Table III. Oxymercuration of 4-Vinylcyclohexene 7[a]

acid or salt/medium	sonication time, h	yield, %/selectivity[b]	entry
$Hg(OAc)_2$/50% aqueous THF	c	20–25/50	1
CH_3CO_2H/50% aqueous THF	0.5	23/50	2
$CH_3(CH_2)_8CO_2H$/ 50% aqueous THF[d]	4	47(40 isolated)/90	3
$Hg(OAc)_2$/0.3 M SDS	c	60/90	4
$CF_3(CF_2)_2CO_2H$/ 0.3 M SDS[e]	2	67/100	5

[a] Same procedure as in footnote a in Table II, replacing limonene by 4-vinylcyclohexene (0.108 g, 1 mmol). [b] By GLPC analysis with n-dodecane as an internal standard. Selectivity = [8]/[8] + monools + ethers + diols. [c] Commercial salt used under usual conditions (ref 2). [d] See corresponding footnote in Table II. [e] 0.257 g (1.2 mmol) of perfluorobutyric acid, 0.216 g (1 mmol) of mercuric oxide, and 0.108 g (1 mmol) of 4-vinylcyclohexene in 10 mL of distilled water containing 0.3 M SDS are sonicated until complete discoloration. The mixture is then worked up as in ref 11.

trasound-generated $Hg(OAc)_2$ (entries 1 and 2). The selectivity is improved by replacing acetic acid with n-decanoic acid (entry 3), and the product distribution is roughly the same as with mercuric acetate under micellar conditions (entry 4). It was of interest to try to combine both methods, i.e. in situ sonochemical generation of the salt and micellar conditions. Thus, perfluorobutyric acid, mercuric oxide, and 4-vinylcyclohexene were sonicated in a 0.3 M aqueous solution of sodium dodecyl sulfate (entry 5). Discoloration of the mixture, which indicates the consumption of the mercuric oxide, occurred after 2 h of sonication. Only monool 8 was obtained along with a small amount of starting material indicating a near 100% selectivity, with a 67% yield (VPC). This result can be put in parallel with that obtained in the same micellar medium without sonication, a "90% purity of compound 8"[5] (unfortunately without yield specification).

This work clearly illustrates the importance of the nature of the counteranion in selective oxymercuration with mercuric salts. It also demonstrates that the preliminary preparation of noncommercial or expensive mercuric salts is not necessary, with ultrasonic activation allowing the easy in situ generation of any salt directly from the acid. Further applications and extensions of this new procedure are presently under investigation.

Acknowledgment. Financial support from the CNRS (UA 332) is gratefully acknowledged. We thank Dr. A. E. Greene for useful discussions and suggestions.

Reactions of Alkylthio-Substituted Chromium Carbene Complexes with Alkynes: Application to Synthesis of Visnagan

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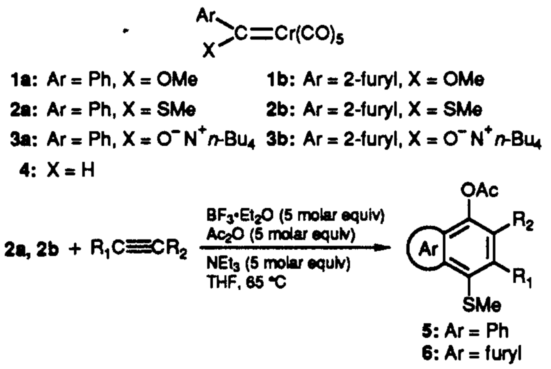
Summary: We report the first examples in which the reaction of the (methylthio)phenyl- or (methylthio)furylcarbene complexes with various alkynes in the presence of 5 molar equiv each of $BF_3{\cdot}Et_2O$, Ac_2O, and Et_3N in THF afford the acetate derivatives of 1,4-dihydrothionaphthoquinone and 4,7-dihydrothiobenzofuran.

