systems can be manipulated without substantial cleavage. Consequently, it appears **2**, under suitably chosen conditions, might serve as a precursor for molecules quoted[6] as possible progenitors for structures which contain a planar tetracoordinate carbon atom. Studies toward this goal are presently being pursued in our laboratory and will be reported in due course.

Acknowledgment. We (Han, Takahashi, and Cook) wish to thank the National Science Foundation (CHE-7910302) and the donors of the Petroleum Research Fund, administered by the American Chemical Society, for generous financial support. We wish to thank Gail Boviall for technical assistance.

Supplementary Material Available: Tables of final anisotropic thermal parameters and structure factor amplitudes as well as ORTEP drawings of **2** and **3** (28 pages). Ordering information is given on any current masthead page.

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(6) Hoffmann, R.; Alder, R. W.; Wilcox, C. F., Jr. *J. Am. Chem. Soc.* **1970**, *92*, 4992. Hoffmann, R. *Pure Appl. Chem.* **1971**, *28*, 181. Keese, R.; Pfenninger, A.; Roesle, A. *Helv. Chim. Acta* **1979**, *62*, 326. Böhm, M. C.; Gleiter, R.; Schang, P. *Tetrahedron Lett.* **1979**, 2575. ten Hoeve, W.; Wynberg, H. *J. Org. Chem.* **1980**, *45*, 2930. Wiberg, K. B.; Olli, L. K.; Golembeski, N.; Adams, R. D. *J. Am. Chem. Soc.* **1980**, *102*, 7467.

Alkynolate Anions via a New Rearrangement: The Carbon Analogue of the Hofmann Reaction[1]

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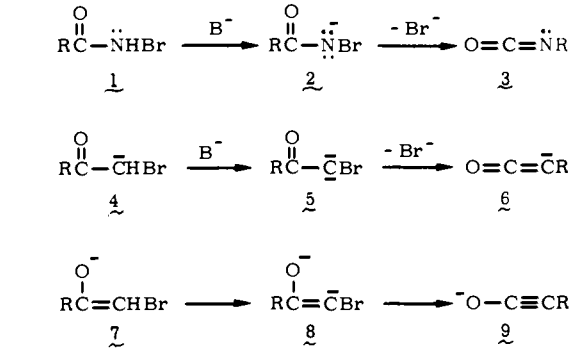
Herein we report the first examples of a previously unknown reaction, the carbon analogue of the Hofmann rearrangement. The classical Hofmann reaction[2] involves deprotonation of an *N*-bromoamide (**1** → **2**) followed by migration of a group to nitrogen with loss of bromide to form an isocyanate (**2** → **3**). The new reaction described herein is formally isoelectronic with that process; i.e., an α-bromoketone enolate is deprotonated (**4** → **5**) and rearranges with loss of bromide to afford a ketene anion (**5** → **6**). Resonance structures **7**–**9** emphasize the enolate nature of the α-keto dianion intermediate **8** and the alkynolate nature of the product anion **9**. While simple haloenolate monoanions such as **4** are stable and not prone to loss of halide,[3] α-halo-α-keto dianions (**5**) possess a much greater charge density on carbon which should facilitate loss of bromide. Our results presented below indicate this is indeed the case; rearrangement of **5** to **6** does occur, and in fact, rapidly even at −78 °C.

Primary bromoenolate **10**, on treatment with *tert*-butyllithium in ether (−78 °C; then 0 °C) cleanly undergoes metal–halogen exchange to afford the expected α-keto dianion **11**.[4] Addition of cyclohexanone (1.4 equiv, −78 °C, 10 min) followed by quenching with dilute acid affords aldol product **12** in 88% yield. When this same sequence is carried out in tetrahydrofuran (THF) rather than ether, however, the yield of **12** drops to 70% and a new product, spiro-β-lactone **16**, is obtained in 12% yield. Formation of **16** is consistent with deprotonation of **10** (in competition with metal–halogen exchange), leading to alkynolate anion **14** via rearrangement of dianion **13**. Preparation of **14** by a different method has been reported by Schöllkopf[5] as well as reaction of

