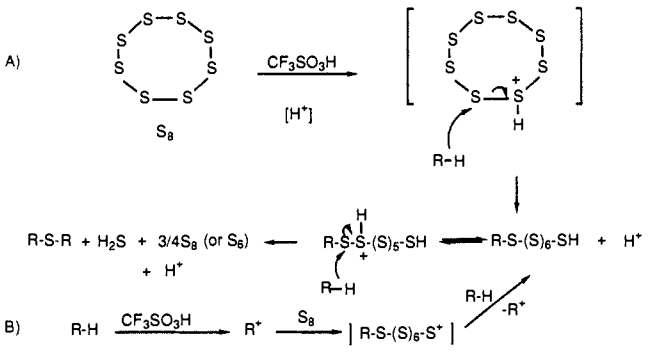
**Scheme I**



Isobutane under similar reaction conditions at 125 °C and a 10-h reaction time gave 33% diisobutyl sulfide. Even though the

$$2\ (CH_3)_3CH \xrightarrow[CF_3SO_3H]{S_8} [(CH_3)_2CHCH_2]_2S + H_2S$$

tertiary C–H $\sigma$-bond in isobutane is more electron rich than the primary methyl C–H $\sigma$-bonds, only the latter undergo reaction due to their steric accessibility. Alternatively, if the reaction proceeded by protolytic ionization of the alkane (vide infra), the secondary butyl cation formed would react with $S_8$. Any tertiary butyl cation formed would be too hindered to react with $S_8$.

Propane when reacted at 125 °C under similar conditions gave diisopropyl sulfide in 29% yield after a 10-h reaction time with a trace of *n*-propyl isopropyl sulfide. However, on prolonged

$$2\ CH_3CH_2CH_3 \xrightarrow[CF_3SO_3H]{S_8} [(CH_3)_2CH]_2S + H_2S$$

reaction at 150 °C for 62 h, a 1.1:1 mixture of diisopropyl sulfide and *n*-propyl isopropyl sulfide is obtained in 47% isolated yield.[9]

Other alkanes such as cyclohexane, cyclooctane, *n*-butane, and norbornane (bicyclo[2.2.1]heptane) are also reactive under the reaction conditions. However, they gave more complex mixtures of sulfides along with other byproducts. In the case of cyclooctane, the major products are aromatics. The norbornane skeleton underwent cleavage under the reaction conditions. In the case of methane and ethane, no reaction was observed under the present reaction conditions.

The suggested mechanism of the new sulfuration reaction of alkanes involves electrophilic sulfuration as depicted in Scheme I. The reaction could involve intermediate formation of thiols followed by bimolecular condensation to the sulfides.[8] Either protolytic activation of sulfur (path A) or protolytic ionization of the alkane (cycloalkane) resulting in a carbocation which alkylates sulfur (path B) can account for the observed results. Observation of isomerized products indicates intermediate formation of carbocations either by protolysis of alkanes by the superacid or reversible ionization of the thiols or sulfide products.

The observed results are in accordance with the proposed mechanism. Hydrogen sulfide is a byproduct of the reaction. Some elemental sulfur is leftover after the reaction, and trifluoromethanesulfonic acid acts as a protic catalyst. In its absence, no reaction takes place under the reaction conditions. As the acid is also used as the reaction medium, turnover numbers cannot be determined, but no loss of acid was observed in the reactions. Moreover, trifluoromethanesulfonic acid is only a mildly oxidizing superacid system, and no byproducts such as sulfoxides or sulfones were observed. Neither was any dehydrogenation of alkanes (cycloalkanes) observed under the reaction conditions with elemental sulfur alone. In the reactions no di- or polysulfuration products were obtained.

Lewis acid catalyzed sulfur insertion into aromatic compounds was well-known previously.[10] Even $AlCl_3$-catalyzed reaction of alkanes with sulfur was reported[11] but gave only complex mixtures of products. The presently described superacid–catalyzed sulfuration is the first selective, preparatively useful sulfuration reaction of saturated hydrocarbons. Further studies are underway to exploit the utility of this potentially significant new reaction.

**Acknowledgment.** Support of our work by the National Science Foundation is gratefully acknowledged.

(9) Trifluoromethanesulfonic acid was found not to isomerize diisopropyl sulfide.

