from the side opposite the one on which the rearrangements occur, in contrast to the acetone ion formed by isomerization from its enol isomer.[8] This is hard to explain, as a nonrandom distribution of energy presumably would stem from the isomerization step to **1**. Nonetheless, in light of the apparent asymmetry of their metastable decompositions, we conclude that the decomposing 3-pentanone ions generated by isomerizations probably contain a nonrandom distribution of internal energy. The above conclusion that loss of ethyl from these ions is orders of magnitude faster than the loss of ethane from **1** indicates that decomposition quickly follows slow isomerizations. Thus, the nonrandom distribution of energy would have to persist for at most 10^{-11}–10^{-10} s.

Experimental Section

Metastable peak intensities were recorded at 70 eV electron energy for decompositions occurring in the first field-free region of a Du Pont 21-491B or a Kratos-AEI MS 50 mass spectrometer by manually lowering the electric sector voltages. Energy releases were determined from uncorrected peak widths for decompositions taking place in the second field-free region of the MS 50. In this mode, metastable spectra were recorded free of normal spectra by deflecting the products of the metastable decompositions to a separate detector by means of a retarding potential. AE measurements were carried out on decompositions occurring in the first field-free region of the MS-50 by manually lowering the electron energy.

1-Ethylcyclopentanol was prepared by the addition of the ethyl Grignard to cyclopentanone. Ethanol-*1,1*-d_2 was prepared by reduction of acetic anhydride with $LiAlD_4$,[21] and converted to 1-bromoethane-*1,1*-d_2 with HBr/concentrated H_2SO_4. 1-Bromoethane-*2,2,2*-d_3 was similarly prepared starting with reduction of acetic-d_6 anhydride with $LiAlH_4$, and 1-bromoethane-*2*-d_1 was obtained starting with reduction of ethylene oxide with $LiAlD_4$. **1-Ethyl-*2*-d_1-cyclopentanol** and **1-ethyl-*1,1*-d_2-cyclopentanol** were prepared by addition of the corresponding ethyl Grignard reagents to cyclopentanone.

4-Methyl-3-heptanone was obtained from Pfaltz and Bauer, Flushing, N.Y. **4-Methyl-3-heptanone-*6,6*-d_2** (98% d_2, 2% d_1) was prepared by the $CuBr(CH_3)_2S$-catalyzed addition of CH_3CD_2MgBr to 2-methyl-1-penten-3-one.[22] **4-Methyl-3-heptanone-*4*-d_1** (93% d_1, 5% d_0) was prepared by the addition of C_2H_5MgBr to the same enone followed by workup with D_2O/DCl. **4-Methyl-3-heptanone-*1*-d_1** (99% d_1, 1% d_0) was prepared by addition of DCH_2CH_2MgBr to 2-methylpentanal followed by Jones oxidation. **4-Methyl-3-heptanone-*1,1,1*-d_3** (94% d_3, 6% d_2) and **4-methyl-3-heptanone-*2,2*-d_2** (96% d_2, 4% d_1) were prepared from the appropriate ethyl bromides and 2-methylpentanoyl chloride via the cadmium reagents.[23] **4-Methyl-3-heptanone-*2,2,4*-d_3** (86% d_3, 14% d_2) was prepared by refluxing 4-methyl-3-heptanone in $DCl/D_3PO_4/D_2O$. **4-Methyl-3-heptanone-*1,1,1,2,2,4*-d_6** (77% d_6, 20% d_5, 3% d_4) was similarly prepared from 4-methyl-3-heptanone-*1,1,1*-d_3.

1-Penten-3-ol, **1-penten-3-ol-*1*-d_1** (91% d_1, 9% d_0), and **1-penten-3-ol-*5,5,5*-d_3** (>54% d_3) were prepared by adding ethyl Grignard reagents to acrolein. **1-Penten-3-ol-*3*-d_1** (>88% d_1) and **1-penten-3-ol-*1,3*-d_2** (>53% d_2) were prepared by oxidation of 1-penten-3-ol and 1-penten-3-ol-*1*-d_1 to the corresponding 1-penten-3-ones in ether with chromic acid[24] followed by reduction with $LiAlD_4$.

1-Ethylcyclopentanol-*O*-d_1 (90% d_1, 10% d_0) and **1-penten-3-ol-*O*-d_1** (93% d_1, 7% d_0) were prepared by mixing the unlabeled compounds with D_2O followed by introduction with D_2O into the batch inlet of the mass spectrometer.

All synthesized compounds were either shown to be pure or were purified by gas chromatography.