Scheme I



Scheme II

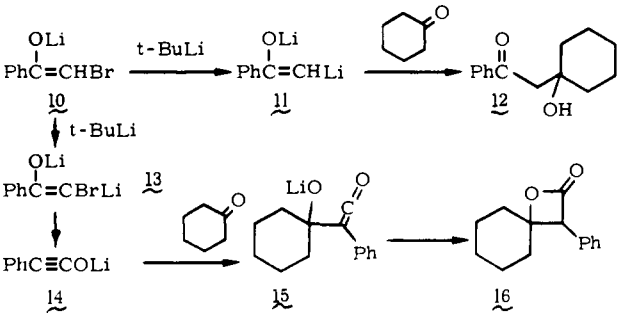


Table I[a]

Entry	Starting Enolate[a]			Product	Yield[b]
1	PhC(OLi)=CHCl (**17**)	n-BuLi,[c] THF, -78° → RT	HCl, H_2O	$PhCH_2CO_2H$	(67%)
2	**17**	"	(1.3 eq), -78°	**16**[5]	(43%)
3	**17**	t-BuLi, THF, -35°; RT[d]	MeOH, -78° → RT	$PhCH_2CO_2Me$ (**18**)	(57%)
4	**17**	"	PhCHO (1 eq), -78° → RT	**19**[7]	(85%)
5	PhC(OLi)=CBr_2 (**20**)	t-BuLi, THF, -78° → RT	PhCHO (2 eq), -78° → RT	**19**	(76%)
6	**20**	"	$PhCH_2OH$ (3 eq), -78° → RT	$PhCH_2CO_2CH_2Ph$ (**21**[19])	(50%)
7	t-BuC(OLi)=CHCl (**22**)	t-BuLi, THF, -78° → RT	N. R., $ClSiMe_3$	t-BuC(OSiMe$_3$)=CHCl (**23**[13])	
8	t-BuC(OLi)=CBr_2 (**24**)	t-BuLi, THF, -78° → RT	$PhCH_2OH$ (5 eq), -78° → RT	$t\text{-}BuCH_2CO_2CH_2Ph$ (**25**[20])	(72%)
9	**24**	"	PhCHO (2.4 eq), -78° → RT	**26**[13]	(75%)[e]

[a] Starting enolates were prepared as noted: **17**,[6] **20**,[8] **22**,[11] **24**.[12] [b] Isolated yields based on precursors of starting enolates. [c] Reactions involving *n*-butyllithium were difficult to reproduce; see text. [d] Reaction mixture was warmed briefly to room temperature before quenching to destroy excess *tert*-butyllithium. [e] Single isomer; stereochemistry as shown.

(1) This work was presented in part at the 1981 Joint Central–Great Lakes Regional ACS Meeting at Dayton, OH, May 21, 1981, and at the I.I.T. Kilpatrick Symposium on Carbenes, Carbenoids, and Cyclopropanes in Organic Synthesis in Chicago, IL, June 2, 1981.
(2) Wallis, E. S.; Lane, J. F. *Org. React.* **1946**, *3*, 267.
(3) (a) In our previous work with haloenolates,[4a,9] we have never observed loss of halide; (b) unsuccessful attempts to induce α-ketocarbene formation from α-chloroenolate anions have been reported by: House, H. O.; Fischer, W. F; Gall, M.; McLaughlin, T. E; Peet, N. P. *J. Org. Chem.* **1971**, *36*, 3429.
(4) (a) Kowalski, C. J.; O'Dowd, M. L.; Burke, M. C.; Fields, K. W. *J. Am. Chem. Soc.* **1980**, *102*, 5411. (b) The bromoenolate **10** was prepared from the corresponding bromoenol acetate and methyllithium at 0 °C.
(5) Hoppe, I.; Schöllkopf, U. *Liebigs Ann. Chem.* **1979**, 219.

