring Amine Groups on Thioester Deacylation

Joyce Takahashi Doi,* Tracy Louise Carpenter, Marilyn M. Olmstead, and W. Kenneth Musker*

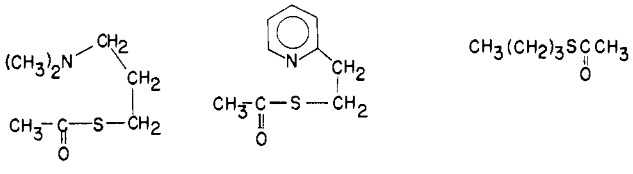
Contribution from the Department of Chemistry, University of California, Davis, California 95616. *Received November 22, 1982*

Abstract: The synergistic effect of a Lewis acid (I_2) and an intramolecular Lewis base facilitates the deacylation of thioesters. When iodine is added to an aqueous solution of *S*-3-(dimethylamino)propyl thioacetate (I), deacylation is accelerated by a factor of 10^3–10^4. A severalfold acceleration is observed for *S*-2-(2-pyridyl)ethyl thioacetate (II), and no rate enhancement is observed in the reaction of *S*-*n*-butyl thioacetate (III). The rate of iodine consumption at invariant pH and thioester and iodide concentrations is zero order in iodine when III reacts and first order in iodine when I reacts. Both kinetic orders are observed when II reacts. The effect of pH and iodide ion concentration on the rates of I and II is explained by an intramolecular interaction between an iodine–thioester complex and the neighboring amine. The product of the reaction of the unsubstituted thioester III is the disulfide. However, overoxidation is observed in the reactions of I and II, and the sulfonic acids were the isolated products. The product from the oxidation of I has been confirmed to be $(CH_3)_2{}^+NH(CH_2)_3SO_3{}^-$ (IV) by single-crystal X-ray crystallography.

Introduction

The present examination of the effect of aqueous iodine on the cleavage of thioesters is an extension of our interest in the effect of neighboring groups on thioether oxidation.[1] In view of recent spectroscopic measurements and calculations[2] that show that the thioester carbonyl group resembles a ketone, its –SR fragment may resemble a thioether and coordinate with iodine. In nonaqueous solvents the proton NMR shifts of thioesters are only very slightly affected by I_2.[3] However, a suggestion that a thioester–iodine complex may be involved in a thioester–ester interchange was proposed by Minato et al., who had investigated the reaction of thioesters with halogens.[4] They found that when iodine was added to *S*-phenyl thioacetate in $CDCl_3$ in the presence of 3 equiv of alcohol, transesterification proceeded, yielding the corresponding alkoxy ester, thiophenol, and diphenyl disulfide. No reaction was observed in the absence of alcohol. Some of the most recent studies of the cleavage of thioesters deal with soft metal ion promoted hydrolysis using aqueous solutions at low pH. Patel and Satchell[5] have shown that Cu^{2+}, Ni^{2+}, Pb^{2+}, and Cd^{2+} ions have little or no effect on the hydrolysis rates of thioesters, but soft metal ions like Tl^{3+}, Au^{3+}, Hg^{2+}, $Hg_2{}^{2+}$ and Ag^+ ions are very powerful promoters of thioester hydrolysis in acid solution. The catalysis of thioester deacylation reactions is an important

Chart I



I II III

---

(1) Doi, J. Takahashi; Musker, W. K.; deLeeuw, D. L.; Hirschon, A. S. *J. Org. Chem.* **1981**, *46*, 1239.

(2) El Aasar, A. M. M.; Nash, C. P.; Ingraham, L. L *Biochemistry* **1982**, *21*, 1972.

(3) Kingsbury, C. A.; Ebert, G. *Phosphorus Sulfur* **1981**, *9*, 315.

(4) Minato, H.; Takeda, K.; Miura, T.; Kobayashi, M. *Chem. Lett.* **1977**, 1095.

(5) Patel, G.; Satchell, R. S. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1406.

0002-7863/83/1505-4684$01.50/0