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Photochemistry of 1,*n*-Dibenzyloxy-9,10-anthraquinones

Saurav J. Sarma and Paul B. Jones*

Department of Chemistry, Wake Forest University, Winston-Salem, North Carolina 27109

jonespb@wfu.edu

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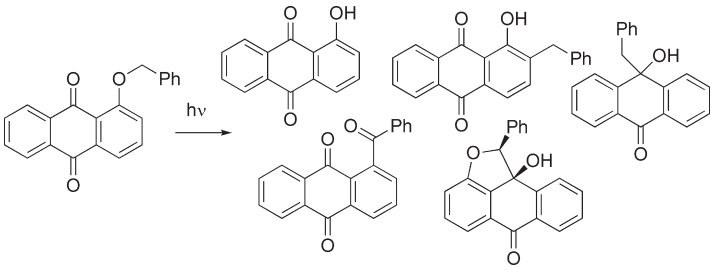

The photochemistry of a series of 9,10-anthraquinones with multiple benzyloxy substituents was investigated. In polar solvent, the expected Blankespoor oxidative cleavage reaction is the major reaction pathway, but in most cases, several minor products were observed. In nonpolar solvents, the abundance of these minor products increases dramatically. Four types of product were observed with the favored reaction pathway shifting with minor changes in substitution on the anthraquinone. Several types of product require cleavage of the C−O bond on the benzyloxy group and, apparently, follow a photo-Claisen-type mechanism. Others involve the expected 1,5-diradical but do not exhibit the single-electron transfer usually observed in the Blankespoor-type reaction. The results indicate the importance of considering the medium and photoredox behavior in anthraquinone photochemistry.

Introduction

Anthraquinones are an important and well-studied organic chromophore.[1−11] Anthraquinones absorb long-wavelength UV and blue light and exhibit highly efficient intersystem crossing, making them useful triplet sensitizers. Excited anthraquinones also act as electron and hydrogen atom acceptors. 1-Alkoxy-9,10-anthraquinones (**1**) undergo an intramolecular δ-hydrogen abstraction/single electron transfer (SET) sequence which leads to the oxidative cleavage of the 1-alkoxy group as an aldehyde (**7**, Scheme 1).[12−15] The multistep reaction involves a relatively slow δ-hydrogen abstraction to give diradical **2**, a reaction common to *o*-alkoxy phenones.[16−20] In the case of anthraquinones, Blankespoor established that the 1,5-diradical thus formed undergoes rapid SET to afford a zwitterion **3**. The zwitterion is then trapped by solvent with the resulting acetal (**4**) being hydrolyzed and the

(1) Lukeman, M.; Xu, M.; Wan, P. *Chem. Commun.* **2002**, 136–137.
(2) Yoshihara, T.; Yamaji, M.; Itoh, T.; Nishimura, J.; Shizuka, H.; Tobita, S. *J. Photochem. Photobiol. A: Chem.* **2001**, *140*, 7–13.
(3) Gan, H.; Whitten, D. G. *J. Am. Chem. Soc.* **1993**, *115*, 8031–8037.
(4) Aquino, A. M.; Abelt, C. J.; Berger, K. L.; Darragh, C. M.; Kelley, S. E.; Cossette, M. V. *J. Am. Chem. Soc.* **1990**, *112*, 5819–5824.
(5) Langhals, H.; Saulich, S. *Chem.—Eur. J.* **2002**, *8*, 5630–5643.
(6) Gorner, H. *Photochem. Photobiol.* **2003**, *77*, 171–179.
(7) Zhu, L.; Khairutdinov, R. F.; Cape, J. L.; Hurst, J. K. *J. Am. Chem. Soc.* **2005**, *128*, 825–835.
(8) Ren, M.-G.; Bi, N.-M.; Mao, M.; Song, Q.-H. *J. Photochem. Photobiol. A: Chem.* **2009**, *204*, 13–18.
(9) Maurino, V.; Borghesi, D.; Vione, D.; Minero, C. *Photochem. Photobiol. Sci.* **2008**, *7*, 321–327.
(10) Gouloumis, A.; Gonzalez-Rodriguez, D.; Vazquez, P.; Torres, T.; Liu, S.; Echegoyen, L.; Ramey, J.; Hug, G. L.; Guldi, D. M. *J. Am. Chem. Soc.* **2006**, *128*, 12674–12684.
(11) Yoshida, K.; Mori, T.; Watanabe, S.; Kawai, H.; Nagamura, T. *J. Chem. Soc., Perkin Trans. 2* **1999**, 393–398.
(12) Blankespoor, R. L.; De Jong, R. L.; Dykstra, R.; Hamstra, D. A.; Rozema, D. B.; VanMeurs, D. P.; Vink, P. *J. Am. Chem. Soc.* **1991**, *113*, 3507–3513.
(13) Blankespoor, R. L.; Smart, R. P.; Batts, E. D.; Kiste, A. A.; Lew, R. E.; Van der Vliet, M. E. *J. Org. Chem.* **1995**, *60*, 6852–6859.
(14) Smart, R. P.; Peelen, T. J.; Blankespoor, R. L.; Ward, D. L. *J. Am. Chem. Soc.* **1997**, *119*, 461–465.
(15) Blankespoor, R. L.; DeVries, T.; Hansen, E.; Kallemeyn, J. M.; Klooster, A. M.; Mulder, J. A.; Smart, R. P.; Vander Griend, D. A. *J. Org. Chem.* **2002**, *67*, 2677–2681.
(16) Wagner, P. J. *Acc. Chem. Res.* **1989**, *22*, 83–91.
(17) Wagner, P. J.; Jang, J. S. *J. Am. Chem. Soc.* **1993**, *115*, 7914–7915.
(18) Wagner, P. J.; Meador, M. A.; Park, B. S. *J. Am. Chem. Soc.* **1990**, *112*, 5199–5211.
(19) Wagner, P. J.; Meador, M. A.; Scaiano, J. C. *J. Am. Chem. Soc.* **1984**, *106*, 7988–7989.
(20) Wagner, P. J.; Laidig, G. *Tetrahedron Lett.* **1991**, *32*, 895–898.

