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Synthesis and Properties of Cycloocta[*def*]biphenylene-1,4-dione

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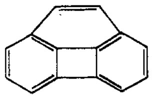
Cycloocta[*def*]biphenylene-1,4-dione (**3**) was synthesized in seven steps from 1,8-dimethylbiphenylene (**4**). A key step in the sequence was the oxidative cyclization of the ketone dienolate derived from 1,8-diacetylbiphenylene (**6**). Preliminary calculations had indicated that **3** would probably exist in a tub-shaped distorted geometry but that it was possible that it would flatten upon protonation. The distorted geometry of **3** was verified in a number of ways, including analysis of ring current shifts in its proton NMR spectrum, observation of its solvatochromic properties, and determination of its X-ray crystal structure. Attempts to induce a transition to a planar species by protonation proved unsuccessful. ^{1}H NMR chemical shift calculations on the protonated species indicated that assumption of a planar geometry resulted in an overestimation of the downfield shift upon protonation while a tub-shaped geometry provided reasonable quantitative agreement.

Introduction

The concept of aromaticity has continued to provide useful insights into the behavior of chemical systems both in terms of suggesting possible areas of inquiry and by providing practical qualitative and quantitative models for the understanding of chemical phenomena. One strategy in exploration and refinement of this concept has been to study systems that exhibit unusual properties in the hope that the limits of traditional models will be revealed.

Recently, our group has focused on the synthesis and study of a series of polycyclic unsaturated hydrocarbons related to biphenylene.[2–5] These compounds are of interest because they exhibit, to varying degrees, properties normally associated with antiaromaticity, yet are generally long-lived enough to permit detailed study. These efforts have culminated in the syntheses of several cyclodeca-,[2] cyclonona-,[3] and cycloocta-fused[4] biphenylenes as well as a number of dicycloocta-fused[5] systems.



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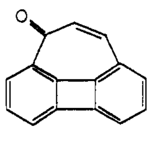
As an extension of this work we contemplated the synthesis of benzo[*def*]biphenylene (**1**). The algebraic structure count (ASC)[6] of **1** is five, indicating that it should exhibit considerable aromatic character. More detailed calculations verified that **1** would possess considerable resonance energy and be strongly diatropic. The synthesis of **1**, however, presented the obvious difficulty of spanning the *d*, *e*, and *f* sides of biphenylene with a two-carbon bridge.

In recent years, a number of annulenones and annulenediones have been studied as analogues of unsaturated hydrocarbons containing one or two fewer carbon atoms. In general, these compounds tend to mimic the behavior of the corresponding hydrocarbons. Cyclopropenone[7] and cycloheptatrienone,[8] which have $4N + 2$ ring electrons in their oxyanion–carbocation resonance forms, are analogues of the aromatic cyclopropenium and tropylium cations and are stable compounds. In contrast, cyclopentadienone[9] and cyclononatetraenone,[10] which have $4N$ π electrons, have proven to be highly elusive species. Larger annulenones containing both $4N$ and $4N + 2$ electrons have been synthesized and exhibit either diatropic[11a] or paratropic[11b,c] ring currents depending on the number of electrons they contain.

In the present case, we hoped that synthesis of annulenone **2** or annulenedione **3** would enable us to span the distance between the 1- and 8-positions of biphenylene while still retaining the aromatic character predicted for **1**. We chose **3** as our target molecule because the asymmetry present in **2** was anticipated as a potentially serious synthetic liability. In addition to its interest to us in terms of theory, **3** could potentially prove useful as a synthetic intermediate by providing access to a variety of more complex materials via cycloaddition reactions. While this was not the major focus of the study, it provided enough additional impetus for us to undertake the synthesis.



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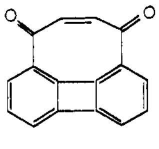

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Results and Discussion

Preliminary Calculations. Molecular mechanics calculations performed at the outset of this study indicated

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[1] Based on the Ph.D. Dissertation submitted by K.R.L. to the Cornell Graduate School, 1988.

[2] (a) Wilcox, C. F., Jr.; Weber, K. A. *J. Org. Chem.* **1986**, *51*, 1088–1094. (b) Wilcox, C. F., Jr.; weber, K. A. *Tetrahedron* **1985**, *41*, 4425–4436. (c) Wilcox, C. F., Jr.; Weber, K. A.; Abruna, H. D.; Cabrera, C. R. *J. Electroanal. Chem.* **1986**, *198*, 99–105.

[3] (a) Wilcox, C. F., Jr.; Blain, D. A.; Clardy, J.; Xu, C.-F. *J. Org. Chem.* **1987**, *52*, 2635–2639. (b) Wilcox, C. F., Jr.; Blain, D. A.; Clardy, J.; Van Duyne, G.; Gleiter, R.; Eckert-Maksic, M. *J. Am. Chem. Soc.* **1986**, *108*, 7693–7702. (c) Wilcox, C. F., Jr.; Blain, D. A. *Tetrahedron* **1986**, *42*, 6389–6398.

[4] (a) Wilcox, C. F., Jr.; Uetrecht, J. P.; Grohman, K. K. *J. Am. Chem. Soc.* **1972**, *94*, 2532–2533. (b) Wilcox, C. F., Jr.; Uetrecht, J. P.; Grantham, G. D.; Grohmann, K. G. *J. Am. Chem. Soc.* **1975**, *97*, 1914–1920. (c) Wilcox, C. F., Jr.; Grantham, G. D. *Tetrahedron* **1975**, *31*, 2889–2895. (d) Obendorf, S. K.; Wilcox, C. F., Jr.; Grantham, G. D.; Hughes, R. E. *Tetrahedron* **1976**, *32*, 1327–1330. (e) Bekarian, P. G. Ph.D. Dissertation, Cornell University, 1981.

[5] (a) Wilcox, C. F., Jr.; Farley, E. N. *J. Org. Chem.* **1985**, *50*, 351–356. (b) Wilcox, C. F., Jr.; Farley, E. N. *J. Am. Chem. Soc.* **1983**, *105*, 7191–7192. (c) Wilcox, C. F., Jr.; Farley, E. N. *J. Am. Chem. Soc.* **1984**, *106*, 7195–7200.

[6] (a) Dewar, M. J. S.; Longuet-Higgens, H. C. *Proc. Roy. Soc.* **1952**, *A214*, 482–493. (b) Wilcox, C. F., Jr. *Tetrahedron Lett.* **1968**, 795–800. (c) Wilcox, C. F., Jr. *J. Am. Chem. Soc.* **1969**, *91*, 2732–2736.

[7] For a review of cyclopropenones, see: Eicher, T.; Weber, J. L. *Top. Curr. Chem.* **1975**, *57*, 1–109.

[8] For reviews of tropones, see: (a) Nozoe, T. *Pure Appl. Chem.* **1971**, *28*, 239–280. (b) Pauson, P. L. *Chem. Rev.* **1955**, *55*, 9–136.

[9] (a) Sprecher, R. F.; Garbisch, E. W., Jr. *J. Am. Chem. Soc.* **1969**, *91*, 6785–6800. (b) DePuy, C. H.; Isaks, M.; Eilers, K. L.; Morris, G. F. *J. Org. Chem.* **1964**, *29*, 3503–3508. (c) Ogliaruso, M. H.; Romanelli, J. G. *Chem. Rev.* **1965**, *65*, 261–367.

[10] Ogawa, H.; Nobuhiro, I. *Kagaku* (*Kyoto*) **1973**, *28*, 399–408.

[11] (a) Cotterell, G. P.; Mitchell, G. H.; Sondheimer, F.; Pilling, G. M. *J. Am. Chem. Soc.* **1971**, *93*, 259–261. (b) Brown, G. W.; Sondheimer, F. *J. Am. Chem. Soc.* **1969**, *91*, 760–761. (c) Pilling, G. M.; Sondheimer, F. *J. Am. Chem. Soc.* **1968**, *90*, 5610–5611.

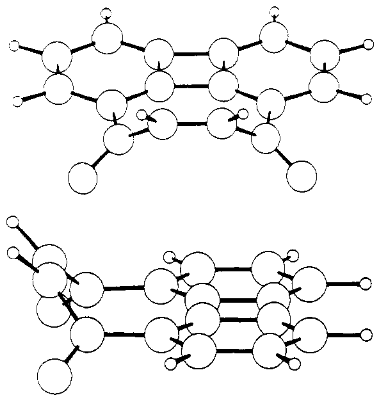

Figure 1. Two views of the MMPM structure of 3.