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## The Chemistry of a Quinone Methide Proposed To Be an Intermediate in Neolignan Biosynthesis

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Neolignans comprise a class of pharmacologically active secondary plant metabolites that are formally derived from the oxidative coupling of two propenylphenols.[1,2] Gottlieb and coworkers have studied many of these compounds in detail and propose that quinone methide **1** is a common branch point in the biosynthesis of three structurally different types of neolignans (Scheme I).[3] This suggestion is quite intriguing, since it requires the quinone methide to react selectively with one of three different internal nucleophiles: (a) C-alkylation of the $\beta$-diketone to afford the bicyclo[3.2.1]octene skeleton found in *epi*-guianin **2**, (b) O-alkylation of the $\beta$-diketone to afford the hydrobenzofuran skeleton found in *epi*-burchellin **3**, or (c) attack of the alkene followed by capture of the resulting cation by the $\beta$-diketone oxygen to afford the spiro[5.5]undecane skeleton found in futoenone **4**.[3,4] The proposed bifurcation of quinone methide **1** might be directed enzymatically or chemically. Pathways a and b both involve the $\beta$-diketone and can be expected to be facile reactions; however, pathway c requires a relatively poor nucleophile, the alkene, to participate in a cyclization in the presence of the more nucleophilic $\beta$-diketone. In spite of the extensive isolation and chemical investigations by Gottlieb[3,5] and synthesis work by Büchi[6] and others,[2,4,7] the chemistry of the proposed quinone methide intermediate has not been explored. Our previous work on the

(1) For leading references on the pharmacological activity of neolignans see: (a) Gottlieb, O. R. In *New Natural Products and Plant Drugs with Pharmacological, Biological or Therapeutic Activity*, Proceedings of the First International Congress, 1976; Wagner, H., Wolff, P. M., Eds.; Springer Verlag: Berlin, 1977; p 227. (b) Gottlieb, O. R. *Quim. Nova* **1984**, *7*, 250.

(2) For current reviews on the isolation, chemistry, and synthesis of lignans and neolignans see: (a) Gottlieb, O. R. *Fortsch. Chem. Org. Naturst.* **1978**, *35*, 1. (b) Gottlieb, O. R. *Rev. Latinoamer. Quim.* **1974**, *5*, 1. (c) Gottlieb, O. R. *Phytochemistry* **1972**, *11*, 1537. (d) Ward, R. S. *Chem. Soc. Rev.* **1982**, *11*, 75. (e) Whiting, D. A. *Nat. Prod. Rep.* **1985**, *2*, 191. (f) Whiting, D. A. *Nat. Prod. Rep.* **1987**, *4*, 499.

(3) (a) Gottlieb, O. R.; De Alvarenga, M. A.; Castro, O. C.; Giesbrecht, A. M. *Phytochemistry* **1977**, *16*, 1801. (b) Barbosa-Filho, J. M.; Yoshida, M.; Gottlieb, O. R. *An. Acad. Bras. Ci.* **1987**, *59*, 335. See also ref 2a and references cited therein.

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(5) For leading references see: (a) Gottlieb, O. R.; Da Silva, M. L.; Ferreira, Z. S. *Phytochemistry* **1975**, *14*, 1825. (b) Gottlieb, O. R.; De Alvarenga, M. A.; Brocksom, U.; Yoshida, M. *J. Chem. Soc., Chem. Commun.* **1978**, 831. See also ref 2a.

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(7) For recent examples and leading references see: (a) Shizuri, Y.; Yamamura, S. *Tetrahedron Lett.* **1983**, *24*, 5011. (b) Thomas, E. J.; Mortlock, S. V.; Seckington, J. K. *J. Chem. Soc., Perkin Trans. 1* **1988**, 2305. (c) Engler, T. A.; Combrink, K. D.; Ray, J. E. *J. Am. Chem. Soc.* **1988**, *110*, 7931.