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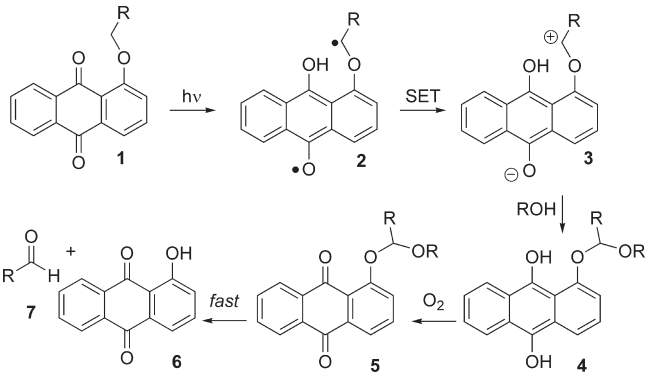
SCHEME 1



dihydroxyanthracene being oxidized in subsequent dark reactions to give an aldehyde (**7**) and 1-hydroxy-9,10-anthraquinone (**6**).

The overall reaction shown in Scheme 1 has been used as an efficient means of preparing aldehydes in both solution and solid phase[15] and to release bioactive aldehydes.[21,22] Our interest in this chemistry arises from a desire to photorelease bioactive aldehydes using visible light.[22] We have previously reported the photorelease of caged 4-hydroxy-2-nonenal (4-HNE), as well as other α,β-unsaturated aldehydes, from 2-alkyl-1-alkoxy-9,10-anthraquinones using visible light (λ = 419 nm) and the investigation of the mechanism and factors affecting the rate of release.[21−23] In an attempt to prepare anthraquinones that could carry out such photochemistry at a longer wavelength, the photochemistry of anthraquinones bearing multiple alkoxy substituents was investigated.

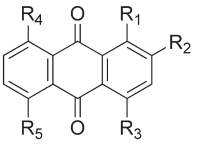
Anthraquinones that produce α,β-unsaturated aldehydes upon photolytic oxidative cleavage generally exhibit both greater efficiency and more complexity than compounds in which a simple alkyl group is cleaved. The reaction is sensitive to solvent polarity and heavy-atom effects[22] and can, in some cases, give significant quantities of rearranged products.[21,23] Little is known about the effect of additional alkoxy groups on the oxidative cleavage reaction. In an early report on the photochemistry of 1-alkoxy-9,10-anthraquinones,[12] Blankespoor reported that dimethoxy-9,10-anthraquinones did undergo the oxidative cleavage but at a reduced efficiency compared to an anthraquinone with only one methoxy substituent; e.g., **8** (Chart 1) underwent photodemethylation with an observed efficiency of approximately 1 order of magnitude greater than that for **9**.

To better understand the reaction, a series of poly(benzyloxy-9,10-anthraquinones) was prepared and photolyzed at 405 nm. The reactions were monitored by following the disappearance of the starting anthraquinone by ^{1}H NMR. As in the case of 1-allyloxy-9,10-anthraquinones, the photocleavage of the benzyloxy groups was not as simple as that for saturated alkoxy groups.

Results and Discussion

Blankespoor reported the relative rate of oxidative cleavage for several methoxy- and dimethoxy-substituted

CHART 1

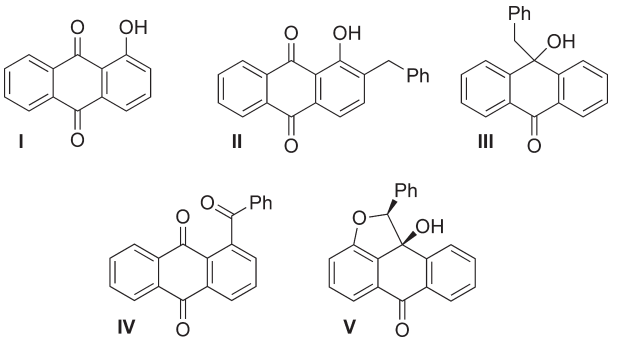


8 $R_1 = OCH_3$; R_2-R_5 = H
9 $R_1 = R_4 = OCH_3$; R_2, R_3, R_5 = H
10 $R_1 = OCH_2Ph$; R_2-R_5 = H
11 $R_1 = R_3 = OCH_2Ph$; R_2, R_4, R_5 = H
12 $R_1 = R_2 = OCH_2Ph$; R_3, R_4, R_5 = H
13 $R_1 = R_4 = OCH_2Ph$; R_2, R_3, R_5 = H
14 $R_1 = R_5 = OCH_2Ph$; R_2, R_3, R_4 = H
15 R_1, R_2, $R_3 = OCH_2Ph$; R_4, R_5 = H
16 $R_1 = R_2 = OC_{12}H_{25}$; R_3, R_4, R_5 = H
17 $R_1 = R_3 = OC_{12}H_{25}$; R_2, R_4, R_5 = H

TABLE 1. Relative Rate of Disappearance upon Photolysis (λ = 405 nm) in CD_3OD/DMSO-d_6 (See the Experimental Section and Supporting Information for Details)

compound	relative rate
10	1.0
11	1.6
12	5.5
13	2.5
14	3.2
15	2.8
16	6.1
17	---

CHART 2



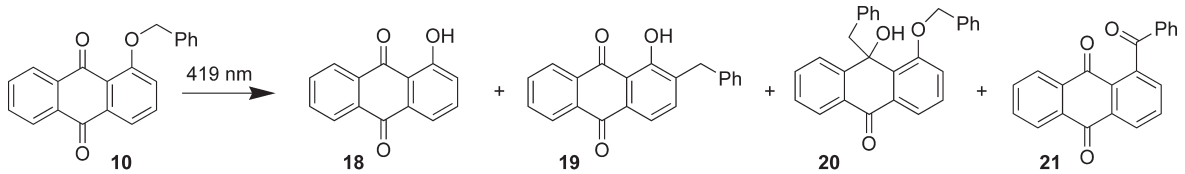
anthraquinones.[13] A general trend is that increasing steric bulk in the 2-position of 1-alkoxy-9,10-anthraquinones increases the rate of the oxidative cleavage reaction. Although data are limited, additional alkoxy groups directly attached to the anthraquinone appear to slow the reaction (Table 1). In order to conduct a more thorough substituent effect study, the series of anthraquinones shown in Chart 1 was prepared.