Scheme I



Sir: Reaction between pentacarbonyl(phenylmethoxycarbene)chromium (**1a**) and alkynes is a direct method for preparation of substituted 1,4-dihydronaphthoquinones[1] and has been applied to the synthesis of natural products.[2] The process is efficient only with methoxy-substituted carbene ligands and therefore is applied only in the synthesis of 1,4-benzoquinone derivatives. Since the methoxy group of **1a** can be readily replaced by nitrogen,[3] sulfur,[4] and carbon nucleophiles,[5] a range of substituted carbene complexes is readily available. With amino-substituted arylcarbene ligands, a general formation of indenes is observed.[6] The carbene–alkyne reaction of the phenyl(alkylthio)carbene complex **2a** to afford 1,4-dihydrothionaphthoquinones has not been described. Such a process would have the advantage in that the alkylthio group can

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[2] (a) Dötz, K. H. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 644. (b) Dotz, K. H. *Pure Appl. Chem.* **1983**, *55*, 1689. (c) Dötz, K. H.; Popall, M. *Tetrahedron* **1985**, *41*, 5797. (d) Hegedus, L. S. *Tetrahedron* **1985**, *41*, 5833. (e) Semmelhack, M. F.; Bozell, J. J.; Keller, L.; Sato, T.; Spiess, E. J.; Wulff, W. D.; Zask, A. *Tetrahedron* **1985**, *41*, 5803. (f) Wulff, W. D.; Tang, P.-C.; Chan, K. S.; McCallum, J. S.; Yang, D. C.; Gilbertson, S. R. *Tetrahedron* **1985**, *41*, 5813. (g) Yamanshita, A. *J. Am. Chem. Soc.* **1985**, *107*, 5823. (h) Yamashita, A.; Scahill, T. A.; Toy, A. *J. Org. Chem.* **1989** in press.

[3] Fischer, E. O.; Kollmeier, H. J. *Chem. Ber.* **1971**, *104*, 1339

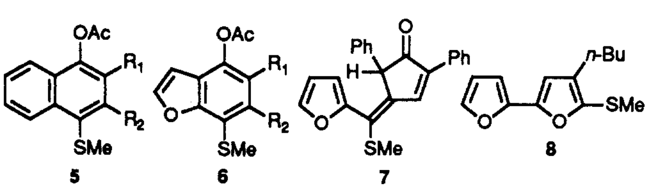
[4] (a) Fischer, E. O.; Leupold, M.; Krieter, C. G.; Muller, J. *Chem. Ber.* **1972**, *105*, 150. (b) Fischer, E. O.; Selmayr, T.; Kreissel, F. R. *Chem. Ber.* **1977**, *110*, 2947.

[5] Casey, C. P.; Burkhardt, T. J. *J. Am. Chem. Soc.* **1973**, *95*, 5833.

[6] (a) Yamashita, A. *Tetrahedron Lett.* **1986**, *27*, 5915. (b) Yamashita, A.; Toy, A.; Watt, W.; Muchmore, C. R. *Tetrahedron Lett.* **1988**, *29*, 3403. Also, the nitrogen-substituted carbene complexes have been used in the synthesis of β-lactams (ref 6c) and aminofurans (ref 6d,e). (c) Hegedeus, L. S.; McGuire, M. A.; Schultze, L. M.; Yijum, C.; Anderson, O. P. *J. Am. Chem. Soc.* **1984**, *106*, 2680. (d) Wulff, W. D.; Gilbertson, S. R.; Springer, J. P. *J. Am. Chem. Soc.* **1986**, *108*, 520. (e) Semmelhack, M. F.; Park, J. *Organometallics* **1986**, *5*, 2550.