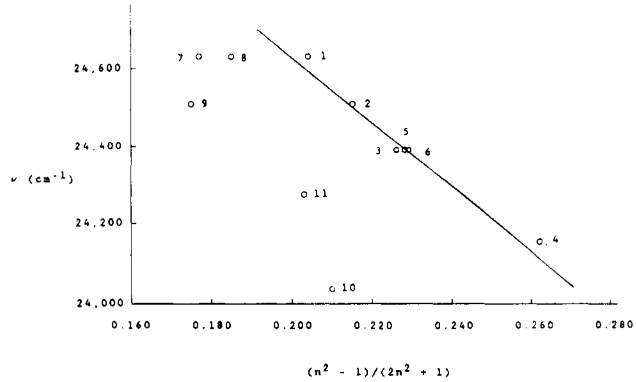

Figure 2. Affect of dispersion forces on the lowest energy transition in 3.

that 3 might exhibit several interesting properties. Contrary to previous expectation in which we reasoned that a biphenylene joined at the 1- and 8-positions with a four-carbon bridge would be constrained to planarity, calculations using the Allinger MMPM force field[12] indicated the minimum energy structure for 3 (Figure 1) was one in which the upper portion of the molecule was severely distorted from planarity. The torsional angle between the carbonyl groups and the plane defined by the biphenylene portion of the molecule in the calculated structure was nearly 34°; the torsional angle between the carbonyl and the olefinic bond in the eight-membered ring was 51.3°.

The energy difference between this distorted structure and one constrained to planarity was, however, only 2.28 kcal/mol. This difference was due primarily to a combination of strain and resonance energy effects. Constraining the system to planarity creates 3.79 kcal/mol of additional strain but results in 1.51 kcal/mol of resonance stabilization. The near balance of these effects brought up the interesting possibility that the distorted structure might be a calculational artifact and that the true structure might indeed be planar. Perhaps more interesting was the possibility that a transition between the distorted and planar structures could be induced by affecting the interplay between strain and resonance energy.

Table I. Hückel π Energies[a] for Planar and Nonplanar 3 as a Function of Oxygen Coulomb Integral

	α_0				
	0.00	-1.00	-2.00	-3.00	-4.00
planar	-24.261	-26.887	-30.323	-34.057	-37.906
nonplanar	-23.475	-26.046	-29.390	-33.061	-36.871
resonance stablization	0.786	0.841	0.933	0.996	1.035

[a] Energy in units of absolute β.

The difference in strain energy between the two forms clearly cannot be changed. The resonance energy, however, can potentially be controlled by variation of the polarity of the medium in which the molecule is contained. An increase in polarity would have the effect of increasing the importance of oxyanion–carbocation resonance forms which aromatize the eight-membered ring. This stabilization would be greater in the planar form, and hence, increased polarity would favor a flattening of the molecule. Since the molecular mechanics calculations refer to the system in the gas phase, it would not be surprising if the ability of solvent to stabilize charge separation might be enough to drive the system to planarity in solution.

In order to model the effect of solvation and to get a crude idea of the direction and magnitude of the stabilization, Hückel molecular orbital calculations were performed. An increase in polarity was modeled by adjusting the effective electronegativity on oxygen by variation of the Coulomb integral α_0. Torsional angles derived from the molecular mechanics calculations were used in calculations on the nonplanar system; the resonance integrals β were varied according to the relationship[13] $\beta = \beta_0 \cos \theta$, where θ is the torsional angle between the orbitals. The results in Table I indicate that, indeed, an increase in the magnitude of α_0 results in a significant preferential resonance stabilization for the planar form. In view of the crudity of the calculations, the magnitude of the stabilization should perhaps not be stressed, but if β is estimated as 20 kcal/mol, and α_0 for an unprotonated carbonyl oxygen is chosen as -1.0, the planar form is predicted to become energetically favored somewhere near an α_0 value of -4.0. While this value is clearly unreasonable for an unperturbed carbonyl oxygen, it is not too far out of line with the value one would expect for a protonated oxygen. Hence, although the calculations seemed to favor the distorted geometry in normal media, it appeared possible that a transition to planarity could be induced by protonation. This possibility, in addition to the potential of 3 as a synthetic intermediate, required that we develop a synthesis of this molecule.

Synthesis. Retrosynthetic analysis indicated 3 could be constructed in a straightforward fashion by oxidative cyclization[14] of the ketone dienolate derived from 1,8-diacetylbiphenylene (6). This strategy represented a significant departure from our standard methodology[2-5] in that the cyclization was to be done *intra*- rather than *inter*molecularly. The higher yield anticipated for this process would hopefully compensate for the additional steps required for the synthesis of 6.

An initial attempt to produce 6 by oxidation[16-19] of 1,8-dimethylbiphenylene[15] (4) followed by addition of

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(12) Allinger, N. L.; Yuh, Y. H. *QCPE* **1981**, *13*, 395.

(13) Streitwieser, A., Jr. *Molecular Orbital Theory for Organic Chemists*; John Wiley and Sons: New York, 1961; p 105.

(14) (a) Ito, Y.; Konoike, T.; Harada, T.; Saefusa, T. *J. Am. Chem. Soc.* **1977**, *95*, 1487–1493. (b) Babler, J. H.; Haack, R. A. *Synth. Commun.* **1983**, *13*, 905–911.

(15) Wilcox, C. F., Jr.; Lassila, K. R.; Kang, S. *J. Org. Chem.* **1988**, *53*, 4333–4339.

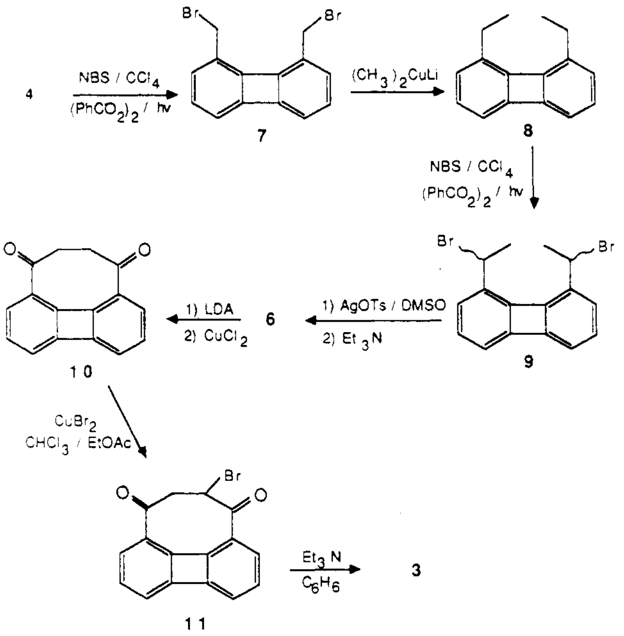
(16) Gilman, H.; Brannen, C. G.; Ingham, R. K. *J. Am. Chem. Soc.* **1956**, *78*, 1686–1689.

(17) (a) Whitmore, F. C.; Woodward, G. E. *Organic Syntheses*; Wiley: New York, 1941; Collect. Vol. I, pp 159–161. (b) Clarke, H. T.; Taylor, E. R. *Organic Synthesis*; Wiley: New York, 1943; Collect. Vol. II, pp 135–136.

(18) Wilcox, C. F., Jr.; Sheffy, F. K. Unpublished results.

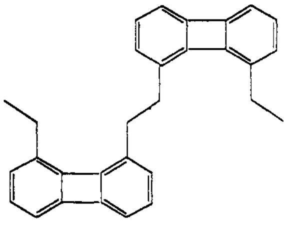
(19) Schmitt, V. G.; Ozman, S.; Klein, P. *Chem. Zeitung* **1980**, *104*, 241–242.

Scheme I



CH_3Li[20] to the resulting diacid produced sufficient material to demonstrate the feasibility of the oxidative coupling reaction, but the low yield (<4% for the conversion of **4** to **6**) led us to explore the route illustrated is Scheme I.