In contrast to Blankespoor's comparison of **8** and **9**, anthraquinones with multiple benzyloxy groups were all consumed faster than the standard (**10**), which had only one benzyloxy group. Dibenzyl alizarin (**12**) was consumed most efficiently, which is consistent with the known effect of increased steric bulk in the 2-position.[13]

Two compounds with dodecyl ethers were irradiated to test the effect of the occurrence of an initial benzylic radical in **10**−**15**. The rate of cleavage of 1,2-didodecyloxy-9,10-anthraquinone (**16**) was virtually identical to that of the corresponding dibenzyl ether. However, the rate of consumption of 1,4-didodecyloxy-9,10-anthraquinone (**17**) was essentially nil. These results were consistent with the 1,2-diethers both undergoing the

(21) Brinson, R. G.; Jones, P. B. *Org. Lett.* **2004**, *6*, 3767–3770.
(22) Jones, P. B.; Brinson, R. G.; Sarma, S. J.; Elkazaz, S. *Org. Biomol. Chem.* **2008**, *6*, 4204–4211.
(23) Brinson, R. G.; Hubbard, S. C.; Zuidema, D. R.; Jones, P. B. *J. Photochem. Photobiol. A: Chem.* **2005**, *175*, 118–128.

SCHEME 2[a]



Selectivity ^{1}H NMR : isolated yield				
In methanol:	1.0 : 67%	0.20 : 9%	0.20	0
In benzene:	1.0 : 36%	0.15 : 6%	0.35	1.51 : 44%
In hexane:	1.0 : 19%	0.25 : 4.5%	0.70	1.38 : 29%

[a]Compounds **20** and **21** were difficult to separate quantitatively. Only **21** could be found as pure.

oxidative cleavage reaction, while the fate of the 1,4-diethers depended upon the nature (stabilized or not) of the initially formed diradical.

The reactions were then run on a larger scale, so that products could be isolated. These reactions revealed that anthraquinones **11**−**15** were consumed more efficiently than **10** due to reactions other than the oxidative cleavage reaction. In most cases, photolysis of **11**−**15** led to a mixture of products. In methanol, the expected oxidative cleavage product was observed, while in nonpolar solvents, this product represented a minor pathway, if it was observed at all. Also, in all cases, the presence of oxygen led to the oxidative cleavage product being the sole product.

The unexpected products could be divided into five types (Chart 2). The first (**I**) was a 1-hydroxy-9,10-anthraquinone that had not undergone rearrangement, the expected oxidative cleavage product. The second (**II**) was a 2-benzyl-1-hydroxy-9,10-anthraquinone. The third (**III**) type was a 10-benzylanthrone, having a benzyl attached to what was formerly a quinone carbonyl carbon. The fourth (**IV**) type was a 1-benzoyl-9,10-anthraquinone. The final (**V**) type was a cyclopentanol. No starting anthraquinone produced all five types of products. Shifting the "second" benzyloxy group around the anthraquinone resulted in significant changes in which products were observed, their relative yields, and favored product type. While all five types of product have been observed previously in aryl ketone photochemistry, it is rare for a single chromophore to give them all or for switching between the reaction pathways to be sensitive to substititution.

Photolysis of **10** in anaerobic methanol until **10** was consumed produced three main products, **18**−**20**, with **18** being by far the major product, as expected, and **19** and **20** being produced in approximately equal amounts (Scheme 2). Phenol **18**, the expected product of the oxidative cleavage, and **19** are known compounds and were easily identified by ^{1}H NMR. Alcohol **20** was identified by 1- and 2-D NMR experiments[24,25] and must be the result of a reductive rearrangement, which bears some similarity to products observed in thermal reactions.[26] Compound **18** could be the result of either oxidative cleavage or a photo-Claisen process in which the radical pair underwent cage escape.[27−34] To test this, **10** was photolyzed in deoxygenated solvents that were less polar and non-nucleophilic (benzene and hexane). The yield of **18** dropped dramatically, and a fourth product (**21**) was formed.

The remaining benzyl ethers in Chart 1 were then similarly irradiated in the three solvents: methanol, benzene ,and hexane, all rigorously deoxygenated. The product distributions are shown in Schemes 3−6. In all cases, alteration of the substituent pattern resulted in a change in product distribution. Also, in all cases, the yield of oxidative cleavage product (Type I) decreased with decreased solvent polarity. Benzaldehyde was observed in every case that the oxidative cleavage product was observed. No evidence, however, was seen for the formation of toluene, bibenzyl, or benzyl alcohol, possible products of C−O homolysis in which the intermediate radicals have escaped the solvent cage.

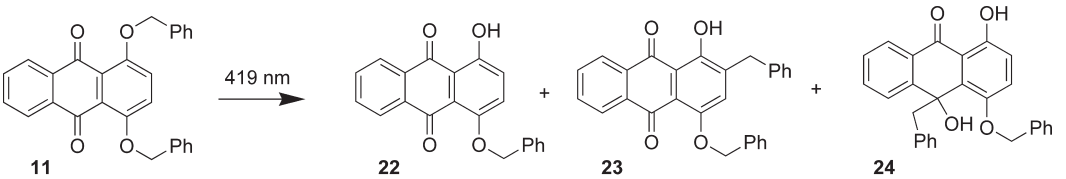
Photolysis of 1,2,4-tribenzyloxy-9,10-anthraquinone (**15**) gave a very complex reaction mixture. It appeared that all three nonequivalent benzyl groups were cleaved. Signals in the ^{1}H NMR were observed that were consistent with the oxidative cleavage product (type I), photo-Claisen (type II), and anthrone (type III). However, due to the high number of products obtained from photolysis of **15**, the simpler disubstituted anthraquinones became our focus.

When the photolyses shown in Scheme 3−6 were carried out in oxygen-saturated solution, the oxidative cleavage product was the major product. The products obtained above were identified by 1D and 2D NMR techniques and/or by crystallization and X-ray diffraction. The data that supports the structures shown above can be found in the Supporting Information.

Reactions in hexane generally gave lower yields and "messier" crude NMR spectra. Each reaction described above was carried to completion, as evidenced by consumption of starting material. To test the effect of reduced photolysis time and to check the mass balance of the reaction, **11** was photolyzed for 4 h in deoxygenated benzene.