0022-3263/89/1954-4481$01.50/0

Table I. Reaction of 2a and 2b with Alkynes



entry	complex	R_1	R_2	products (% yield)[a]
1	2a	Ph	CO_2Et	**5a** (43)
2	2a	Et	Et	**5b** (13)
3	2a	Ph	Me	**5c** (9)
4	2a	Ph	H	**5d** (42)
5	2a	*n*-Bu	H	**5e** (45)
6	2b	Ph	CO_2Et	**6a** (52)
7	2b	Et	Et	**6b** (41)
8	2b	Ph	Me	**6c** (25)
9	2b	Ph	H	**6d** (32) + **7** (32)
10	2b	*n*-Bu	H	**6e** (28) + **8** (48)
11	2b	*t*-Bu	CO_2Me	**6f** (55)
12	2b	Ph	Ph	**6g** (23)

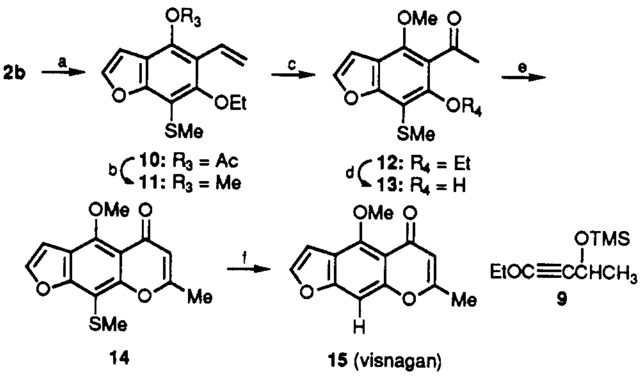
[a] Based on weighed samples purified by flash chromatography.

be readily replaced by a hydrogen under reductive conditions. In this paper we report the first examples of the reaction of the (methylthio)phenyl- or (methylthio)furylcarene complexes (**2a**, **2b**; Scheme I) with alkynes to afford the acetate derivatives of 1,4-dihydronaphthoquinone (**5**) and benzofuran (**6**) in good yield. Thus, the structures **5** and **6** could serve as surrogates for the structures that might result from the reactions of the hydrogen-substituted arylcarbene complex (**4**)[7] with alkynes. Since **4** is not known to cyclize with alkynes, the reaction of **2a** and **2b** to form **5** and **6** is a useful synthetic equivalent. To illustrate the synthetic utility of this type of reaction, we describe the synthesis of visnagen (**15**),[8] a natural furochromone isolated from *Ammi visnaga*, from **2b** and **9**.

The complex **2a** was prepared in two steps (Scheme I) according to the procedure of Fischer.[4] The reaction of phenyllithium and chromium hexacarbonyl ($Cr(CO)_6$) [ether, 0 °C], followed by treatment with tetra-*n*-butylammonium bromide in H_2O, formed the isolable ammonium salt **3a** (90%). Acetylation of the salt [AcCl, CH_2Cl_2, −40 °C] and sequential treatment with methanethiol produced **2a** (purple oil, 85%).[9] Complex **2b** (purple low-melting solid) was prepared in 80% yield in a similar fashion. Reaction of 2-lithiofuran with $Cr(CO)_6$ [THF, −30 °C], followed by treatment with tetrabutylammonium bromide, produced the salt (**3b**, 81%), which was converted to **2b** (74%) by acetylation and treatment with MeSH. Altneratively, **2a** was also formed by direct treatment of **1** with excess thiol.[4] However, treatment of **1b** with excess thiol resulted in predominant nucleophilic addition of the thiol to the furan ring. Methylthio complexes **2a** and **2b** are thermally unstable compared with methoxy complexes **1a** and **1b** and slowly decompose even when they are stored at −10 °C under argon. Upon being heated in THF at 65 °C, **2a** and **2b** decompose within 1 h.

Complexes **2a** and **2b** reacted with alkynes only in the presence of 5 mol excess each of a Lewis acid, Ac_2O, and Et_3N [THF, 65 °C, argon]. $BF_3{\cdot}Et_2O$ was found to be superior to $MgCl_2$, $MgBr_2{\cdot}Et_2O$, $AlCl_3$, BCl_3, $TiCl_4$, and Ti(*i*-PrO)$_4$.[10] Without the Lewis acid, the yield of cycloaddition dropped while the complex decomposes under these conditions.[11] A series of alkynes was chosen to test the generality and selectivity and the results are shown in Table I.[12] Alkynes bearing an electron-withdrawing group, such as ethyl phenylpropiolate and methyl pentynoate, gave good yields of benzannulation (entries 1, 6, and 11). Alkynes bearing bulky substituents were relatively less reactive (entry 3). Terminal alkynes worked well for cycloaddition. The reaction of **2b** with phenylacetylene (entry 9) produced **6d** (32%) and diphenylcyclopentenone **7**[13] (32%), but **2a** reacted with the same alkyne to form only **5d**[14] (42%, entry 4). Reaction of 1-hexyne with **2a** produced only the naphthoquinone (**5e**, 45%, entry 5), while the reaction with **2b** gave bifuran **8**[15] (48%) and a