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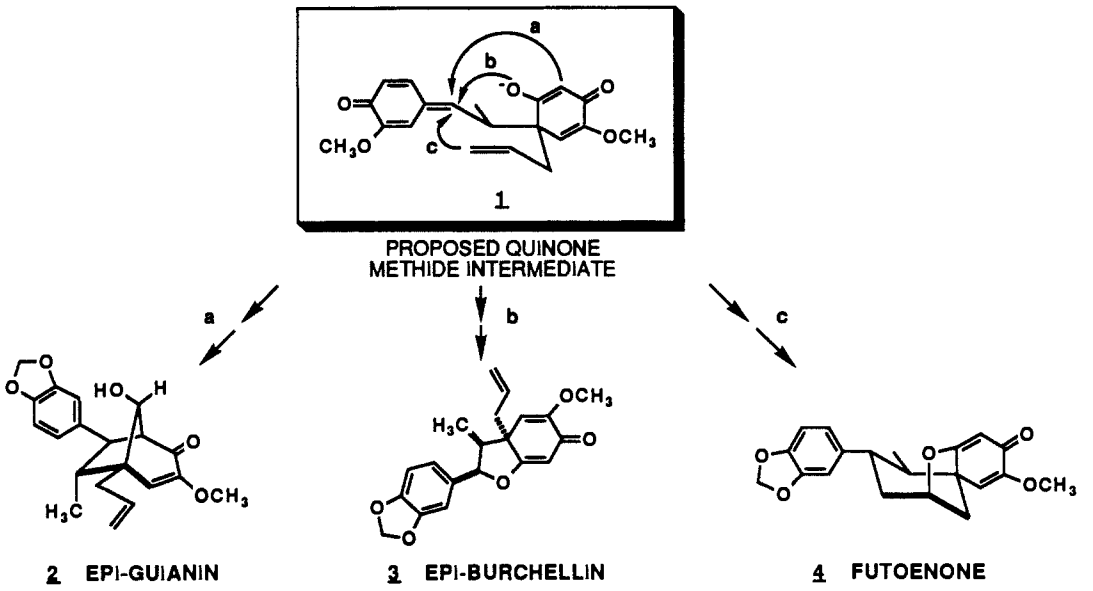
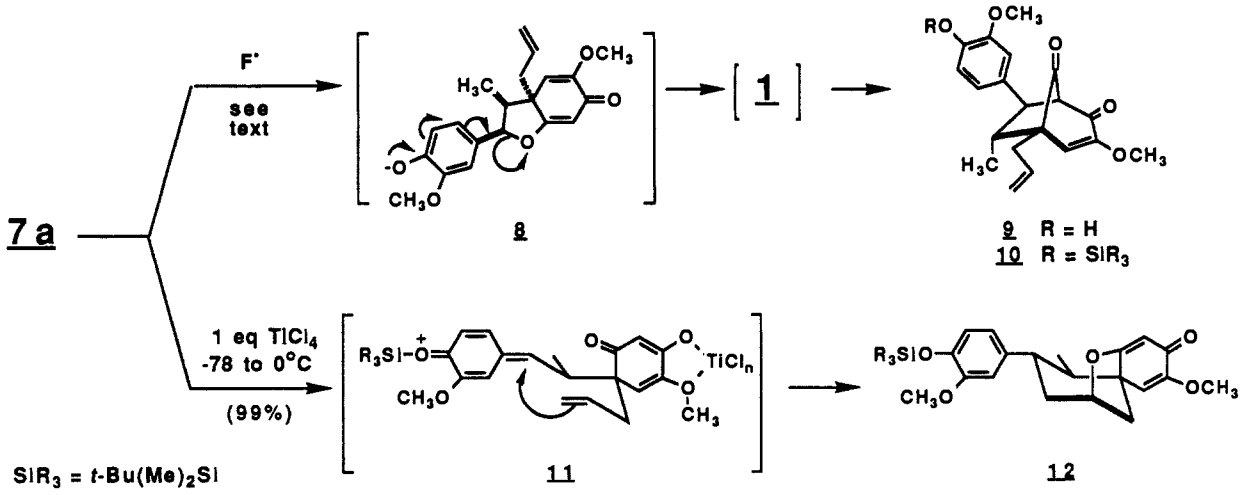
**Scheme I**

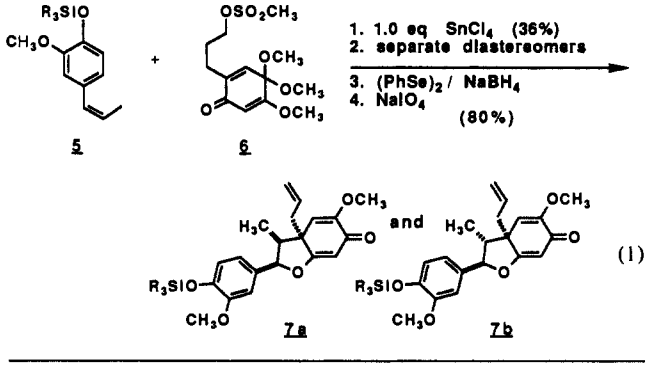



**Scheme II**




chemistry of quinone methides and benzyl cations[8] led us to believe the origin of the selectivity for a particular cyclization mode is chemical, rather than enzymatic, in nature. We wish to report the initial results of an investigation examining the chemistry of quinone methide **1** and its role in the three competitive cyclization pathways.