(24) Dimmel, D. R.; Shepard, D. *J. Org. Chem.* **1982**, *47*, 22–29.
(25) Dimmel, D. R. *J. Org. Chem.* **1982**, *47*, 29–34.
(26) Harrington-Frost, N. M.; Milbank, J. B. J.; Rutledge, P. S. *Aust. J. Chem.* **1997**, *50*, 379–389.
(27) Pincock, A. L.; Pincock, J. A.; Stefanova, R. *J. Am. Chem. Soc.* **2002**, *124*, 9768–9778.
(28) Gonzalez, C. M.; Pincock, J. A. *Can. J. Chem.* **2008**, *86*, 686–690.
(29) Galindo, F. *J. Photochem. Photbiol. Chem. C: Photochem. Rev.* **2005**, *6*, 123–138.
(30) Gu, W.; Warrier, M.; Schoon, B.; Ramamurthy, V.; Weiss, R. G. *Langmuir* **2000**, *16*, 6977–6981.
(31) Galindo, F.; Miranda, M. A.; Tormos, R. *J. Photochem. Photobiol. A: Chem.* **1998**, *117*, 17–19.
(32) Jimenez, M. C.; Miranda, M. A.; Scaiano, J. C.; Tormos, R. *Chem. Commun.* **1997**, 1487–1488.
(33) Pitchumani, K.; Warrier, M.; Ramamurthy, V. *J. Am. Chem. Soc.* **1996**, *118*, 9428–9429.
(34) Fleming, S.A.; Pincock, J.A. In *Organic Molecular Photochemistry*; Ramamurthy, V., Schanze, K. S., Eds.; Marcel Dekker: New York, 1999; Vol. 3, pp 211−282.

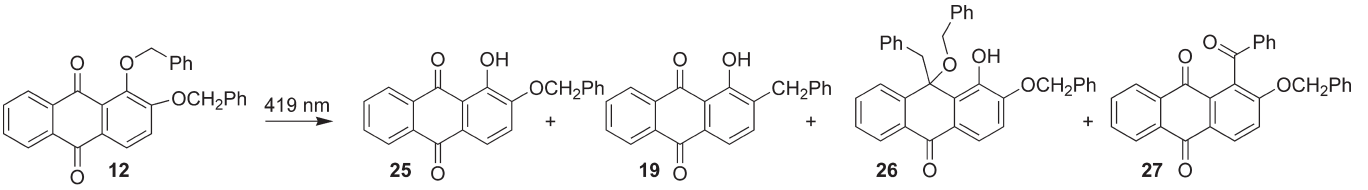
SCHEME 3[a]



Selectivity (1H NMR) : isolated yield			
In methanol:	1.0 : 20%	1.0 : 20%	0.6 : 14%
In benzene:	1.0 : 30%	0.7 : 20%	0.8 : 22%
In hexane:	1.0	1.3	1.9

[a]Overall isolated in hexane yields were poor with apparent polymerization.

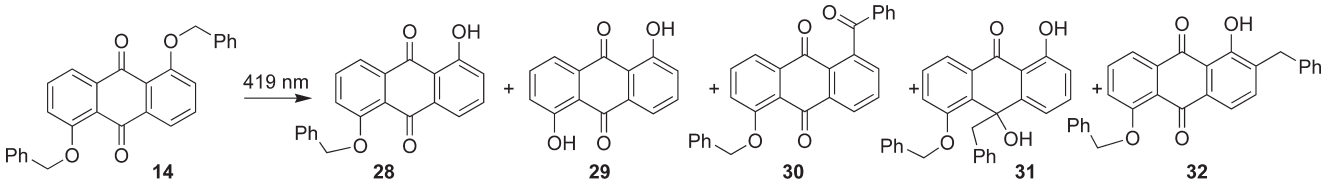
SCHEME 4[a]



Selectivity (^{1}H NMR) : isolated yield				
In methanol:	1.0 : 77%	0	0	0
In benzene:	1.0 : 21.5%	0.5 : 11%	0.6 : 9%	2.0 : 38%
In hexane:	1.0 : 16%	0.45: 7%	1.00: 11%	3.5 : 48%

[a]Compound **26** could not be purified quantitatively; the structure was inferred by 1D and 2D NMR experiments.

SCHEME 5[a]



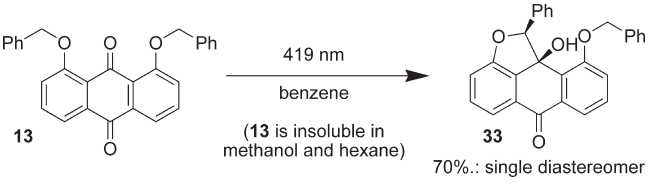
Selectivity (^{1}H NMR) : isolated yield					
In methanol:	1.0	0.6	0	0	0
In benzene:	1.0	0.35	2.0 : 37%	2.0	0.8
In hexane:	1.0	0.35	1.0 : 10%	1.75	0.25

[a]Compounds **28** and **32** were difficult to completely separate. Compound **28** was obtained as pure, but **32** was always found mixed with some **28**. Structure of **32** inferred by similarity in 1D and 2D NMR experiments with **23**.

The crude ^{1}H NMR spectrum indicated that 50% of the starting material had been consumed and that the ratio of the three main products (**22**−**24**) was the same as when the reaction was taken to completion. Isolated yields of **11**, **22**, **23**, and **24** were 49%, 15%, 10%, and 11%, respectively.

The simplest and cleanest reaction presented above was that of **13**. Cyclization of 1,5-diradicals to form cyclopentanols is a well-studied photochemical reaction.[16−19,35−38] In the case of **13**, the cyclopentanol **33** was the only product observed. Presumably, the fate of excited **13** followed the mechanistic paradigm established by Wagner and others.[16−19] The cyclopentanol was formed when **13** absorbed a photon

SCHEME 6

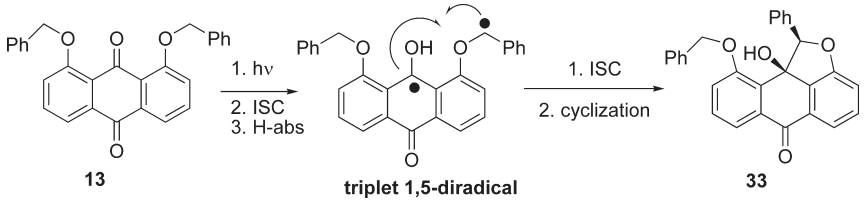


and underwent ISC (intersystem crossing) to give the T1 (lowest triplet) state of the quinone (Scheme 7). The triplet quinone abstracted a hydrogen from the benzyloxy group to give a triplet 1,5-diradical. The triplet diradical underwent ISC to the singlet state, which then rapidly cyclized to give the cyclopentanol (**33**).