Scheme II[a]



[a] (a) **9**, $BF_3{\cdot}Et_2O$, Ac_2O, NEt_3, THF, 65 °C, 96 h, 33%; (b) NaH, MeI, THF, 0–25 °C, 86%; (c) O_2 gas, $PdCl_2$, CuCl, DMF, H_2O, 25°C, 75%; (d) $BF_3{\cdot}Et_2O$, CH_2Cl_2, 0–25 °C, 70%; (e) EtOAc, NaH, THF, reflux, 5 h; then, 1 N HCl, MeOH, 84%; (f) Raney Ni, absolute EtOH, 60%.

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(8) Spath, E.; Gruber, W. *Chem. Ber.* **1938**, *71*, 106.

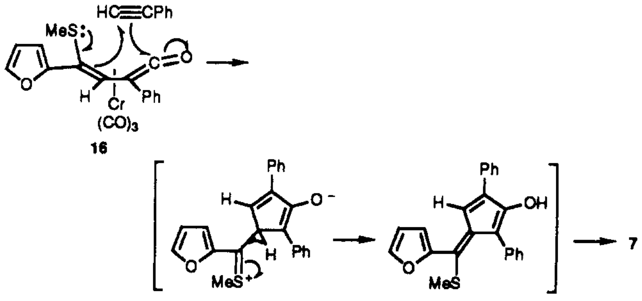
(9) (a) Fischer, E. O.; Maasbol, A. *Chem. Ber.* **1967**, *100*, 2445. (b) Connor, J. A.; Jones, E. M. *J. Chem. Soc. A* **1971**, 3368. (c) Connor, J. A.; Jones, E. M. *J. Chem. Soc. Chem. Commun.* **1971**, 570. (d) Semmelhack, M. F.; Bozell, J. J. *Tetrahedron Lett.* **1982**, *23*, 2931.

(10) Reaction of **2a** with ethyl phenylpropiolate as a representative procedure: A mixture of **2a** (2.0 g, 6.1 mmol), ethylphenylpropiolate (2.1 g, 12.2 mmol), $BF_3{\cdot}Et_2O$ (3.7 mL, 30.5 mmol), Ac_2O (2.9 mL, 30.5 mmol), and Et_3N (4.2 mL, 30.5 mmol) in THF (200 mL) was heated at 65 °C (bath temperature) for 72–90 h under argon. The mixture was cooled and the solvent was removed by rotary evaporation. The residue was dissolved in ether (500 mL), washed with aqueous NaCl solution (3 × 100 g), dried ($MgSO_4$), filtered, and concentrated. Flash column chromatography (SiO_2; *n*-hexane/ether, 9:1) provided 1.0 g (43%) of **5a** as white needles, mp 97.5–98.0 °C.

(11) Without Ac_2O and/or Et_3N, complexes **2a** and **2b** decompose under these conditions.

(12) Regioselectivity of carbene–alkyne cycloaddition reaction was determined on the basis of substantial literature procedent and confirmed by the conversion of **10** into visnagan (**15**). Yamashita, A.; Toy, A. *Tetrahedron Lett.* **1986**, 3471 and references therein.

(13) The structure of **7** was verified by X-ray analysis.[21] The cyclopentenone (**7**) may be formed via a [4 + 2] cycloaddition between phenylacetylene and the vinylketene intermediate (**16**).