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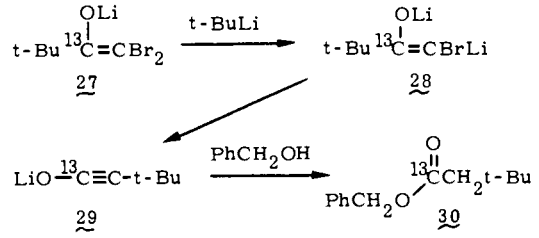
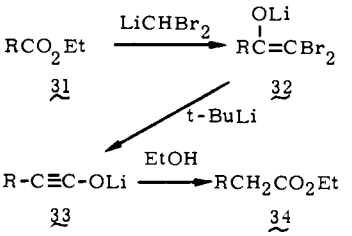
Scheme III



Scheme IV



14 with cyclohexanone to afford **16** in 51% yield. Substitution of *n*-butyllithium for reaction with enolate **10** leads to an anticipated reduction in the formation of dianion **11** (7% as determined by protonation to afford acetophenone) and an increase in production of alkynolate anion **14** (50% as determined by aqueous hydrochloric acid quench to afford phenylacetic acid).

Several methods for achieving such rearrangements more cleanly and in better yield are listed in Table I, demonstrating a number of different quenches for the alkylnolate anions as well. Entries 1–4 utilize the enolate anion (**17**)[6] of α-chloroacetophenone to block metal–halogen exchange, and in none of these cases are any products formed from α-keto dianion **11**. When *n*-butyllithium (1.25–2.5 equiv) is used as base (entries 1 and 2), the mixture must be warmed slowly to room temperature to effect deprotonation; the exact rate of warming appears to be critical, and this procedure is *not* readily reproducible. Better results are obtained by using *tert*-butyllithium (1.5–2.1 equiv; entries 3 and 4) which does not react with the chloroenolate anion appreciably at −78 °C but does lead reproducibly to alkynolate anion **14** at −35 °C after 1 h. Quenching the reaction with methanol affords ester **18** directly, while use of benzaldehyde and then dilute hydrochloric acid affords unsaturated acid **19**;[7] this latter product is thought to arise from opening of an intermediate β-lactone analogous to **16** on workup (or opening of the lactone enolate in the reaction mixture).

Yet another method of generating bromo-α-keto dianion 13 for rearrangement, which completely precludes formation of dianion **11**, involves utilization of dibromoenolate **20** as the precursor (entries 5 and 6). When enolate **20**[8] was treated with *tert*-butyllithium (3.3 equiv, −78 °C), both the metal–halogen exchange to form **13** and the rearrangement to **14** were complete within 5 min at −78 °C. This was determined by protonation at −78 °C, which afforded only a trace of dibromoketone starting material, no monobromoacetophenone, but principally phenylacetic acid. Quenching these alkynolate anion solutions (after brief warming to room temperature)[10] at −78 °C with benzaldehyde or benzyl alcohol produced the expected products (entries 5 and 6).

The extreme ease and rapidity of metal–halogen exchange/rearrangement for a dibromoketone enolate proved of great importance in attempting to prepare *tert*-butylalkynolate anion **9** (R = *t*-Bu). In this instance, the enolate (**22**) of α-chloropinacolone was inert to excess *tert*-butyllithium in THF, even at room temperature. No products derived from deprotonation of **22**, with or without rearrangement, or from metal–halogen exchange were observed (entry 7). In marked contrast, treatment of α,α-dibromopinacolone enolate anion (**24**)[12] with *tert*-butyllithium for 5 min at −78 °C completely effected both metal–halogen exchange and rearrangement (as determined by aqueous acid quench at −78 °C to afford 3,3-dimethylbutyric acid). Solutions of alkynolate anion **9** (R = *t*-Bu), after brief warming to room temperature,[10] were treated at −78 °C with benzyl alcohol or benzaldehyde to afford the expected ester or enone products **25** and **26** (entries 8 and 9) in good yields.