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The Quinones of Azulene. A Theoretical Prognosis

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Abstract: Azuloquinones are unknown species of great interest because they are both quinones, which have important redox chemistry and appear in a variety of biologically important molecules, and derivatives of a nonalternant hydrocarbon. MINDO/3, Hückel, PPP, and ab initio SCF calculations with the STO-3G basis set have been used to predict the structures, stabilities, spectral properties, and reactivities of all members of this class of molecules.

Introduction

Quinones constitute one of the oldest known and most interesting classes of compounds in all of chemistry.[2] Naturally occurring quinones were exploited by the Chinese for medicinal purposes as early as 2700 B.C.,[3] and many more recently have been found to exhibit significant antifungal, antibiotic, antimalarial, or antitumor activity.[2,3] The birth of our organic chemical manufacturing industry in the middle 1800s was built around quinone pigments, some of which had been used for the dyeing of cotton since the days of ancient Egypt.[4] Still other quinones are known to play vital roles in photosynthesis[5] and in the respiratory electron transport chain,[6] in the biosynthesis of tetra-

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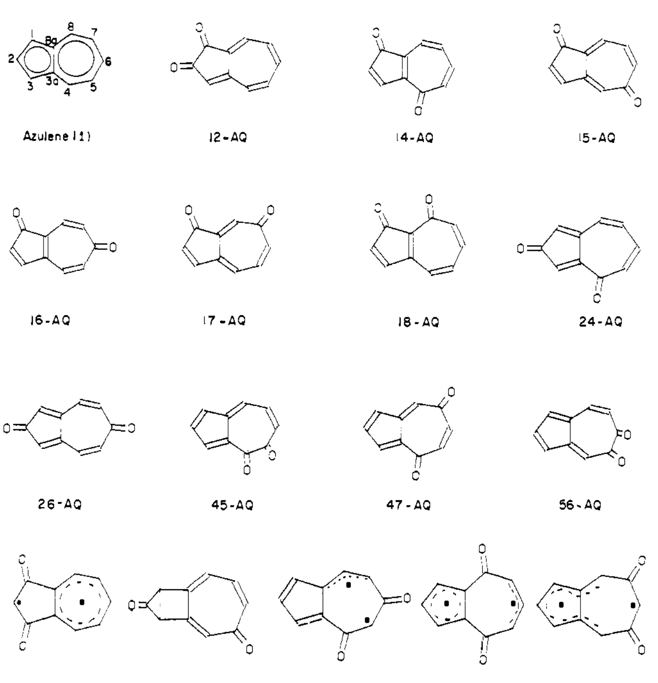

Figure 1. Azulene and the azuloquinones (AQs). Geometries shown are those obtained by MINDO/3 optimizations.[46]

cycline antibiotics[7] and of the aflatoxins,[8] in the mechanism of blood clotting,[9] in the defense mechanisms of various insects,[2b] and possibly also in the aging process.[10] The ease with which quinones suffer reversible reduction to semiquinones and hydroquinones is thought to account for their special ability to function in many of these roles.[3,11]

Nearly all quinones known today can be viewed as benzoquinones or quinones of polybenzenoid aromatic hydrocarbons. The last 2 decades, however, have witnessed an almost explosive growth in the field of nonbenzenoid aromatics,[12] i.e., compounds which display aromatic character despite the absence of benzene rings. The oldest and perhaps best known of these is azulene (**1**).[13] Figure 1 illustrates all the possible quinones of azulene ("azuloquinones" or AQs), including those for which no bicyclic Kekulé structure can be drawn, i.e., "nonclassical quinones" (cf. *m*-benzoquinone). The various compounds are given abbreviated names, 12-AQ for 1,2-azuloquinone, etc. Considering the long and colorful history of both azulene chemistry[13] and quinone chemistry,[2] it is surprising that not a single member of this extensive family is currently known.[47] Scattered reports of fused-ring derivatives have appeared,[14] and the fleeting existence of 1,3-bis(carboethoxy)-2,6-azuloquinone has been suggested,[15] but to our knowledge no simple quinone of azulene has ever been prepared and characterized.[47] At the confluence of two venerable avenues of research, these compounds will surely occupy a central position in the emerging field of nonbenzenoid quinone chemistry.