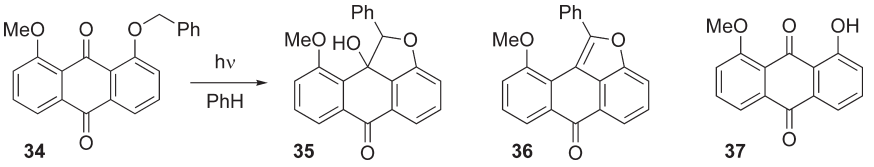
This type of chemistry was only observed with 1,8-dialkoxy-9,10-anthraquinones. Although **13** could not be dissolved in methanol or hexane, a solution of **13** in wet acetonitrile, a more polar medium in which oxidative cleavage

(35) Perez-Ruiz, R.; Hinze, O.; Neudorfl, J.-M.; Blunk, D.; Gorner, H.; Griesbeck, A. G. *Photochem. Photobiol. Sci.* **2008**, *7*, 782–788.
(36) Abdul-Aziz, M.; Auping, J. V.; Meador, M. A. *J. Org. Chem.* **1995**, *60*, 1303–1308.
(37) Sumathi, T.; Balasubramanian, K. K. *Tetrahedron Lett.* **1992**, *33*, 2213–2216.
(38) Lappin, G. R.; Zannucci, J. S. *J. Org. Chem.* **1971**, *36*, 1808–1811.

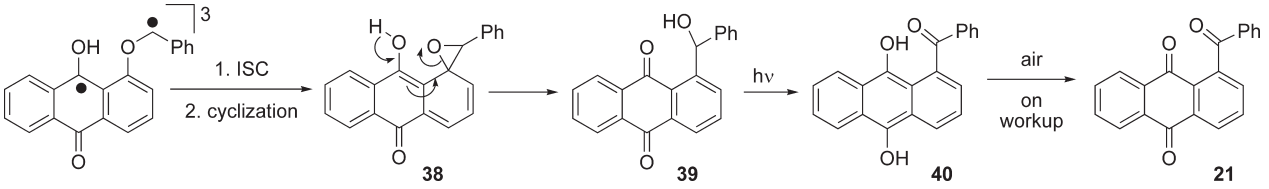
SCHEME 7



SCHEME 8



SCHEME 9



should be favored, **33** was still the major product (65%). It was also unclear if the cyclization of **13** was favored because of an electronic or steric effect of the "second" benzyloxy group in the 8-position. Thus, **34** was prepared and photolyzed (Scheme 8). Having a methoxy group in place of the second benzyloxy group, **34** should have similar electronics to **13** but a different steric profile. Photolysis of **34** in benzene was not as clean as that of **13**. However, the major product was again a cyclopentanol (**35**) corresponding to that expected from cyclization of the 1,5-diradical. Also formed were alkene **36** and phenol **37**.

The alkene obviously came from elimination of water from alcohol **35**, while **37** may have arisen through either oxidative cleavage or C−O homolysis followed by cage escape (see below). When treated with acid, **33** also undergoes elimination readily. Presumably, the increased steric bulk of the 8-benzyloxy in **33**, relative to the smaller 8-methoxy in **35**, slows the rate of elimination in **33**. Taken together, **35** and **36** accounted for approximately 70% of the material in the photolysis of **34**. Thus, it appeared that an alkoxy group in the 8-postion facilitates cyclization of the 1, 5-diradical. A possible explanation is that the 8-alkoxy group forms a hydrogen bond to the hydroxyl group in the intermediate diradical, which would increase electron density around C-9. The increased electron density on the C-9 radical should slow reduction of C-9 by SET from the 1-alkoxy radical. With SET slowed, the diradical has more time in which to cyclize, giving the observed product.

The formation of 1-benzoyl-9,10-anthraquinones (**IV**) was also consistent with a 1,5-diradical intermediate and has precedent in the photochemistry of simpler phenones (Scheme 9).[17,39,40] Formation of a 1,5-triplet diradical proceeded as described above (Scheme 7). Cyclization of the radical to form spiro-epoxide **38** followed ISC to the singlet state. The spiro-epoxide opened with regeneration of the quinone ketone to give alcohol **39**. A photoredox reaction between the quinone and secondary alcohol gave ketone **40**, which oxidized to the observed triketone **21** upon exposure to air at the end of the reaction. Alternatively, anthrahydroquinone **40** may reduce another anthraquinone in the mixture (see below). The conversion of an alkoxy substituent to an acyl substituent is a potentially useful reaction in the synthesis of natural products such as mumbaistatins.[41−43]

Formation of 2-benzyl-1-hydroxy-9,10-anthraquinones (**II**) can be explained by a photo-Claisen mechanism (Scheme 10). Such a mechanism also provided an alternative route to produce 1-hydroxy-9,10-anthraquinones via cage escape of the initially formed diradical pair.[27−34] Homolytic cleavage of the ether bond could proceed either from the S1 (lowest excited singlet) state or the T1 state, though it is energetically less feasible to occur from the T1 state due to the greater stability of the triplet. Additionally, photo-Claisen reactions that involve triplets generally show a significant amount of products due to the intermediate radicals escaping the solvent cage; no such products were detected. Recombination of the benzyl radical to C-2, followed by keto−enol tautomerization, gave the Claisen product. Alternatively, the

(39) Horaguchi, T.; Tsukada, C.; Hasegawa, E.; Shimizu, T.; Suzuki, T.; Tanemura, K. *J. Heterocycl. Chem.* **1991**, *28*, 1261–1272.

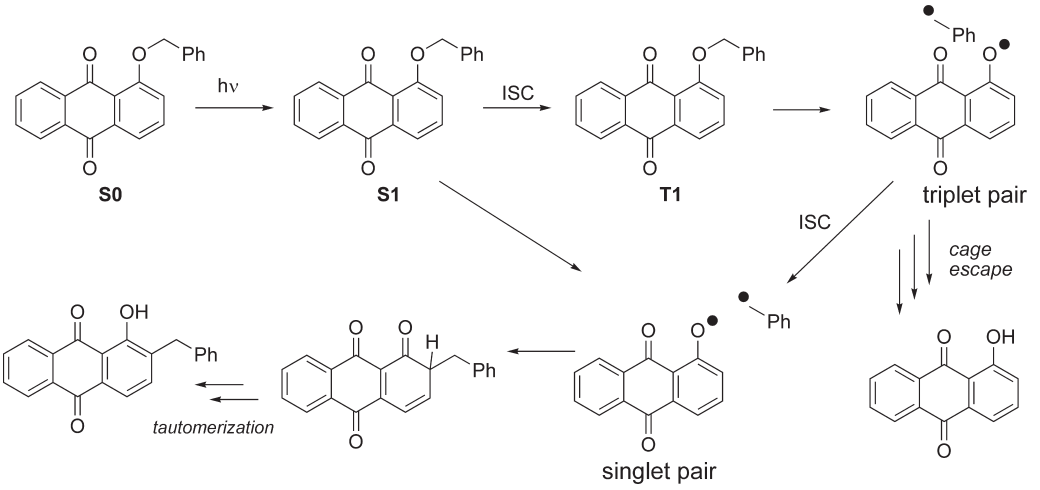
(40) Baroudi, A.; Mauldin, J.; Alabugin, I. V. *J. Am. Chem. Soc.* **2009**, *132*, 967–979.