In order to determine whether these rearrangements do indeed parallel the Hofmann rearrangement, an experiment was performed to distinguish between the possiblity of oxygen vs. carbon migration in the formation of alkynolate anions. For this purpose, α,α-dibromopinacolone was prepared with 90% ^{13}C enrichment at the carbonyl carbon,[15] and this was converted to enolate **27** (Scheme III). Treatment of **27** with *tert*-butyllithium and then benzyl alcohol led to ester **30** under the same conditions utilized for the nonlabled compound (entry 8). In this case, however, spectral evidence clearly indicated almost complete ^{13}C enrichment at the ester carbonyl carbon [IR 1690 cm^{-1} ($^{13}C{=}O$) vs. 1730 ($^{12}C{=}O$) for ester **25**; ^{13}C NMR ($CDCl_3$) 172.005 ppm, single large peak; ^1H NMR ($CDCl_3$) 7.37 (S, 5 H, aromatic), 5.10 (d, $^3J_{^{13}C-H}$ = 3 Hz, 2 H, $-CH_2-O^{13}C{=}O$), 2.23 (d, $^2J_{^{13}C-H}$ = 6 Hz, 2 H, $-CH_2-^{13}C{=}O$), 1.02 ppm (s, 9 H, *t*-Bu)]. No evidence of ^{13}C enrichment at any other position of the product was observed. This result indicates that it is the *tert*-butyl group of dianion **28**, not the oxygen, which migrates to afford alkynolate anion **29**; the rearrangement, therefore, is indeed analogous to the Hofmann reaction.

While this rearrangement may be of some fundamental interest due to its isoelectronic relationship with the Hofmann process, it would be especially interesting if it offered some potential utility as well; therefore, we present a preliminary result which demonstrates utilization of the rearrangement to effect a single-step homologation of an ester (**31** → **34**). Underlying this procedure is the earlier work of Villieras and Normant[16] in which the addition of excess dibromomethyllithium to ethyl isobutyrate is reported to generate a dibromoenolate anion (i.e., **31** → **32**, R = Me_2CH). Coupling their result with Yamamoto's insitu procedure for preparing dibromomethyllithium[17] led us to the method outlined in Scheme IV. A mixture of ethylcyclohexanecarobxylate (**31**, R = C_6H_{11}) and dibromomethane (2.4 equiv) in THF was treated at −78 °C with lithium dicyclohexylamide (2.4 equiv). The resulting enolate **32** (R = C_6H_{11}) was then treated with *tert*-butyllithium (7.5 equiv, −78 °C room temperature) to effect rearrangement and alkynolate anion **33** was quenched with excess 10%

(6) Enolate anion **17** was generated in THF at 0 °C from the corresponding trimethylsilyl enol ether[3b] and methyllithium.

(7) Ketchem, J.; Jambotkar, D. *J. Org. Chem.* **1963**, *28*, 1034.

(8) Enolate anion **20** was prepared in THF from α,α-dibromoacetophenone by using lithium hexamethyldisilazide[9] (1.05 equiv at −78 °C and then 0 °C); the dibromoketone was prepared by heating acetophenone with ~3 equiv of bromine in acetic acid *without* sodium acetate, in a modification of the procedure of: Aston, J. G.; Newkirk, J. D.; Dorsky, J.; Jenkins, D. M. *J. Am. Chem. Soc.* **1942**, *64*, 1413.

(9) Kowalski, C.; Creary, X.; Rollin, A. J.; Burke, M. C. *J. Org. Chem.* **1978**, *43*, 2601.

(10) To destroy any excess *tert*-butyllithium.

(11) Enolate anion **22** was prepared in THF from the corresponding trimethylsily enol ether by using methyllithium at room temperature via the methodology of House[3b]. Stork, G.; Hudrlik, P. F. *J. Am. Chem. Soc.* **1968**, *90*, 4462, 4464. The silyl enol ether[14] was prepared by using the method of House.[3b]

(12) Enolate anion **24** was prepared in THF from the dibromoketone[13] and lithium hexamethyldisilazide[9] (1.05 equiv at −78 °C and then 0 °C); the dibromoketone was prepared as described in footnote 8.