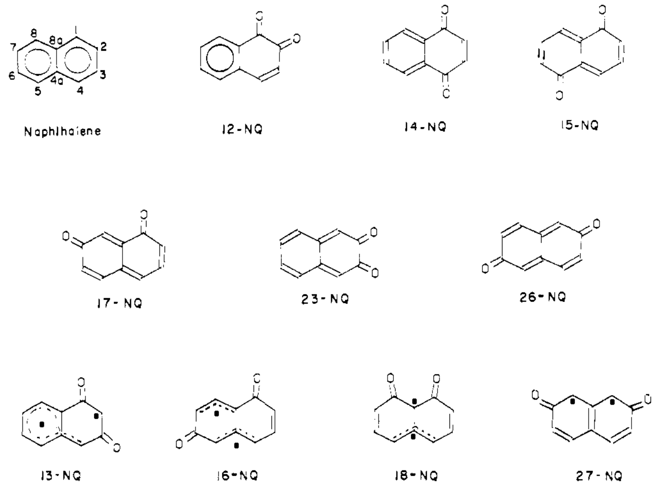

Figure 2. Naphthalene and the naphthoquinones (NQs). Geometries shown are those obtained by MINDO/3 optimizations.[46]

The azuloquinones belong also to another class of compounds which has attracted increasing attention in recent years, namely, fused bicyclics in which *both* rings comprise a nonbenzenoid cycle of p orbitals.[16] Several of the compounds in Figure 1 can be seen to contain a cyclopentadienone ring, a tropone ring, or both.[17] Theory and experiment suggest that the properties of neutral, purely hydrocarbon "annulenoannulenes" are dictated by the properties of the constituent rings, with the smaller ring dominating.[16] It will be interesting to see whether this generalization carries over to fused annulenones[17] and to what extent the mode of fusion plays a role (cf. 14-AQ vs. 16-AQ vs. 18-AQ).

As a testing ground for theories of structure, bonding, and reactivity in unsaturated carbonyl compounds, the azuloquinones appear uniquely attractive for several reasons. The abundance of isomers, for example, will permit extensive comparisons to be made within the set. Since it is well-known that theoretical calculations on the electronic nature of molecules generally prove more successful in predicting *differences* between similar substances than in predicting absolute quantities, no group of compounds could be more valuable than a set of isomers. Such a plethora of isomeric π systems as that shown in Figure 1 has little precedent in organic chemistry. The likelihood that some members of this family will exhibit very similar properties ensures a demanding challenge for whatever theoretical models are applied.

Aside from their abundance, the azuloquinones offer the added attractive feature of modest size. With only 18 atoms, $C_{10}H_6O_2$, these molecules fall well within the manageable range for even fairly sophisticated SCF-MO treatments. The fact that no simple azuloquinone has yet been characterized guarantees that all present calculations will constitute genuine predictions, rather than after-the-fact rationalizations. As these compounds become known in the future, their properties can be measured against the predictions. Finally, an immediate link to experimental data can be made through the naphthoquinones (also $C_{10}H_6O_2$, Figure 2), several of which are currently known.

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Table I. Results of Calculations on the Azuloquinones in Figure 1

compd	ΔH_f MINDO/3, kcal/mol	π-DE MINDO/3, kcal/mol	REPE Hückel, β	π-HOMO/LUMO gap MINDO/3, eV	π-HOMO/LUMO gap Huckel, β	π LUMO MINDO/3, eV	π LUMO Hückel, β	π HOMO MINDO/3, eV	π HOMO Hückel, β	highest n_0 MINDO/3, eV	second n_0 MINDO/3, eV
					"Classical"						
12-AQ	−0.4	+12.7	−0.001	7.72	0.46	−0.70	−0.24	−8.41	0.22	−8.71	−10.55
14-AQ	−0.8	+9.1	−0.003	7.77	0.40	−1.03	−0.11	−8.80	0.29	−9.34	−9.88
15-AQ	−6.4	+14.7	−0.002	8.64	0.53	−0.63	−0.24	−9.27	0.30	−9.52	−9.74
16-AQ	−0.6	+8.9	−0.002	7.70	0.41	−1.17	−0.11	−8.87	0.30	−9.63	−9.70
17-AQ	−5.3	+13.6	−0.001	8.35	0.51	−0.66	−0.23	−9.01	0.29	−9.25	−10.15
18-AQ[a]	−0.6	+8.9	−0.004	8.06	0.42	−0.94	−0.11	−9.01	0.31	−9.12	−9.97
24-AQ	+4.7	+3.6	−0.009	7.78	0.42	−1.16	−0.05	−8.94	0.37	−9.42	−10.02
26-AQ	+4.7	+3.6	−0.008	7.91	0.49	−1.28	−0.05	−9.18	0.44	−9.82	−9.74
45-AQ[a]	+7.0	+5.3	−0.001	7.86	0.52	−0.95	−0.03	−8.82	0.49	−9.26	−9.35
47-AQ	+7.2	+1.1	−0.005	8.23	0.50	−1.16	−0.04	−9.40	0.46	−9.71	−9.74
56-AQ[a]	+9.5	+2.8	−0.003	7.78	0.42	−0.96	−0.04	−8.74	0.38	−9.11	−9.96
					"Nonclassical"						
13-AQ	+14.2			6.16	0.38	−1.75	−0.23	−7.91	0.15	−8.81	−9.15
25-AQ[b]											
46-AQ	+56.8			5.20	0.22	−2.82	+0.15	−8.02	0.36	−9.06	−9.57
48-AQ	+54.1			4.99	0.35	−2.94	+0.11	−7.93	0.46	−9.63	−9.80
57-AQ	+50.5			5.28	0.08	−2.60	+0.07	−7.88	0.15	−8.98	−9.33