This approach involved synthesis of **6** by functionalization of 1,8-diethylbiphenylene (**8**). Attempted synthesis of **8** by reaction of the dianion derived from **4**, generated either by direct deprotonation or by metalation of 1,8-bis(bromomethyl)biphenylene (**7**), followed by treatment with electrophiles was unsuccessful under a variety of conditions.[19,21] However, treatment of **7** with $(CH_3)_2CuLi$[22] afforded 1,8-diethylbiphenylene (**8**) in 54% yield. This yield was somewhat lower than would be expected even after accounting for the fact that there are two reactive sites in the molecule. Further analysis of the reaction mixture revealed that a major side reaction was the formation of **12**, which was present in 24% yield. The formation of this material clearly points to the involvement of electron-transfer steps in cuprate additions.[23]



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NBS bromination of **8** led cleanly to 1,8-bis(1-bromoethyl)biphenylene (**9**, 90%). Attempted oxidation of **9**, using conditions previously employed for the preparation of 1,8-biphenylenedicarboxaldehyde from the corresponding dibromide (DMSO/collidine),[24] or by reaction with K_2CrO_4 in the presence of dicyclohexyl-18-crown-6 in HMPT,[25] produced only unchanged **9** even after reaction times as long as 5 days. Presumably S_N2 displacement of halide by DMSO or CrO_4^{2-} is slowed sufficiently in the presence of the additional bulk of the methyl group to become inoperative. We reasoned that the methyl could be used to advantage if the substitution were directed toward an S_N1 pathway and have found that indeed, silver-assisted departure of the halide allows the substitution to occur rapid and relatively cleanly. Addition of silver *p*-toluenesulfonate[26] to a solution of **9** results in immediate formation of a precipitate of AgBr. Elimination of dimethyl sulfide from the intermediate DMSO adduct by addition of NEt_3 followed by extractive workup and chromatography provided **6** in 59% yield. Small amounts of 1-acetyl-8-(1-bromoethyl)biphenylene (10%), 1-acetyl-8-vinylbiphenylene (5%), and 1-acetylbiphenylene-8-carboxaldehyde (8%) were also isolated.

The cyclization reaction[14] proceeded smoothly. The dienolate of **6**, generated by addition to a THF solution of LDA, was cyclized by treatment with either $CuCl_2$ or I_2. Under optimized conditions, the cyclized adduct **10** could be isolated in 56% yield. This represents a significant improvement over the intermolecular cyclizations that typically proceed in ca. 10% yield.[2-5]

Attempted direct oxidation of **10** to **3** failed under a number of conditions,[27,28,14] and an indirect procedure was therefore employed. Treatment of **10** with either pyridinium hydrobromide perbromide in HOAc[29] or with $CuBr_2$ in 1:1 $CHCl_3$–EtOAc[30] produced a mixture of starting material, 2-bromo-8*H*,9*H*-cycloocta[*def*]biphenylene-1,4-dione (**11**), and a small amount of a mixture of *meso*- and *d*,*l*-dibromides. These compounds were easily separated by chromatography.

Dehydrohalogenation of **11** with Et_3N provided **3** in 57% isolated yield. The formation of the unsaturated linkage was verified in several ways. The CO absorptions in both ^{13}C NMR and IR spectra of **3** (188.3 ppm, 1679 cm^{-1}) and **10** (195.0 ppm, 1692 cm^{-1}) indicate an increase in conjugation consistent with the formation of an olefinic bond. The ^1H NMR spectrum of **3** exhibits a singlet at 6.507 ppm. Although the observation of this resonance verifies the formation of the double bond, its relatively upfield position, and the fact that the biphenylenic protons are not shifted downfield significantly relative to those in **10**, seemed to indicate at least qualitatively that **3** was not significantly more conjugated than its unsaturated precursor. This conclusion is consistent with a number of other observations. Both **3** and **10** are nearly the same color and have similar R_f values in their thin-layer chromatograms. In addition, **3** is freely soluble in organic solvents as nonpolar as CCl_4, indicating that there is probably little dipolar character in the ground state of the molecule. The presence of unsaturation and the absence of dipolar character can be reconciled by postulating that **3** exists in the distorted geometry discussed above. In order to find out whether more detailed investigation would bear this out, a number of physical properties of **3** were studied. These results are described in the following sections.

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(20) Jorgenson, M. J. *Org. React.* **1970**, *18*, 1–97.

(21) Wilcox, C. F., Jr.; Farley, E. N.; Weber, K. A.; Lassila, K. R. Unpublished results.

(22) Posner, G. H. *Org. React.* **1975**, *22*, 253–422.

(23) Ashby, E. C.; Coleman, D. *J. Org. Chem.* **1987**, *52*, 4554–4565.

(24) Grantham, G. D. Ph.D. Dissertation, Cornell University, Ithaca, NY, 1975.

(25) Cardillo, G.; Orena, M.; Sandri, S. *Chem. Commun.* **1965**, 190.

(26) (a) Hoffmann, H. M. R. *J. Chem. Soc.* **1965**, 6748–6753. (b) Kornblum, N.; Jones, W. J.; Andersen, G. J. *J. Am. Chem. Soc.* **1958**, *81*, 4113–4114.

(27) (a) Walker, K.; Hiebert, J. D. *Chem. Rev.* **1967**, *67*, 153–195. (b) House, H. O.; Bashe, R. W., II *J. Org. Chem.* **1967**, *32*, 784–791. (c) Ringold, H. J.; Turner, A. *Chem. Ind.* **1962**, 211–212.

(28) Schaefer, J. P. *J. Am. Chem. Soc.* **1962**, *84*, 713–716.

(29) Fieser, L. F. *Experiments in Organic Chemistry*; D. C. Heath and Co.: Boston, 1955; p 65.

(30) King, L. C.; Ostrum, G. K. *J. Org. Chem.* **1964**, *29*, 3459–3461.

Table II. Solvatochromic Properties of 3 and 10[a]

				3		10
no.	solvent	refractive index (n)	$(n^2 - 1)/(2n^2 + 1)$	wavelength, nm	energy, cm^{-1}	wavelength, nm
1	C_6H_{12}	1.4260	0.204	406	24631	
2	CCl_4	1.4608	0.215	408	24510	410
3	toluene	1.4969	0.226	410	24390	
4	CS_2	1.6270	0.262	414	24155	414
5	benzene	1.5010	0.228	410	24390	410
6	*o*-xylene	1.5048	0.229	410	24390	
7	ether	1.3506	0.177	406	24631	406
8	EtOAc	1.3720	0.185	406	24631	408
9	CH_3CN	1.3440	0.175	408	24510	410
10	H_2NCHO	1.4440	0.210	416	24038	422
11	CH_2Cl_2	1.4240	0.203	412	24272	414

UV–Visible Spectroscopy. If 3 became significantly planar, the resulting increase in aromatic character would manifest itself physically as a substantial increase in the polarity of the ground state of the molecule. This should lead to a shift of electronic transitions to higher energy with increasing solvent polarity as a result of preferential stabilization of the polar ground state with respect to the excited state. Such a solvatochromic effect would be an indicator of the degree to which 3 is planar and aromatic.[31–33]

The energies of the longest wavelength transitions of 3 (and 10) in a variety of solvents are provided in Table II. The extinction coefficient for this transition (3550 M^{-1} cm^{-1}) indicate that it is a π–π^* transition. Inspection of the data for 3 in Table II indicates that for a wide range of solvent polarities, the change in energy for this transition in 3 varies by less than 600 cm^{-1} (1.7 kcal/mol). There appears to be no correlation with the polarity of the solvent, indicating there is relatively little dipolar character to the ground state of 3.

Both MINDO/3 and MNDO calculations[34] on the tub form of 3 indicate that the longest wavelength UV band is a π–π^* transition largely localized on the biphenylene ring (but with some charge transfer to the eight-membered ring) with the transition moment lying along the long axis of the biphenylene. These calculations are consistent with the data and support the thesis that 3 exists primarily in the distorted conformation even in solvents as polar as formamide.

Perhaps more convincing evidence that no marked flattening of 3 is occurring can be obtained by comparison with the data for the saturated analog, 10 (Table II). The parallelism between the data clearly indicates that delocalization about the eight-membered ring need not be invoked to explain these spectroscopic properties of 3.