(13) Duhamel, P.; Duhamel, L.; Gralak, J. *Bull. Soc. Chim. Fr.* **1970**, 3641.

(14) All new compounds afforded proper combustion or exact mass spectral analysis as well as suitable IR and NMR spectra.

(15) 90% ^{13}C enriched CO_2 from KOR Isotopes, Cambridge, MA, was circulated into a flask containing ≤1 equiv of *tert*-butyllithium in ether at −78 °C. When a small amount of 1,10-phenanthroline in the mixture lost its color, 1.3 equiv of methyllithium was added and the mixture warmed to room temperature for 15 h. After aqueous workup, the crude [^{13}C]pinacolone was heated with 2 equiv of bromine in acetic acid;[12] after recrystallization, α,α-dibromopinacolone was obtained, 90% ^{13}C enriched at the carbonyl carbon.

(16) Villieras, J.; Bacquet, C.; Normant, J.-F. *Bull. Soc. Chim. Fr.* **1975**, 1797.

(17) Taguchi, H.; Yamamoto, H.; Nozaki, H. *J. Am. Chem. Soc.* **1974**, *96*, 3010.

sulfuric acid in ethanol. Ethyl cyclohexaneacetate (**34**, R = C_6H_{11}) was thus obtained in an unoptimized yield of 63%. Compared to the multistep Arndt-Eistert procedure,[18] this homologation was effected in a single reaction, without use of hazardous diazomethane. This method also offers the option of utilizing the intermediate alkynolate anion (**33**) for transformations other than simple ester formation. Little is known of the reactions of such alkynolates[5] which should have a rich chemistry of their own (e.g., the β-lactone formation already cited). Further studies of this rearrangement reaction and the utility of the alkynolate anions produced are under way.

Acknowledgment. Support of this investigation was provided by the National Cancer Institute, DHEW, under Grant 27157, the National Science Foundation under Grant CHE-8111128, the 3M Corporation under a 3M Corporation Young Faculty Grant, and the Lubrizol Corporation by providing a Fellowship to K.W.F. (1980-1981).

(18) Backmann, W. E.; Struve, W. S. *Org. React.* **1942**, *1*, 38.
(19) Walling, C.; Lepley, A. R. *J. Am. Chem. Soc.* **1972**, *94*, 2007.
(20) Homeyer, A. H.; Whitmore, F. C.; Wallingford, V. H. *J. Am. Chem. Soc.* **1933**, *55*, 4209.

Syn and Anti Transition States in the Addition of Ammonia to Cyanoacetylene. Formation of a Stable Zwitterionic Intermediate†

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Recent interest in the theory of nucleophilic additions[1] prompts us to report calculations on the addition of ammonia to cyanoacetylene, a process which has a nonzero activation barrier and also gives stable zwitterionic intermediates, in contrast to calculated gas-phase additions of nucleophiles to carbonyls.[1]

Ab initio (4-31G) calculations on the addition of a model nucleophile, hydride, to acetylene,[2] give a single transition state in which the acetylene moiety is bent in an anti fashion. Since the barrier to inversion of a vinyl anion is sufficiently high (37 kcal/mol by 4-31G)[2] to preclude rapid inversion, protonation in solution will occur faster than inversion. Anti addition is predicted for nucleophilic additions to unactivated acetylenes,[2] and this is observed experimentally.[3] However, the additions of nucleophiles to activated acetylenes give variable stereochemical results.[3] In polar or proton-donating solvents, anti stereochemistry is frequently observed, while in nonpolar aprotic solvents, syn addition often occurs (Figure 1). Some examples of kinetically controlled stereochemistries (at 25 °C) are given in Table I.[4-7] This variable

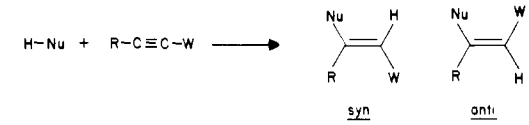

Figure 1. Definition of stereochemistries of nucleophilic additions to acetylenes.