A readily available precursor to quinone methide **1** is the silyl-protected *epi*-burchellin derivative **7a**. Benzofuranones **7a** and **7b** were prepared in a straightforward manner using modifications of chemistry developed in the Büchi laboratory (eq 1).[6,9] It was




(1)

hoped that treatment of **7a** with fluoride ion would cleave the *tert*-butyldimethylsilyl group to afford phenoxide **8** (Scheme II). This anion, or the corresponding silicon-ate complex, should then fragment the furan ring of the hydrobenzofuran to afford quinone methide β-diketone enolate **1**.

Treatment of **7a** with several different fluoride ion sources under a variety of conditions afforded high yields (>89%) of phenol **9** with the bicyclo[3.2.1]octene skeleton.[9,10] No products with the spiro[5.5]undecane skeleton could be detected in the crude reaction mixtures. This transformation occurs in the presence of fluoride ion with no detectable intermediates at temperatures as low as −95 °C,[11] providing convincing evidence that loss of the silyl group drives the conversion of **7a** to **9**.[10]

A possible, but highly unlikely, mechanism for the **7a** to **9** conversion is an anionic (phenol anion) accelerated [1,3]-sigma-

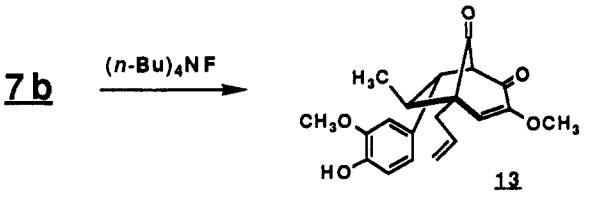
(8) (a) Angle, S. R.; Turnbull, K. D. *J. Am. Chem. Soc.* **1989**, *111*, 1136. (b) Angle, S. R.; Louie, M. S.; Mattson, H. L.; Yang, W. *Tetrahedron Lett.* **1989**, *30*, 1193. (c) Angle, S. R.; Louie, M. S. *Tetrahedron Lett.* **1989**, *30*, 5741.

(9) All new compounds showed satisfactory 300-MHz $^1$H NMR, $^{13}$C NMR, IR, UV, MS, and HRMS or elemental analysis. See supplementary information for complete spectral details and NOE data used for stereochemical assignments.

(10) Conditions include the following: ($n$-Bu)$_4$NF, KF, and HF in solvents such as, THF, $Ac_2O$, $CH_2Cl_2$, and $CH_3CN$, at temperatures from −95 to +80 °C. Reactions in $Ac_2O$ afforded phenol-acylated hydrobenzofuran, providing additional evidence that silyl cleavage occurs prior to the formation of **9**. In addition, acidic (AcOH, $CF_3CO_2H$), basic (NaOH), and thermal conditions (50 to 120 °C) failed to afford any products with the spiro[5.5]undecane skeleton.

(11) Following the reaction by UV at ambient temperature and $^1$H NMR and FT-IR at low temperature (−70 and −95 °C, respectively) failed to provide evidence for any intermediates in the **7** to **9** transformation.

tropic rearrangement. This pathway is expected to give the observed inversion of configuration. To explore this possibility, **7b** was treated with fluoride ion [1.0 equiv $(n\text{-Bu})_4NF$, THF, 25 °C] to afford **13** (mp 145.0–145.5 °C) in 78% yield with *retention* of configuration (eq 2). This result argues against a sigmatropic pathway.




(2)

The conversion of **7a** to **9** must involve the proposed biosynthetic intermediate, quinone methide β-diketone enolate **1**, which is short-lived and present in steady-state concentrations too low to be observed spectroscopically.