NMR Spectroscopy. In order to firm up this conclusion, we examined the NMR spectra of 3, 6, and 10 in $CDCl_3$ solution in some detail. If 3 were in fact significantly delocalized, one would qualitatively expect to see the cycloocta protons as well as those in more remote positions be shifted downfield because of ring current effects.[5a,35] NMR spectra, referenced to internal TMS, were obtained at 200 MHz under standardized conditions and analyzed by using LAOCOON3.[36] The ortho proton (H_a) was distinguished from the para proton (H_c) on the basis of its larger coupling constant to the meta proton (H_b). This larger coupling constant is due to double-bond localization induced by the presence of the four-membered ring.[37] ^{13}C spectra were completely and unambiguously assigned by correlation of the proton resonances to ^{13}C resonances both one and three bonds away by using heteronuclear correlation two-dimensional NMR spectroscopy (HETCOR[38]).

Table III. ^1H and ^{13}C NMR Data for 3, 6, and 10[a,b]

	6	10	3
H_a	6.928	7.324	7.312
H_b	6.874	7.000	7.030
H_c	6.727	6.884	6.902
H_d	2.470	2.887	6.507
C_1	126.60	125.92	126.29
C_2	129.66	130.84	131.27
C_3	118.97	121.47	121.66
C_4	151.79	150.29	150.22
C_5	148.66	151.69	149.89
C_6	132.32	126.40	126.18
C_7	199.15	195.09	187.93
C_8	29.07	31.15	133.09

[a] δ values. [b] Numbering refers to Figure 2.

Examination of the ^1H NMR data in Table III indicates at least qualitatively that 3 is not significantly more diatropic than either 6 or 10. The quinonoid protons, which resonate at 6.507 ppm, appear somewhat upfield of the corresponding protons in benzoquinone (δ 6.80 ppm), naphthoquinone (δ 7.80 ppm), and 1,4-diphenyl-2-butene-1,4-dione (δ 8.00 ppm).[39] The biphenylenic protons in 3 resonate quite closely to the corresponding protons in 6 and 10. The absence of downfield shifts in both the quinonoid protons and those at remote positions seems to indicate that 3 is not significantly more diatropic than either 6 or 10. However, since the observed chemical shift differences arise from the superposition of ring current,[35] charge,[40] and local anisotropy[41] effects, it is conceivable that the charge and local anisotropy effects might be masking an enhanced eight-membered ring diatropism, and their influence needs to be considered.

The proximity of the quinonoid protons to the carbonyl groups, for example, makes them particularly susceptible

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(31) (a) Bayliss, N. S.; McRae, E. G. *J. Phys. Chem.* **1954**, *58*, 1002–1006. (b) Kosower, E. M. *J. Am. Chem. Soc.* **1958**, *80*, 3253–3260.

(32) For an excellent discussion of solvent polarity, see: Reichardt, C. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 29–40.

(33) (a) Bayliss, N. S. *J. Chem. Phys.* **1950**, *18*, 292–296. See also: (b) Longuet-Higgins, H. C.; Pople, J. A. *J. Chem. Phys.* **1957**, *27*, 192–194. (c) Weigang, O. E. *J. Chem. Phys.* **1960**, *33*, 892–899.

(34) Unpublished calculations done in collaboration with P. Bischoff, Organisch-Chemisches Institut der Universitat, Heidelberg, West Germany.

(35) For an extensive review of ring current theories, see: Haigh, C. W.; Mallion, R. B. *Prog. Nucl. Magn. Reson. Spectrosc.* **1980**, *13*, 303–344.

(36) (a) Bothner-By, A. A.; Castellano, S. M. In *Computer Programs for Chemistry*; Detar, D. F., Ed.; W. A. Benjamin, Inc.: New York, 1968; Vol. 1. (b) Bothner-By, A. A.; Castellano, S. LAOCN3; *QCPE* **1967**, *10*, 111.

(37) Barton, J. W.; Rowe, O. J. *Tetrahedron* **1985**, *41*, 1323–1328.

(38) (a) Bax, A. *J. Magn. Reson.* **1983**, *53*, 517–520. (b) Bax, A. *J. Magn. Reson.* **1983**, *52*, 330–334. (c) Rutar, V. *J. Am. Chem. Soc.* **1983**, *105*, 4095–4096.

(39) Pouchert, C. J.; Campbell, J. R. *The Aldrich Library of NMR Spectra*; Aldrich Chemical Company, Inc.: Milwaukee, 1974.

(40) For a review of charge density–NMR shift correlations, see: Farnum, D. G. *Adv. Phys. Org. Chem.* **1975**, *11*, 123–175.

(41) Gunther, H. *NMR Spectroscopy*; John Wiley and Sons: New York, 1980; pp 70–77.

Table IV. ^{1}H Chemical Shift Differences Due to Charge: Comparison with Observed Differences

compds	position	$\Delta\delta_C$	$\Delta\delta_H{}^q$	$\Delta\delta_H{}^{obsd}$	error
6–10	a	0.674	0.042	−0.396	0.438
	b	−1.176	−0.074	−0.126	0.052
	c	−2.479	−0.156	−0.179	0.001
6–3	a	0.306	0.019	−0.384	0.403
	b	−1.611	−0.101	−0.156	0.055
	c	−2.691	−0.168	−0.175	0.007
10–3	a	−0.368	−0.023	0.012	0.035
	b	−0.435	−0.027	−0.030	0.003
	c	−0.194	−0.012	−0.018	0.006

to local anisotropy effects.[42] Examination of molecular models indicates that the environment of the olefinic protons can vary from strongly deshielding to somewhat shielding depending on the conformation of the molecule. Inasmuch as distortion of the molecule would cause upfield shifts due to both local anisotropy and ring current effects, the upfield position of the cycloocta resonance is consistent with the distorted structure.

Local anisotropies are also a cause for concern in the consideration of the chemical shifts of the ortho protons (H_a) in **3**, **6**, and **10**, although evaluation of this effect can be avoided by limiting the analysis to the chemical shifts of the meta (H_b) and para (H_c) protons. In this case, however, the effect of charge on the chemical shifts proves to be a complication. For example, H_2 and H_3 in **3** resonate slightly downfield from the corresponding protons in **6** and **10**, but the difference is relatively small. In view of MMPM calculations, which indicate that the torsional angle between the carbonyl and the biphenylene portion of the molecule differs substantially in **3** (34°), **6** (45°), and **10** (17°), the small downfield shift of the biphenylenic protons in **3** relative to those in **10** could reasonably be interpreted as arising from the superposition of an upfield shift due to charge superposed on a downfield shift due to ring current.

In order to exclude this possibility, we developed a simple empirical model in which we estimated the magnitude of ring currents by analysis of a combination of ^{1}H and ^{13}C NMR data. A basic, and perhaps drastic, assumption in this treatment is that the chemical shift difference of a pair of protons in the meta and para positions of **1**, **6**, and **10** is due only to ring current and charge effects. In view of the structural similarity of these molecules it seems reasonable to assume that other contributions chemical shift difference are essentially constant.

If the charge sensitivity of ^{1}H chemical shifts is taken as 10 ppm/unit charge[43] and that of ^{13}C shifts is 160 ppm/unit charge,[44] the charge contribution of the ^{1}H chemical shift difference is given by eq 1. Since contributions other than those due to charge and ring currents have been assumed constant, any difference between $\Delta\delta_H{}^{obsd}$ and $\Delta\delta_H{}^q$ can be ascribed to ring current effects:

$$\Delta\delta_H{}^q = (10/160)\Delta\delta_C{}^q \qquad (1)$$

$$\Delta\delta_H{}^{rc} = \Delta\delta_H{}^{obsd} - \Delta\delta_H{}^q \qquad (2)$$

The results in Table IV indicate that except for protons adjacent to the carbonyl group, the fit between the $\Delta\delta_H{}^q$ values calculated from the ^{13}C NMR data and $\Delta\delta_H{}^{obsd}$ is quite remarkable considering the crudity of the model. The discrepancy for the ortho protons is not surprising in view of local anisotropy effects discussed above. The fact that it is unnecessary to invoke additional ring currents to account for any of the NMR data again indicates that, at least in normal media, **3** exists in a severely distorted conformation.