syn and anti addition stereochemistry could arise from three possible mechanisms: (1) electron-withdrawing substituents could cause the formation of two separate transition states, resulting in formation of both syn and anti anionic or zwitterionic intermediates and syn and anti products; (2) a single stereochemistry of attack could be preferred, but syn and anti intermediates could equilibrate;[3,5] (3) linear vinyl intermediates could form,[3,6] with the product stereochemistry determined by the preferential site of protonation.[3]

We have found strong evidence for the first of these mechanisms by ab initio calculations[8] on the addition of a typical nucleophile, ammonia, to an activated acetylene, cyanoacetylene. Figure 2 and Tables II and III summarize the results of these calculations. Transition states were found with the STO-3G basis set and were identified by determining that each possessed only one negative force constant, which corresponds to the reaction coordinate. Single point calculations were then carried out on the stationary points on the surface by using the 4-31G basis set. Two distinct transition states are found, one corresponding to syn bending of the acetylene and the other to anti. As for acetylene, the anti bent transition state is preferred, a manifestation of the easier trans-bending mode of acetylenes.[2] When addition is accompanied, or followed, by rapid protonation, anti addition is preferred.

Two zwitterionic intermediates are shallow energy minima at the STO-3G level. The anti zwitterion is no longer predicted to be an intermediate at the 4-31G level, but we believe that this is an artifact of use of STO-3G geometries without reoptimization. The anti-bent zwitterion is higher in energy than the syn-bent zwitterion. Equilibration of these two zwitterions should lead to a greater percentage of the syn zwitterion and ultimately to syn addition product. These calculations, which are appropriate for the gas phase, indicate that there is no intramolecular mechanism of inversion but that dissociation and recombination should occur readily.

In solution, the various zwitterionic species should be highly stabilized with respect to the neutrals. A crude estimate of the influence of solvation on the relative energies of the various species calculated here was made from the calculated dipole moments and the Kirkwood equation.[9] The results for two solvents are given in Table III. Even with solvation estimates, calculated activation energies are too high, since values are of the order of 5-10 kcal/mol for such reactions in solution.[3] Anti addition is still favored, although less so in the nonpolar solvent than in the polar solvent. The stability of the zwitterions is greatly increased, and the barrier to inversion is now comparable to the barrier for reversion to reactants. Because of its smaller size, the anti zwitterion becomes slightly more stable than the syn in highly polar solvents, which may account for the greater proportion of anti product formed under these conditions.

The dipole moment changes calculated here are quite similar to those deduced for zwitterions formed in enol ether-tetracyanoethylene reactions on the basis of solvent polarity changes.[10] Similar solvent polarity rate effects have been measured for additions of secondary amines to acetylenic esters.[11]

† Dedicated to Professor Rolf Huisgen on the occasion of his 60th birthday.
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(1) Williams, I. H.; Spangler, D.; Femec, D. A.; Maggiora, G. M.; Schowen, R. L. *J. Am. Chem. Soc.* **1980**, *102*, 6619 and references therein.
(2) Strozier, R. W.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1979**, *101*, 1340. Dykstra, C. E.; Arduengo, J. E.; Fukunaga, T. *Ibid.* **1978**, *100*, 6007.
(3) Dickstein, J. I.; Miller, S. I. In "Chemistry of the Carbon-Carbon Triple Bond Part 2"; Patai, S., Ed.; Wiley: New York, 1978.
(4) Winterfeldt, E.; Krohn, W.; Preuss, H. *Chem. Ber.* **1966**, *99*, 2572.
(5) Herbig, K.; Huisgen, R.; Huber, H. *Chem. Ber.* **1966**, *99*, 2546.
(6) Huisgen, R.; Giese, B.; Huber, H. *Tetrahedron Lett.* **1967**, 1883.
(7) Truce, W. E.; Tichenor, G. J. W. *J. Org. Chem.* **1972**, *37*, 2391.
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(10) Steiner, G.; Huisgen, R. *J. Am. Chem. Soc.* **1973**, *95*, 5056.

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