(41) Vertesy, L.; Kurz, M.; Paulus, E. F.; Schummer, D.; Hammann, P. *J. Antibiot.* **2001**, *54*, 354–363.

(42) Kaiser, F.; Schwink, L.; Velder, J.; Schmalz, H.-G. *Tetrahedron* **2003**, *59*, 3201–3217.

(43) Kaiser, F.; Schwink, L.; Velder, J.; Schmalz, H.-G. *J. Org. Chem.* **2002**, *67*, 9248–9256.

SCHEME 10



SCHEME 11

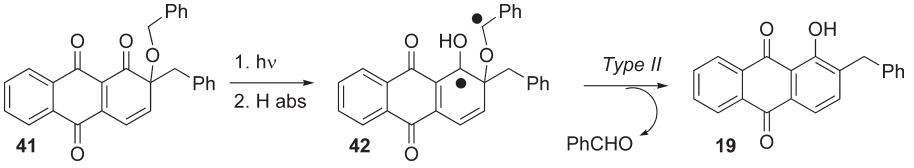


photo-Claisen step could follow reduction to the anthrahydroquinone. This possibility is discussed below.

It was somewhat surprising that no photo-Claisen rearrangement to the 4-position was observed. However, there is evidence that similar systems give primarily rearrangement to the 2-position.[27,33] Further, alkyl groups *ortho* to the anthraquinone carbonyl are well-known to be photooxidized.[44−48] Apparently, migration of the benzyl radical to the 4-position is a minor event, and the product obtained from such migration is further transformed over the course of the reaction. Attempts to detect a 4-benzyl product in all reactions failed.

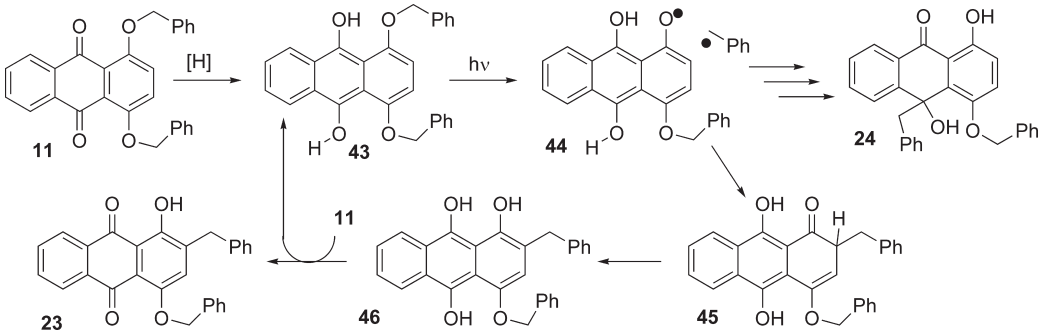
The observation of 2-benzyl-1-hydroxy-9,10-anthraquinone (**19**) from photolysis of **12** was also puzzling. If excited **12** underwent a photo-Claisen reaction as described in Scheme 10, it should result in an anthraquinone with a 1-keto group and two substituents on the 2-position (**41**). Instead, the entire 2-benzyloxy group was lost. The loss of the group can be explained by a second photochemical reaction, as shown in Scheme 11. The expected photo-Claisen product **41** underwent a second photochemical reaction, Norrish Type II cleavage via diradical **42**, to produce benzaldehyde and the observed product **19**.[49,50] Benzaldehyde was observed in this reaction, although it might also be produced from the oxidative cleavage reaction. Attempts to synthesize **41** or detect it unambiguously using NMR and MS of reactions at low conversion failed.

The most difficult products to explain are the benzyl anthrones (**III**), formed in several of the reactions described above. The observed anthrones can be classified in two types. The first type includes **24** and **31** where the benzyl radical adds to the carbonyl group on the opposite side of the cleaved C−O bond. The second type includes **20** and **26** where the benzyl radical adds to the carbonyl group closer to the original alkoxy groups on the anthraquinone ring. The anthrones mark not only a migration of a benzyl group but also an overall reduction. Two questions are raised by the possibility of reduction: (1) what is the reductant and (2) does reduction occur prior to benzyl migration, after the migration, or do the two processes occur simulataneously? The yield of anthrone was never higher than 50%, which led to the hypothesis that the reductant might be another molecule of quinone that had been reduced through some other means. The oxidative cleavage mechanism (Scheme 1) results in an anthrahydroquinone (**4**) that could serve as a reductant, as does the proposed mechanism for production of 1-benzoylanthraquinones (e.g., **40**, Scheme 9). Any anthrahydroquinone might reduce, either thermally or photochemically, an equivalent of quinone.[23]

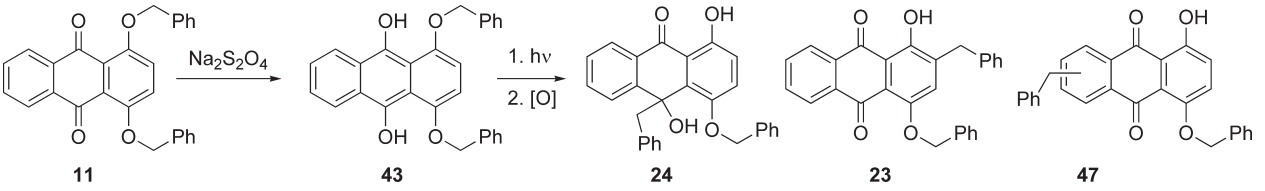
One can draw several plausible mechanisms for this type of anthrone production, if prior reduction of the quinone is stipulated. The simplest is that shown in Scheme 12. In this mechanism, the quinone **11** is first reduced to give **43**, which then undergoes photochemical C−O homolysis to give the radical pair **44**. The benzyl radical can recombine directly at C-10 to give anthrone **24**. The benzyl radical could, alternatively, recombine *ortho* to the phenolate oxygen to give