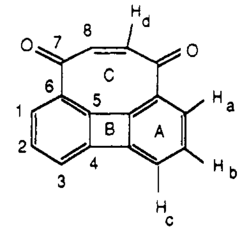

Figure 3. Numbering scheme for NMR data.

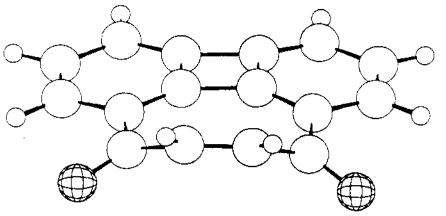

Figure 4. X-ray crystal structure of **3**.

X-ray Crystal Structure. The X-ray crystal structure of **3** was determined. Complete tables of fractional coordinates, thermal parameters, interatomic distances, interatomic angles, and torsional angles are available in the supplementary material.

The structure (Figure 3) is somewhat less distorted than the MMPM-generated structure. The torsional angle between the carbonyl and the plane of the biphenylene is about 19° and that between the carbonyl and the olefinic bond is 43°. There are, however, clear indications that the cycloocta portion of the molecule is highly localized. The quinonoid double bond, with a length of 1.344 Å, is very nearly a full double bond (1.337 Å).[45] In contrast, the bond from the quinonoid carbon to the carbonyl carbon (1.499 Å), is very nearly a full single bond (1.541 Å).[45]

The tub-shaped structure provides ready explanation for the NMR and UV–vis results above. We next explored the possibility of inducing a transition to planarity by protonation.

Spectrophotometric Titration of 3. Dissolution of **3** in CF_3CO_2H (TFA) containing CF_3SO_3H (TfOH) produces a purple solution. Although some decomposition occurs, **3** can be reisolated by extraction. A yellow solution is formed in pure TFA, indicating that the longer wavelength absorbances are due to species formed by protonation with TfOH. In order to study the protonation reaction more closely, a spectrophotometric titration of **3** was performed. The result of the titration is shown in Figure 4.

Incremental addition of TfOH to a TFA solution of **3** causes a diminution in the intensity of the band at 434 nm and the concomitant formation of a new band at 566 nm. The single set of isobestic points indicates that only one species is being formed by the protonation. The spectrum of **3** obtained in neat TfOH is the same as that obtained at the endpoint of the titration. Since 1,3-diacetylbenzene and 1,3,5-triacetylbenzene are fully protonated in TfOH[46] (Hammet acidity function $H_0 = 13$),[47] the species formed in the titration is most likely the diprotonated carbonyl compound. This is consistent with a titrimetric deter-

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(42) For an example of this effect, see: Gatto, K.; Reinheimer, J. D.; Shafer, K.; Gerig, J. T. *Org. Magn. Reson.* **1974**, *6*, 577–579.

(43) Garratt, P.; Sargent, M. V. *Nonbenzenoid Aromatics*; Snyder, J. P., Ed.; Academic Press: New York, 1971; Vol. 2, p 227.

(44) Spieseke, H.; Schneider, W. G. *Tetrahedron Lett.* **1961**, 468–472.

(45) Weast, R. C., Ed. *CRC Handbook of Chemistry and Physics*, 56th ed.; CRC Press: Cleveland, 1975; p F-211.

(46) Levy, G. C.; Cargioli, J. D.; Racela, W. *J. Am. Chem. Soc.* **1970**, *92*, 6238–6246.

(47) Howells, R. D.; McCown, J. D. *Chem. Rev.* **1977**, *77*, 69–92.

Table V. Chemical Shifts[a] for 3 in Protic Media

proton[b]	solvent			
	$CDCl_3$	TFA	TFA–TfOH[c]	TfOH
a	7.312	7.403	7.352	7.411
b	7.030	7.177	7.380	7.253
c	6.902	7.046	7.265	7.149
d	6.507	6.787	7.196	7.414

[a] Parts per million downfield from internal tetramethylsilane. [b] Figure 2. [c] Ratio of TFA TfOH is 2:1

mination of the number of protons reacting with **3**, which gave a value of 2.6 ± 0.5 (standard deviation).

The direct formation of the diprotonated species can reasonably be explained if **3** is half-protonated in TFA or if it reacts directly with two protons. It seems unlikely that the former is the case since in TFA ($H_0 = 0.04$),[48] the ratio of protonated to unprotonated dibenzotropone ($pK_a = -5.2$)[49] is only about 10^{-5}. The latter possibility seems plausible based on iterated Hückel calculations,[50] which indicate that protonation of the first carbonyl group actually *increases* the electron density on the other oxygen atom. It seems reasonable to conclude that **3** reacts directly with two protons.

NMR Spectra of 3 in Acidic Media. In order to determine if this diprotonation had induced a flattening of **3**, NMR spectra were determined in a number of solvents. Spectra were determined at concentrations of 4%, so it is unlikely that the chemical shift values differ significantly from values at infinite dilution. Field stability was maintained by locking the spectrometer with D_2O contained in a capillary inside the sample tube. Assignments were made by using LAOCOON3.[37] The chemical shifts are presented in Table V.

Chemical shift differences for the protonated and unprotonated species were calculated by assuming a distorted geometry for the unprotonated molecule and either a distorted or planar structure for the protonated species. The MMPM geometry was used for calculations on the distorted structure. The effect of twist angles in the distorted structure was again accounted for by variation of the resonance integral according to the relation $\beta = \beta_0 \cos \theta$, where θ is the torsional angle between the orbitals.[13] In the unprotonated species α_0 was set equal to -1.0; for the protonated species a value of either -2.0 or -3.0 was used.

Electron densities and ring currents were calculated by using iterated Hückel and Hückel–McWeeny models,[51] respectively. These results are tabulated in Table VI. Ring current shifts were determined by combining the ring currents with an in-plane segmented (Biot–Savart)[52] geometric model.[53] Charge shifts were calculated by assuming a 10 ppm downfield shift per unit positive charge. The chemical shift differences calculated for the protonated and unprotonated species were then added to the values for the unprotonated species observed in $CDCl_3$ to obtain the expected chemical shifts upon protonation. These values are reported in Table VII.

The values calculated using the distorted geometry clearly agree quite well with the experimental values determined in TfOH. It would appear that the best quantitative fit would be obtained with an α_0 value somewhere between -2.0 and -3.0, although this point was not investigated. This is in good agreement with the recommended value of -2.5 for a protonated carbonyl group.[54] In general, the assumption that the molecule becomes planar on protonation results in overestimation of both ring current and charge shifts, causing the calculated values to appear significantly downfield from those observed. Thus the hypothesis that the molecule flattens significantly in TfOH solution is inconsistent with the data.

Experimental Section

All melting points were determined with a Thomas Hoover oil immersion capillary melting point apparatus and are uncorrected. ^1H NMR spectra were recorded at 200 MHz on a Varian XL200 spectrometer (chemical shifts in ppm downfield from internal tetramethylsilane at 0.000 ppm). Concentrations were typically 5 mg per 0.5 mL. The data are presented as follows: chemical shift (number of protons, multiplicity, coupling constants in hertz). ^{13}C NMR spectra were recorded on a JEOL FX90Q at 22.49 MHz or a Varian XL400 at 100.53 MHz and are proton decoupled. Chemical shifts are reference to the central resonance of the solvent multiplet ($CDCl_3$ δ 77.000 ppm). Mass spectra were obtained on AEI MS902 or Finnigan 3300 mass spectrometers using 70-eV electron impact ionization. UV–vis spectra were obtained on a Hewlett-Packard HP8450A diode array spectrometer in 1.0-cm quartz cuvettes.

All reaction products were spectroscopically (NMR, MS) homogeneous and exhibited acceptable melting point ranges; purities are estimated as >95%.

The HETCOR[36] experiments were performed on a Varian XL400 spectrometer using the software supplied with the instrument. The experiments were optimized for the observation of 140-Hz couplings in the one-bond correlations and 8-Hz couplings in the three-bond correlations.

Polygram Sil G/UV_{240} plates were used for TLC; Baker silica gel (ca. 40 nm average particle diameter) activated at 120 °C for 12 h was used for flash chromatography.