(14) Buggle, K.; O'Sullivan, D. *J. Chem. Soc., Perkin Trans. 1* **1975**, 572.

(15) Bifuran formation was described in our earlier work; Yamashita, A.; Toy, A.; Watt, W.; Muchmore, C. R. *Tetrahedron Lett.* **1988**, *29*, 3403. The mechanism of furan ring formation from the reaction of an amino-substituted iron carbene complex with an alkyne was reported; see ref 6e.

benzofuran acetate **6e** (28%) (entry 10). Substrate **2b** provided better generality for cyclization than **2a**, presumably due to a difference in thermal stability between the two complexes. For example, the reaction of **2b** with methyl 4,4-dimethylpentynoate (entry 11) and diphenylacetylene (entry 12) resulted in efficient benzofuran formation, while **2a** decomposed under identical conditions with the same alkynes.

Considering our earlier work on the carbene–alkyne cycloaddition with in situ protection,[2g,16] the role of $BF_3 \cdot Et_2O$, Ac_2O, and Et_3N is apparently more than that of an acetylation reagent. Presumably, it also promotes the cycloaddition. The Lewis acid would strongly coordinate to the very basic alkylthio group, which could increase the electrophilicity of the metal–carbene carbon bond, favoring CO dissociation and then alkyne coordination.[17] The synthetic utility of this reaction is illustrated is illustrated in Scheme II by formation of the key intermediate (**10**) in the synthesis of **15**. The reaction of **2b** with an alkoxyalkyne **9**[2g] under the conditions described above provided the benzofuran acetate **10** in 33% yield. During this process, the (trimethylsilyl)oxy group was eliminated, producing an olefin. Direct conversion of the acetate to the methyl ether was effected with NaH and methyl iodide in THF (**11**, 75%).[18] The Wacker procedure [$PdCl_2$, Cu_2Cl_2, DMF, H_2O, O_2 gas, 25 °C][19] converted the olefin to the ketone **12** in 75% yield. Selective cleavage of the ethyl ether [$BF_3 \cdot Et_2O$, CH_2Cl_2, 0 °C to 25 °C; **13**, 70%],[2g] followed by a Claisen-type condensation [EtOAc, NaH, THF, reflux, 5 h] and acid treatment [1 N, HCl, MeOH, 25 °C],[2g,8] produced the furochromane **14** in 56% overall yield. Treatment of **14** with Raney Ni [absolute EtOH] replaced the methylthio group with hydrogen, generating visnagan (**15**)[20] in 60% yield.

In summary, we have demonstrated the first use of [(alkylthio)arylcarbene]chromium complexes for the alkynecarbene cycloaddition to form the 1,4-dihydrothioquinones. The application of the process to the synthesis of visnagan illustrates the potential utility of the reaction of sulfur-substituted carbene complexes with alkynes in organic synthesis.

Supplementary Material Available: Characterization data (^1H NMR, IR, mass spectra, and combustion analyses) on all new compounds and X-ray crystallographic data for compound **7** (12 pages). Ordering information is given on any current masthead page.

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[16] Yamashita, A.; Scahill, T. A.; Toy, A. *Tetrahedron Lett.* **1985**, *26*, 2969.

[17] (a) Alternatively, the Lewis acid may coordinate to CO ligands to remove electron density from the metal–carbene ligand center, favoring CO dissociation. This is the case in the literature where there are no strong Lewis bases available to the acid. (i) Nolan, S. P.; de la Vega, R. L.; Hoff, C. D. *J. Am. Chem. Soc.* **1986**, *108*, 7852. (ii) Waymouth, R. M.; Grubbs, R. H. *Organometallics* **1988**, *7*, 1631. Increasing electron density on the metal center could intercept carbon monoxide insertion: Yamashita, A. *Tetrahedron Lett.* **1986**, *27*, 5915. (b) Treatment of pentacarbonyl(methyl- or phenylmethoxycarbene)chromium (or molybdenum, tungsten) with boron trihalides in alkanes is known to afford thermolabile trans halogen methyl- or phenylcarbyne tetracarbonyl complexes of chromium (or Mo, W). (i) Fischer, E. O.; Kreis, G.; Kreiter, C. G.; Muller, J.; Huttner, G.; Lorenz, H. *Angew. Chem. Int. Ed. Engl.* **1973**, *12*, 564. (ii) Fischer, E. O.; Kreis, G.; Kreissl, F. R.; Kalbfuus, W.; Winkler, E. *J. Organomet. Chem.* **1974**, *65*, C53–C56. However, the carbyne formation from the methylthio-substituted carbene complex with Lewis acid is not known. Since the products from the reaction of **2a** and **2b** with alkynes did not loose the methylthio group, the carbyne formation from **2a**,**b** with Lewis acid can be eliminated. The role of the Lewis acid, combined with Ac_2O and Et_2N seems to be coordination to the basic sulfur and/or the weakly basic CO groups.