(44) Konosonoks, A.; Wright, P. J.; Tsao, M.-L.; Pika, J.; Novak, K.; Mandel, S. M.; Krause Bauer, J. A.; Bohne, C.; Gudmundsdottir, A. D. *J. Org. Chem.* **2005**, *70*, 2763–2770.
(45) Fekarurhobo, G. K.; Obomanu, F. G.; Carless, H. A. J. *J. Chem. Soc. Niger.* **2002**, *27*, 24–25.
(46) Yoshioka, M.; Nishizawa, K.; Suzuki, J.; Iwata, Y.; Kumakura, S.; Hasegawa, T. *J. Chem. Soc., Perkin Trans. 1* **1995**, 3097–3101.
(47) Saito, M.; Kamei, Y.; Kuribara, K.; Yoshioka, M.; Hasegawa, T. *J. Org. Chem.* **1998**, *63*, 9013–9018.
(48) Elkazaz, S.; Jones, P. B. *J. Org. Chem.* **2009**, *75*, 412–416.
(49) Wagner, P. J.; Hammond, G. S. *J. Am. Chem. Soc.* **1966**, *88*, 1245–1251.
(50) Turro, N. J.; Weiss, D. S. *J. Am. Chem. Soc.* **1968**, *90*, 2185–2186.

SCHEME 12



SCHEME 13



ketone **45**, which should rapidly tautomerize to **46**. Oxidation of **46** when the reaction is stopped and opened to air would give the observed photo-Claisen product **23**. However, anthrahydroquinone **46** could reduce starting anthraquinone. Such a redox pathway would provide a catalytic cycle where a single reduction early in the photolysis, via the oxidative cleavage pathway, perhaps, could lead to a relatively high yield of anthrone and photo-Claisen products. Anthrahydroquinone **40**, proposed previously (Scheme 10), could also play the role of **46** in Scheme 12 or, indeed, initiate the redox cycle.

To test the mechanistic hypothesis in Scheme 12, anthraquinone **11** was photolyzed in 2:1 dioxane/water both alone and in the presence of sodium dithionite, a reductant (Scheme 13).[51] In the presence of dithionite, the ratio of anthrone (**24**)/Claisen (**23**)/oxidative cleavage (**22**) was 1:0.18:0, while without dithionite the ratio was 1:3.2:3.6. The photo-Claisen product, **23**, was also formed under the reductive conditions, but the oxidative cleavage product **22** was not. The lack of **22** in the photolysis of anthrahydroquinone suggests that the radicals forming the observed photo-Claisen products do not escape the solvent cage. In turn, this suggests that the photochemistry of the anthrahydroquinone proceeds through an excited singlet state.

Several other minor products were observed in the presence of dithionite, although these were not isolated. The ^{1}H NMR signals of these minor products were consistent with their being photo-Claisen type products where the benzyl group has reattached to the anthracene at carbons other than 2 or 10 (**47**). Anthrone **24** was clearly favored under reductive conditions, which supports our proposed mechanism, shown in Scheme 12.

The second type of anthrone apparently does not go through this reductive mechanism. The participating benzyl group seems to have come from the homolysis of another alkoxy anthraquinone molecule, and thus, this type of anthrone should be the result of an intermolecular reaction. Further studies are required to establish a general mechanism that explains the formation of this type of anthrone.

Conclusions

Five different types of reaction products are observed in the photochemistry of 1-benzyloxy-9,10-anthraquinones. Four come at the expense of the expected oxidative cleavage described by Blankespoor.[12−15] There are two explanations for the reduced yield of the oxidative cleavage products, both likely operative in most of the reactions described above. The first is that the additional substituents slow the rate of 1,5-hydrogen abstraction relative to other pathways such as homolysis. This must be the explanation for the photo-Claisen- and anthrone-type products. These products require a homolytic bond cleavage, which could not occur if anthraquinone underwent 1,5-hydrogen transfer.

The second is that alternate pathways must arise that compete favorably with SET from the 1,5-diradical (formed by 1,5-hydrogen transfer). This is the case for the cyclopentanol and 1-benzoyl products. The intermediate 1,5-diradical is formed but undergoes cyclization prior to SET. This is not entirely unexpected in less polar solvent, as SET is a polar process and we have previously shown that the rate of cleavage does depend on solvent polarity.[22] Having additional electron-donating substituents on the anthraquinone could be expected to both stabilize the intermediate semiquinone radical and slow electron transfer into the quinone. Given the relatively fast cyclizations observed, the effect of substituents on SET would not have to be great to dramatically alter the favored reaction pathway.

The observations described above present new reaction pathways for excited anthraquinones that mirror those observed in simpler phenones. The results demonstrate the importance of considering the potential for redox chemistry between anthrahydroquinone and the corresponding anthraquinone in anthraquinone photochemistry. They also demonstrate that relatively small changes in substitution pattern on the anthraquinone can dramatically influence

(51) Kaur, N.; Kumar, S. *Tetrahedron* **2008**, *64*, 3168–3175.

the favored pathway. The pathways provide potential for synthetic application in natural product synthesis and a mechanism to produce diradicals using visible light. More work is needed to understand how substituents and medium direct the reaction down a particular pathway, so that synthetically significant yields can be reliably obtained.

Experimental Section

General Procedure for Relative Photolysis Rates (Method A). Solutions of anthraquinone were prepared in 1:1 CD_3OD/DMSO-d_6. A solution of anthraquinone was then photolyzed alongside a control solution of **10** with equal A_{405}. Each solution was irradiated in borosilicate NMR tubes using a monochromator set to 405 nm with a 10 nm bandpass in conjunction with a focused 150 W Hg/Xe lamp. The disappearance of the 1-benzyloxymethylene ^{1}H NMR signal was followed over time. Each experiment was repeated at least three times.