N,*N*-Dimethylformamide (DMF) was dried over powdered 4-Å molecular sieves. Hexamethylphosphoric triamide (HMPT), dimethyl sulfoxide (DMSO), Et_3N, and i-Pr_2NH were dried by distillation from CaH_2. Tetrahydrofuran (THF) was freshly distilled from Na/benzophenone ketyl. *N*-Bromosuccinimide (Mallinkrodt) was used as received. $CuCl_2$ was dried at 120 °C until it was the brown color characteristic of the anhydrous form.

1,8-Biphenylenedicarboxylic Acid (5). To a stirred suspension of *t*-BuOK (11.9 g, 100 mmol) in dry HMPT (20 mL) was added **4** (0.90 g, 5.0 mmol). Dry O_2 was admitted to the reaction vessel by means of a tube with a sintered-glass end placed at the bottom of the mixture. The mixture was heated to 100 °C, first become purple and then lightening to tan. After 24 h, O_2 flow was stopped, and the bright yellow emulsion was poured into ice-water (500 mL). The resulting yellow solution was acidified to pH 1 with concentrated HCl, and the precipitate was collected, rinsed with H_2O, and dried in a heated vacuum dessicator to afford 0.98 g of bright yellow powder. A suspension of this powder was brought to boiling in 200 mL of EtOH and filtered hot, and the filtrate was concentrated to 50 mL and cooled. Filtration afforded 0.28 g (23%) of yellow solid having properties that agreed with those reported[55] for **5**.

1,8-Diethylbiphenylene (8). $(CH_3)_2CuLi$ was prepared by adding CH_3Li (280 mL, 1.8 M solution in Et_2O, 500 mmol) to a stirred suspension of CuI (47.5 g, 250 mmol) in 200 mL of dry THF at 0 °C under N_2. Under positive N_2 purge, **7** (8.45 g, 25 mmol) was added to the reaction vessel as a solid. The mixture was stirred at 0 °C for 6 h and then allowed to stand at that temperature for an additional 14 h. The resulting black solution was poured carefully into a separatory funnel containing 500 mL of 4 N HCl. The suspension that formed was extracted with 500 mL of Et_2O. The aqueous layer and much of the solid were removed, and the organic layer was washed with H_2O (3 × 500

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(48) Rochester, C. H. *Acidity Functions*; Academic Press: New York, 1970; p 65.

(49) Arnett, E. M. *Prog. Phys. Org. Chem.* **1963**, *1*, 223–403.

(50) These calculations were performed assuming a planar geometry with $\alpha_0 = -1.0$. An α_0 value of -2.5 was used to simulate protonation of the oxygen. The actual electron densities obtained after eight iterations were 1.4816 (protonated) and 1.4802 (unprotonated).

(51) McWeeny, R. *Mol. Phys.* **1958**, *1*, 311–321.

(52) (a) Mallion, R. B. *Mol. Phys.* **1973**, *25*, 1415–1432. (b) Haddon, R. C. *Tetrahedron* **1972**, *28*, 3613–3633, 3635–3655.

(53) Wilcox, C. F., Jr.; Rigos, A. A., manuscript in preparation.

(54) Reference 13, p 135.

(55) Sheffy, F. K. Ph.D. Dissertation, Cornell University, 1982.

Table VI. Ring Currents and Electron Densities for Planar and Nonplanar 3

	α_0					
	distorted[b]			planar		
ring or position[a]	-1.00	-2.00	-3.00	-1.00	-2.00	-3.00
A	0.575	0.570	0.573	0.579	0.646	0.684
B	-0.799	-0.804	-0.813	-0.803	-0.840	-0.869
C	0.028	0.163	0.308	0.133	0.654	0.932
a	0.984	0.968	0.960	0.978	0.965	0.966
b	0.997	0.990	0.982	0.992	0.972	0.955
c	0.985	0.967	0.953	0.977	0.951	0.944
d	0.972	0.940	0.919	0.923	0.862	0.838

[a] Figure 2. [b] Using the MMPM geometry.

Table VII. Chemical Shifts Calculated for Protonated 3

	α_0			
	distorted		planar	
proton	-2.00	-3.00	-2.00	-3.00
a	7.532	7.692	7.926	8.112
b	7.122	7.286	7.513	7.796
c	7.114	7.286	7.502	7.694
d	7.081	7.637	8.811	9.588

mL) and brine (1 × 500 mL) and dried over $MgSO_4$. Filtration and evaporation of the solvent yielded a yellow oil. This was loaded onto a large silica gel column with minimal CCl_4 and eluted with hexane. The pale yellow oil that was isolated solidified on standing: 2.84 g (54%); mp 42–45 °C; TLC $R_f(C_6H_6)$ = 0.32; ^1H NMR ($CDCl_3$) δ 6.68–6.45 (6 H, m), 2.47 (4 H, q, J = 7.6 Hz), 1.19 (6 H, t, J = 7.6 Hz); ^{13}C NMR ($CDCl_3$) δ 150.5, 149.0, 133.5, 128.9, 128.3, 114.8, 25.7, 15.3; mass spectrum m/z (intensity) 209 (18.31), 208 (100.00), 194 (27.12), 193 (17.02), 191 (5.95), 189 (7.56), 179 (21.10), 178 (45.00), 177 (5.88), 176 (7.49), 165 (11.86), 152 (8.06), 89 (8.28), 76 (6.84); mass spectrum m/z 208.1253, calcd 208.1252 for $C_{16}H_{16}$. Further elution of the column with hexane–EtOAc (70:30) gave 2.08 g of material composed substantially of one compound. An analytical sample was prepared by column chromatography on silica gel (1.15 g, $R_f(CCl_4)$ = 0.32) followed by recrystallization from EtOH. The analytical data below were used to identify the material as **12**: mp 138.5–139.5 °C; ^1H NMR ($CDCl_3$) δ 6.727–6.455 (12 H, m), 2.707 (4 H, s), 2.485 (4 H, q, J = 7.6 Hz), 1.117 (6 H, t, J = 7.6 Hz); ^{13}C NMR ($CDCl_3$) δ 150.574, 150.379, 149.550, 148.770, 133.558, 130.632, 129.218, 128.828, 128.584, 128.389, 128.243, 115.079, 114.835, 33.899, 25.805, 15.326; mass spectrum m/z (intensity) 387 (43.00), 386 (100.00), 372 (20.76), 194 (12.53), 193 (79.54), 179 (18.14), 178 (49.43), 165 (17.48); mass spectrum m/z = 386.2026, calcd 386.2034 for $C_{30}H_{26}$.

1,8-Bis(1-bromoethyl)biphenylene (9). Into a 250-mL one-necked round-bottomed flask equipped with magnetic stirrer and reflux condenser were placed **8** (4.20 g, 20.2 mmol), NBS (7.3 g, 41 mmol), benzoyl peroxide (10 mg), and CCl_4 (150 mL). The mixture was refluxed for 12 h and cooled to room temperature, and the succinimide was removed by gravity filtration. The solvent was evaporated, and the residue was dissolved in 200 mL of boiling hexane, treated with Norit (1 g), and filtered hot. Removal of the solvent afforded 6.68 g (90%) of yellow solid: mp 107–111 °C (mixture of diastereomers); ^1H NMR ($CDCl_3$) δ 6.946–6.670 (6 H, m), 5.397–5.229 (2 H, apparent sextet, J = 7.0 Hz), 2.058–2.007 (6 H, overlapping doublets, J = 7.0 Hz); ^{13}C NMR ($CDCl_3$) δ 150.0, 149.9, 147.6, 146.9, 133.5, 132.9, 129.7, 129.5, 126.2, 125.4, 116.8, 116.6, 45.7, 45.5, 26.2, 25.1; mass spectrum m/z (intensity) 369 (1.30), 368 (8.07), 367 (3.37), 366 (16.51), 365 (1.70), 364 (9.09), 287 (32.68), 285 (31.05), 206 (38.17), 205 (100.00), 190 (33.80); mass spectrum m/z = 363.9464, calcd 363.9463 for $C_{16}H_{14}{}^{79}Br_2$.