With the development of a selective route to the bicyclo[3.2.1]octene skeleton via the quinone methide, we sought conditions to divert the cyclization toward formation of the spiro[5.5]undecane skeleton. If the alkene is to participate in the cyclization, the nucleophilicity of the β-diketone needs to be reduced and the electrophilicity of the quinone methide increased. Accordingly, **7a** was treated with $TiCl_4$ (1 equiv, −78 °C, $CH_2Cl_2$) to afford a 99% isolated yield of *tert*-butyldimethylsilyl ether **12** possessing the spiro[5.5]undecane skeleton (Scheme II).[9] Since the silyl group is retained, the intermediate is not the quinone methide; rather, it must be benzyl cation **11**. Thus, the complete diversion of the reaction pathway toward spiro[5.5]undecane **12** can be attributed to two reinforcing factors: (1) the benzyl cation provides a highly electrophilic intermediate for reaction with the terminal alkene, and (2) complexation of the β-diketone with Ti(IV) decreases its nucleophilicity.

To probe the possible formation of the bicyclo[3.2.1]octene in the Lewis acid mediated reaction, *tert*-butyldimethylsilyl ether **10** was treated with $TiCl_4$ (1.8 equiv, −78 to 25 °C, 1 h, $CD_2Cl_2$) to afford a 98% yield of spiro[5.5]undecane **12**. Thus, bicyclo[3.2.1]octene **10** is a possible kinetic product in the **7a** to **12** transformation, which reversibly opens to benzyl cation **11** and ultimately affords **12** as the thermodynamic product.[12]

We have provided circumstantial chemical evidence for the intermediacy of quinone methide **1** in the formation of bicyclo[3.2.1]octene **9**. When a benzyl cation initiated the cyclization *and* the β-diketone was complexed to a Lewis acid, the cyclization was diverted toward the exclusive formation of spiro[5.5]undecane **12**. Certainly, nature might select a particular cyclization mode in a similar manner. A protonated or alkylated quinone methide/benzyl cation with the β-diketone complexed to a metal could afford futoenone, and the free quinone methide could afford the bicyclo[3.2.1]octene skeleton. Our results support Gottlieb's assertion that quinone methide **1** might serve as a precursor to neolignans with several different skeletons. Efforts to isolate quinone methide **1** are currently in progress.

**Acknowledgment.** We thank Dr. Dan Borchardt for assistance with the UV and low-temperature IR and NMR experiments and Professor T. H. Morton for helpful discussions. We gratefully acknowledge the National Institutes of Health (GM 39354) and the UCR Chancellor's Patent Fund (to K.D.T.) for financial support.

**Supplementary Material Available:** Full spectral data, including NOE data used for stereochemical assignments, for **7a**, **7b**, **9**, **12**, and **13** (4 pages). Ordering information is given on any current masthead page.

(12) In an attempt to study the protonated quinone methide/benzyl cation under identical conditions, phenol **9** was treated with $TiCl_4$ (1 or 2 equiv, −78 to 25 °C, 1 h, $CH_2Cl_2$) but afforded only unreacted starting material. The failure of this isomerization may be due to the complexation of Ti(IV) with the free phenol in **9**, thereby inhibiting opening of the bicyclo[3.2.1]octene.

## Benzoquinone–Olefin Exciplexes: The Observation and Chemistry of the *p*-Benzoquinone–Tetraphenylallene Exciplex[1]

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The Paterno–Büchi reaction has traditionally been thought to proceed through a preoxetane biradical (**1** in Scheme I).[2] It has become apparent that a preoxetane biradical alone is insufficient to account for the photochemical behavior of carbonyl–olefin systems.[3] These photoadditions may involve charge-transfer (CT) exciplexes (**2**) as well as preoxetane biradicals. While preoxetane biradicals[4a–c] and triplet exciplexes,[4d] including chloranil–arene exciplexes,[4e,f] have been observed by transient spectroscopy, triplet carbonyl–olefin exciplexes have yet to be observed directly. In this account, we report the direct observation of a *p*-benzoquinone–olefin exciplex and the characterization of its chemical behavior.

Excitation of *p*-benzoquinone (PBQ) with 355- or 532-nm light[5a] in the presence of various olefins in $CCl_4$[5b] produces transients at 400–405 nm which decay as single exponentials in all cases studied (Table I and Figure 1A). While these transients exhibit very similar spectroscopic properties, their lifetimes vary over an appreciable range, and the allene transients are quenched by

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