[18] Yamashita, A.; Toy, A. *Synth. Commun.* **1989**, *19*, 755.

[19] Tsuji, J.; Nagashima, H.; Sato, K. *Tetrahedron Lett.* **1982**, *23*, 3085.

[20] MP 145 °C (undepressed on admixture with a natural specimen, mp 140–142 °C). The physical behavior of the product was the same as that of the authentic sample (purchased from Aldrich Co.).

[21] Satisfactory spectral data (high resolution mass, IR and ^1H NMR) were obtained for all new compounds, **2a**, **3a**, **3b**, **5a–e**, **6a–f**, **7**, **8**, **10**, **11**, **12**, **13**, **14**, **15**, and **16**. Combustion analyses were obtained for **5a–e**, **6a–f**, **7**, **8**, **10**, **11**, **12**, **13**, **14**, and **15**. These data are recorded as supplementary material. The X-ray crystallographic data for compound **7** were submitted to *Acta Crystallographr.* for publication.

Stereoselective Formation of Tetrahydrofuran Rings via Intramolecular Alkoxycarbonylation of Hydroxyalkenes

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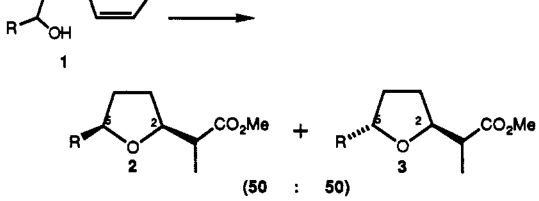
Summary: Starting from 5-hydroxy-1-pentenes, palladium-catalyzed intramolecular alkoxycarbonylation produces 2,5-disubstituted tetrahydrofurans in good yield. In the simplest cases, mixtures of cis- and trans-2,5-substitution are obtained. With a methyl group at C-4, the mixture is 1:1 or 2:1 depending on the relative configuration of the Me. With a methyl or phenyl group at C-3, the selectivity is much higher, producing either cis-2,5- or trans-2,5-disubstituted furans in >9:1 selectivity. In the best case, with a 3-phenyl derivative, the selectivity is >99%. The formation of cis or trans isomers depends on the configuration at C-3 in a predictible way.

Sir: Methods of preparation of substituted oxygen heterocycles have attracted attention since furan and pyran rings appear frequently in polyether antibiotics and other biologically active natural products.[1] Tetrahydrofurans bearing 2,5-substituents have been synthesized stereoselectively in some cases, but there are few completely satisfactory general methods.[1,2] We have been attracted to a palladium-catalyzed cyclization process for hydroxyalkenes with concomitant chain extension with CO (alkoxycarbonylation).[3,4] The process (eq 1) is efficient for



(eq 1)

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[1] For a review, see: Boivin, T. L. *Tetrahedron* **1987**, *43*, 3309.

[2] For a recent successful example and leading references, see: Mulholland, R. L., Jr.; Chamberlin, A. R. *J. Org. Chem.* **1988**, *53*, 1082.

[3] For a review of palladium-promoted nucleophile addition to alkenes, including oxygen nucleophiles, see: Hegedus, L. S. *Tetrahedron* **1984**, *40*, 2415.