1,8-Diacetylbiphenylene (6). A. By Oxidation of 7. To a solution of **7** (2.33 g, 6.34 mmol) in dry DMSO (70 mL) was added AgOTs (3.89 g, 13.95 mmol) in one portion as a solid. A white precipitate formed immediately. The mixture was stirred at room temperature for 60 min and then treated with Et_3N (10 mL, excess). After being stirred at room temperature for 30 min, the mixture was filtered into a separatory funnel; the filter paper was rinsed thoroughly with Et_2O (7 × 100 mL). The combined filtrates were washed with 5% H_2SO_4 (2 × 250 mL), and brine (3 × 250 mL), dried ($MgSO_4$), and filtered. Evaporation of the solvent yielded a yellow crystalline solid (1.39 g), which was recrystallized from 40 mL of CH_3OH to give dark yellow flakes: (0.79 g, 53%); mp 164–165 °C; TLC R_f (70:30 hexane–EtOAc) = 0.32, $R_f(CH_2Cl_2)$ = 0.08; ^1H NMR ($CDCl_3$) δ 6.928 (2 H, dd, J = 8.4 Hz, J = 0.6 Hz)8 6.874 (2 H, dd, J = 8.4 Hz, J = 7.0 Hz), 6.627 (2 H, dd, J = 7.0 Hz, J = 0.6 Hz), 2.46 (6 H, s); ^{13}C NMR ($CDCl_3$) δ 199.149, 151.789, 148.611, 132.315, 129.663, 126.595, 118.968, 29.072; mass spectrum m/z (intensity) 237 (21.86), 236 (94.25), 222 (17.58), 221 (100.00), 193 (22.56), 165 (59.36), 164 (14.72), 163 (19.72), 151 (12.50), 150 (14.75), 139 (13.94), 43 (26.11); mass spectrum m/z = 236.0834, calcd 286.0837 for $C_{16}H_{12}O_2$. The solvent was evaporated from the mother liquor, and the residue was purified by flash chromatography on silica gel with CH_2Cl_2 elution. This provided an additional 0.10 g of **6** (total yield 0.89 g, 59%). In another run, 1-acetylbiphenylene-8-carboxaldehyde (A, 8% yield), 1-acetyl-8-(1-bromoethyl)biphenylene (B, 10% yield), and 1-acetyl-8-vinylbiphenylene (C, 5% yield) were isolated. Their structures were determined by ^1H and ^{13}C NMR. A: ^1H NMR ($CDCl_3$) δ 10.61 (1 H, s), 7.30–6.73 (6 H, m), 2.51 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 196.994, 192.219, 153.633, 152.203, 151.556, 149.782, 130.619, 130.400, 129.843, 129.208, 127.983, 125.155, 120.361, 120.079, 27.373. B: ^1H NMR ($CDCl_3$) δ 7.10–6.54 (6 H, m), 5.03 (1 H, q, J = 7 Hz), 2.52 (3 H, s), 1.46 (3 H, d, J = 7 Hz); ^{13}C NMR ($CDCl_3$) δ 199.454, 152.249, 151.988, 151.519, 146.631, 139.934, 139.181, 128.794, 128.035, 127.391, 127.278, 119.079, 116.081, 66.538, 27.613, 23.275. C: ^1H NMR ($CDCl_3$) δ 7.51 (1 H, dd, J = 19 Hz), 7.04 (2 H, apparent, J = 8 Hz), 6.90–6.77 (2 H, complex m), 6.70 (1 H, d, J = 8 Hz), 6.54 (1 H, d, J = 7 Hz), 5.66 (1 H, d, J = 19 Hz), 5.34 (1 H, d, J = 12 Hz), 2.49 (3 H, s).

B. By Addition of CH_3Li to 5. Into an oven-dried 50-mL one-necked round-bottomed flask equipped with magnetic stirrer, septum cap, and N_2 inlet were placed **5** (234 mg, 0.98 mmol) and 30 mL of dry THF. The reaction vessel was cooled to −78 °C, and a solution of CH_3Li (3.40 mL 1.47 M solution in Et_2O, 5.0 mmol) was added to the bright yellow solution dropwise via syringe. Addition of slightly over 2 equiv caused a sudden onset of a deep purple color. After the addition was completed, the mixture was warmed to 0 °C and stirred for 2 h. The thick slurry was poured carefully into a separatory funnel containing 100 mL of iced 4 N HCl, and this was extracted with Et_2O (2 × 75 mL). The combined Et_2O layers were extracted with 10% NaOH (3 × 50 mL) and brine (1 × 50 mL), dried ($MgSO_4$), filtered, and evaporated to give a yellow solid. Chromatography as above produced 47 mg (20%) of **6** with spectral properties identical with those in the previous experiment.

8*H*,9*H*-Cycloocta[*def*]biphenylene-1,4-dione (10). LDA was prepared by adding n-BuLi (1.90 mL of a 1.16 M solution in hexanes, 2.2 mmol) to a stirred solution of i-Pr_2NH (350 μL, 250 mg, 2.5 mmol) in 30 mL of dry THF at 0 °C under N_2. After 15 min, the solution was cooled to −78 °C and treated dropwise with a solution **6** (236 mg, 1.0 mmol) in 20 mL of dry THF. The solution was stirred at −78 °C for 15 min, warmed to 0 °C, and transferred dropwise via cannula over a 15-min period to a solution of dry $CuCl_2$ (2.7 g, 20 mmol) dissolved in 100 mL of dry DMF cooled to −78 °C. The resulting solution, originally green and now quite dark, was stirred for 15 min, warmed to room temperature, and poured into a separatory funnel containing 4 N HCl (500 mL). The aqueous layer was extracted with $CHCl_3$ (3 × 150 mL), and the combined organic layers were washed with 4 N HCl (1 × 300 mL), H_2O (1 × 300 mL), saturated aqueous $NaHCO_3$ (1 × 300

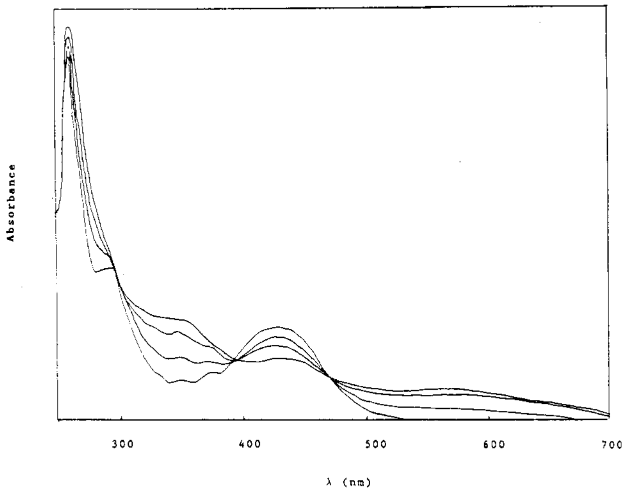

Figure 5. Spectrophotometric titration of **3**. Spectra shown were measured after the addition of 0, 10, 20, and 40 μL of TfOH.

mL), and brine (1 × 300 mL). The solution was dried (Na_2SO_4) and filtered, and the solvent was evaporated to afford a yellow solid. This was purified by flash chromatography on silica gel (hexane–EtOAc 70:30) to give 167 mg of yellow solid. A second chromatography with CH_2Cl_2 was necessary to obtain pure material: 131 mg, 56%; TLC R_f (hexane–EtOAc 70:30) = 0.34, $R_f(CH_2Cl_2)$ = 0.07; ^1H NMR ($CDCl_3$) δ 7.324 (2 H, dd, *J* = 8.6 Hz, *J* = 1.1 Hz), 6.999 (2 H, dd, *J* = 8.6 Hz, *J* = 6.7 Hz), 6.884 (2 H, dd, *J* = 6.7 Hz, *J* = 1.1 Hz), 2.887 (4 H, s); ^{13}C NMR δ 195.087, 151.686, 150.284, 130.833, 126.397, 125.915, 121.459, 34.150; mass spectrum *m/z* (intensity) 235 (18.84), 234 (97.33), 206 (13.06), 178 (57.97), 165 (23.73), 151 (20.14), 150 (100.00), 89 (18.62), 75 (52.37), 58 (14.97), 43 (48.29); mass spectrum *m/z* = 234.0676, calcd 234.0681 for $C_{16}H_{10}O_2$.