General Procedure for Preparative Photochemical Reactions (Method B). A solution of anthraquinone was prepared in the solvent of choice (methanol, hexane, or benzene) and Ar was passed through the solution for 2 h to remove oxygen. The solution was photolyzed in a Rayonet photoreactor fitted with eight lamps with peak emission at 419 nm. The reaction was followed by TLC and stopped when the starting material was found to be completely consumed. Solvent was removed in vacuo and the crude product analyzed by ^{1}H NMR. Major products were then isolated using column chromatography.

Representative Procedures. 10-(Benzyloxy)-10b-hydroxy-1-phenyl-1*H*-anthra[1,9-*bc*]furan-6(10b*H*)-one (33). A solution of **13**[52] (75 mg, 0.178 mmol) in 75 mL of benzene was irradiated using method B for 18 h. Flash column chromatography with 1:1 hexane/EtOAc followed by recrystallization from hexane gave **33** as a yellow solid (53 mg, 0.126 mmol, 71%): mp 159−161 °C ; IR (KBr) 3447, 3061, 3034, 2925, 1668, 1630, 1591, 1465, 1303, 1287, 1260, 1217, 1018, 888, 757, 733 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.84−7.79 (m, 3H), 7.56 (d, 1H, J = 7.7 Hz), 7.47−7.36 (m, 4H), 7.27−7.22 (m, 5H), 7.12 (d, 1H, J = 7.9 Hz), 6.97−6.89 (m, 3H), 5.86 (s, 1H), 4.84 (d, 1H, J = 14.0 Hz), 4.68 (d, 1H, J = 14.0 Hz), 2.57 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 184.0, 158.7, 154.6, 136.3, 136.0, 135.1, 134.1, 131.3, 130.9, 130.7, 130.5, 129.7, 128.8, 128.7, 128.0, 127.8, 126.6, 121.6, 118.2, 118.1, 114.6, 95.1, 73.7, 68.8; HRMS (EI) calcd for $C_{28}H_{20}O_4Na^+$ $[M + Na]^+$ 443.125380, found 443.125090.

Photolysis of 11. A solution of **11**[53] (200 mg, 0.476 mmol) in 200 mL of benzene was irradiated using method B for 40 h. Flash column chromatography with a hexane/EtOAc gradient gave the following products:

1-(Benzyloxy)-4-hydroxy-9,10-anthraquinone (22). Compound **22** was obtained as a brick red solid and recrystallized from hexanes/EtOAc to give 47.2 mg (0.143 mmol, 30%): mp 137−138 °C; IR (KBr) 3064, 3031, 2864, 1662, 1632, 1593, 1570, 1475, 1442, 1429, 1352, 1237, 1169, 1041, 1071, 830, 787, 725 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 13.00 (s, 1H), 8.29 (dt, 2H, J = 7.6, 1.4 Hz), 7.82−7.72 (m, 2H), 7.58 (d, 2H, J = 7.3 Hz), 7.43−7.24 (m, 6H), 5.30 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 187.6, 180.2, 156.9, 152.1, 135.7, 134.3, 134.0, 132.6, 131.7, 128.1, 127.4, 126.8, 126.5, 125.9, 125.8, 125.5, 119.9, 115.6, 72.2; HRMS (EI) calcd for $C_{21}H_{14}O_4$ Na^+ $[M + Na]^+$ 353.078430, found 353.078143.

2-Benzyl-4-(benzyloxy)-1-hydroxy-9,10-anthraquinone (23). Compound **23** was obtained as an orange solid (40 mg, 0.095 mmol, 20%): mp 169−171 °C; IR (KBr) 3433, 3027, 2918, 1661, 1630, 1588, 1427, 1348, 1262, 1243, 1008, 814, 799, 738 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 13.52 (s, 1H), 8.30 (m, 2H), 7.83−7.72 (m, 2H), 7.45−7.27 (m, 8H), 7.18−7.16 (m, 2H), 7.1 (s, 1H), 5.18 (s, 2H), 4.10 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 189.2, 181.3, 156.3, 152.6, 139.7, 138.3, 136.4, 135.1, 134.7, 133.2, 132.4, 129.2, 128.7, 128.6, 127.9, 127.3, 127.2, 126.6, 126.4, 126.3, 118.5, 115.4, 71.7, 35.8; HRMS (EI) calcd for $C_{28}H_{20}O_4$ Na^+ $[M + Na]^+$ 443.125380, found 443.125221.

10-Benzyl-4-(benzyloxy)-1,10-dihydroxyanthracen-9(10*H*)-one (24). Compound **24** was obtained as an orange solid (44.2 mg, 0.104 mmol, 22%): mp 118−119 °C; IR (KBr) 3090, 3065, 3026, 2854, 1640, 1599, 1460, 1402, 1352, 1233, 1050, 1004, 780, 702 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ12.47 (s, 1H), 8.00 (dd, 1H, J = 1.2, 6.7 Hz), 7.90 (dd, 1H, J = 0.6, 7.4 Hz), 7.70 (dt, 1H, J = 1.4, 6.5 Hz), 7.54−7.42 (m, 6H), 7.34 (d, 1H, J = 9.2 Hz), 7.05−6.84 (m, 4H), 6.08 (d, 2H, J = 7.1 Hz), 5.77 (s, 1H), 5.24 (s, 2H), 3.58 (d, 1H, J = 12.2 Hz), 3.20 (d, 1H, J = 12.2 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 188.3, 157.3, 147.9, 145.9, 135.6, 134.9, 134.2, 132.5, 129.9, 129.7, 129.1, 128.8, 127.9, 127.8, 127.4, 126.7, 126.2, 125.7, 121.5, 117.3, 115.6, 74.9, 72.1, 53.6, 36.6; HRMS (EI) calcd for $C_{28}H_{22}O_4$ Na^+ $[M + Na]^+$ 445.141030, found 445.140743.

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Supporting Information Available: Additional experimental procedures, 1D and 2D NMR spectra, and X-ray crystallographic information. This material is available free of charge via the Internet at http://pubs.acs.org.

(52) Prinz, H.; Ishii, Y.; Hirano, T.; Stoiber, T.; Gomez, J. A. C.; Schmidt, P.; Duessmann, H.; Burger, A. M.; Prehn, J. H. M.; Guenther, E. G.; Unger, E.; Umezawa, K. *J. Med. Chem.* **2003**, *46*, 3382–3394.

(53) Kitamura, C.; Hasegawa, M.; Ishikawa, H.; Fujimoto, J.; Ouchi, M.; Yoneda, A. *Bull. Chem. Soc. Jpn.* **2004**, *77*, 1385–1393.