2-Bromo-8*H*,9*H*-cycloocta[*def*]biphenylene-1,4-dione (11). A. With $CuBr_2$. A 10-mL one-necked flask was charged with **10** (91 mg, 0.39 mmol), $CuBr_2$ (174 mg, 0.78 mmol), $CHCl_3$ (2 mL), and EtOAc (2 mL). The mixture was refluxed for 30 min, during which time the suspended solid became a fine white powder. The solvent was removed, and the residue was purified by flash chromatography on silica gel; the column was eluted with CH_2Cl_2 followed by hexane–EtOAc, 70:30. The major product was **11**: 70 mg, 57%; mp 163–168 °C dec; TLC $R_f(CH_2Cl_2)$ = 0.32; ^1H NMR ($CDCl_3$) δ 7.370 (1 H, d, *J* = 8.8 Hz), 7.325 (1 H, d, *J* = 9.4 Hz), 7.066–6.732 (4 H, m), 5.025 (1 H, br s), 3.333 (2 H, br s); a ^{13}C NMR spectrum was not obtained due to dynamic NMR behavior at room temperature; mass spectrum *m/z* (intensity) 315 (10.80), 314 (55.52), 313 (16.66), 312 (60.11), 234 (14.97), 233 (86.48), 232 (10.44), 205 (18.11), 178 (43.15), 177 (18.35), 176 (63.01), 175 (13.10), 151 (34.52), 150 (100.00), 103 (10.68), 98 (14.12), 89 (16.29), 87 (10.68), 75 (41.52), 74 (18.41), 62 (10.74), 43 (11.95); mass spectrum *m/z* = 311.9815, calcd 311.9786 for $C_{16}H_9BrO_2$. Further elution of the column with hexane–EtOAc (70:30) afforded 30 mg (33%) of **10**.

B. With Pyridinium Hydrobromide Perbromide. Into a 10-mL one-necked round-bottomed flask were placed **10** (33 mg, 0.14 mmol), pyr·HBr_3 (46 mg, 0.14 mmol), and glacial HOAc (5 mL). The mixture was stirred at room temperature for 1 h and poured into 50 mL of H_2O. The resulting precipitate was extracted into $CHCl_3$ (3 × 30 mL), and the combined extracts were washed with H_2O (1 × 30 mL), saturated aqueous $NaHCO_3$ (2 × 30 mL), and brine (1 × 30 mL). The yellow solution was dried ($MgSO_4$), and the solvent was removed. Chromatography as above afforded **11** (13 mg, 30%) and starting material (11 mg, 33%).

Cycloocta[*def*]biphenylene-1,4-dione. Et_3N (39 μL, 28.3 mg, 0.28 mmol) was added to a stirred solution of **11** (77 mg, 0.25 mmol) in C_6H_6 (5 mL). The solution was stirred at room temperature for 5 h; a white precipitate formed. The mixture was applied directly to a column of silica gel and eluted with hexane–EtOAc (70:30). The fractions containing product were further purified by silica gel flash chromatography with $CHCl_3$ elution to afford a yellow solid: 33 mg (57%); mp 162–165 °C; TLC R_f (hexane–EtOAc, 70:30) = 0.32, $R_f(CHCl_3)$ = 0.29; ^1H NMR ($CDCl_3$) δ 7.312 (2 H, dd, *J* = 8.8 Hz, *J* = 1.1 Hz), 7.030 (2 H, dd, *J* = 8.8 Hz, *J* = 6.9 Hz), 6.902 (2 H, dd, *J* = 6.9 Hz, *J* = 1.1 Hz), 6.507 (2 H, s); ^{13}C NMR ($CDCl_3$) δ 187.926, 150.221, 149.888, 133.086, 131.274, 126.289, 126.181, 121.659; mass spectrum *m/z* (intensity) 234 (30.95), 233 (26.96), 232 (100.00), 205 (9.46), 204 (35.33), 178 (27.97), 177 (12.04), 176 (69.14), 175 (8.75), 174 (7.72), 151 (18.63), 150 (98.12), 149 (10.97), 99 (8.84), 98 (12.82), 89 (14.00), 88 (12.32), 87 (11.67), 76 (9.43), 75 (48.46), 74 (19.67), 62 (13.27); mass spectrum *m/z* = 232.0525, calcd 232.0524 for $C_{16}H_8O_2$.

Spectrophotometric Titration of 3. A solution of ca. 1 × 10^{-4} M **3** in TFA was prepared, and a 3.0-mL aliquot was introduced to a quartz cuvette by means of a pipette. The cuvette was placed in the UV–visible spectrometer, and the spectrum was recorded for wavelengths between 250 and 700 nm. The solution had a maximum absorbance intensity between 1 and 2. Additional spectra were obtained after TfOH had been added in 10-μL increments to a total of 100 μL and then after 50-μL increments to 300 μL. A few of these spectra are displayed in Figure 5.

The number of protons reacting was determined from the slope of a plot of log *R* vs log [TfOH) where *R* is the ratio of the concentration of the protonated species to that of the unprotonated species. The concentration of the unprotonated species was obtained from the intensity of the band at 434 nm; the concentration of the protonated species was obtained by difference. The slope of the plot was 2.6 ± 0.5, indicating that within experimental error the compound is reacting with two protons.

Single-Crystal X-ray Structure Determination of 3. Crystals of **3** were grown by slow evaporation of a CH_2Cl_2 solution. A roughly cubic crystal with edges ca. 0.4 mm was cut from a larger crystal and used in all subsequent experiments. Preliminary X-ray photographs displayed monoclinic symmetry and accurate lattice constants of a = 14.0270 (15) Å, b = 3.7860 (8) Å, c = 19.9310 (15) Å, and β = 94.927 (84)° were determined from a least-squares fit of 15 diffractometer measured 2θ values. The crystal density, 1.46 g/cm³, indicated that four molecules of **3** made up the unit cell. The systematic extinctions were consistent with the space group $P2_1/c$. All unique diffraction maxima with $2\theta \leq 114°$ were collected on a computer-controlled four-circle diffractometer using variable speed 1° ω-scans and graphite monochromated Cu Kα radiation (1.54178 Å). Of the 1408 reflections measured in this fashion, 970 (69%) were judged observed ($F_o \geq 3\sigma(F_o)$) after correction for Lorentz, polarization, and background effects.[56] A phasing model was found without difficulty using a multisolution tangent formula approach.[56] All non-hydrogen atoms were located on a ΔF synthesis after partial refinement of the non-hydrogen positions and thermal parameters. Block-diagonal least-squares refinements with anisotropic non-hydrogen atoms and fixed isotropic hydrogens converged to a crystallographic residual of 0.063 (R_w = 0.065).

Registry No. **4**, 36230-17-8; **5**, 119414-44-7; **6**, 119392-57-3; **7**, 36396-04-0; **8**, 115941-66-7; **9** (isomer 1), 119392-54-0; **9** (isomer 2), 119392-58-4; **10**, 119392-59-5; **11**, 119392-60-8; A, 119392-55-1; B, 119392-61-9; C, 119392-62-0; cycloocta[*def*]biphenylene-1,4-dione, 119392-56-2.

Supplementary Material Available: Tables of fractional coordinates, thermal parameters, iteratomic distances, interatomic angles, and torsional angles (7 pages). Ordering information is given on any current masthead page.

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(56) All crystallographic calculations were done on a PRIME 9955 computer operated by the Cornell Chemistry Research Computing Facility. Principle programs employed were the following: REDUCE and UNIQUE, data reduction programs by M. E. Leonwicz, Cornell University, 1978; MULTAN 81, and RANTAN 81, systems of computer programs for the automatic solution of crystal structures from X-ray diffraction data (locally modified to perform all Fourier calculations including Patterson syntheses) written by P. Main, S. E. Hull, L. Sessinger, G. Germain, J. P. Declercq, and M. M. Woolfson, University of York, England, 1978 and 1980; DIRDIF written by P. T. Beurskens et al., University of Nijmegen, Netherlands, 1981; MITHRIL, an automatic solution package by C. J. Gilmore, University of Glasgow, Scotland, 1983; BDLS78A, an anisotropic block diagonal least-squares refinement written by K. Hirotsu and E. Arnold, Cornell University, 1980; PL1PLOT, a crystallographic illustration program; and BOND, a program to calculate molecular parameters and prepare tables written by K. Hirotsu, Cornell University, 1978.