[a] Nonplanar geometry after optimization; some atoms out of plane by 0.1–0.3 Å. [b] This quinone is not an energy minimum but collapses to tricyclo[5.3.0.0^{8,10}]deca-1,4,6-triene-3,9-dione on optimization.

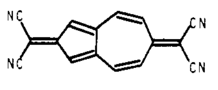
Table II. Calculated π-LUMO Coefficients of the Azuloquinones in Figure 1 (MINDO/3)

compd	C-1	C-2	C-3	C-3a	C-4	C-5	C-6	C-7	C-8	C-8a	O-1	O-2
						"Classical"						
12-AQ	0.28	0.22	0.15	−0.25	−0.38	0.33	0.34	−0.36	−0.22	0.33	−0.27	−0.21
14-AQ	0.29	0.29	−0.28	−0.48	−0.12	−0.25	−0.02	−0.36	0.17	0.44	−0.28	−0.11
15-AQ	0.33	0.25	−0.33	−0.23	0.08	0.28	0.34	−0.35	−0.28	0.36	−0.29	−0.24
16-AQ	−0.29	−0.31	0.28	0.47	0.13	−0.34	−0.01	0.32	−0.11	−0.44	0.29	0.01
17-AQ	0.25	0.37	−0.34	−0.41	0.34	0.34	−0.37	−0.22	0.03	0.12	−0.22	0.19
18-AQ[a]	0.28	0.31	−0.25	−0.45	−0.19	0.37	0.38	−0.23	0.08	0.46	−0.28	−0.08
24-AQ	0.37	0.30	0.37	−0.27	−0.23	−0.24	0.24	0.28	−0.26	−0.32	−0.30	−0.24
26-AQ	0.38	0.30	0.38	−0.31	−0.23	0.25	0.23	0.25	−0.23	−0.31	−0.30	−0.23
45-AQ[a]	−0.33	0.27	0.39	−0.27	−0.16	0.12	−0.33	0.24	0.43	−0.33	0.11	0.05
47-AQ	0.33	−0.25	−0.42	0.25	0.22	0.23	−0.20	−0.29	−0.38	0.32	−0.22	−0.28
56-AQ[a]	−0.42	−0.28	0.34	0.31	−0.43	−0.19	−0.12	−0.24	0.21	0.31	0.13	0.05
						"Nonclassical"						
13-AQ	0.09	0.01	−0.09	−0.42	−0.23	0.50	−0.01	−0.50	0.24	0.41	−0.12	0.12
46-AQ	−0.20	0.29	0.39	−0.09	−0.10	−0.27	0.02	0.54	0.10	−0.55	0.15	−0.07
48-AQ	0.28	−0.04	−0.32	−0.11	0.10	0.58	−0.02	−0.61	0.08	0.21	−0.17	−0.14
57-AQ	−0.57	0.00	0.56	−0.01	0.39	0.09	0.00	0.09	0.39	0.01	0.14	0.14

[a] Nonplanar geometry after optimization; p_z coefficient taken perpendicular to the approximate plane of the molecule.

Recent developments in theoretical chemistry have produced some remarkably successful methods for calculating physical and chemical properties of organic molecules. Prior calculations on benzenoid quinones,[18,24] including the naphthoquinones, have given results in good agreement with available experimental data; however, we are unaware of any previous theoretical work on the quinones of azulene.

Beyond the historical and theoretical interest in azuloquinones, these novel compounds could ultimately find certain practical applications. For example, a large number of quinones exhibit significant in vivo antitumor activity,[19] e.g., adriamycin, mitomycin C, streptonigrin, lapachol, the aziridinylquinones, and relatives thereof. More than 1500 quinones have been tested for antitumor activity by the National Cancer Institute; however, without exception, these have been *benzenoid* quinones.[19] The wide range of redox potentials and alkylating abilities expected for the azuloquinones and their derivatives qualifies them as promising candidates for antitumor testing. The preparation of tetracyanoquinodimethide analogues of the azuloquinones (e.g., **2**) would greatly expand the range of π acceptors available in the search for better solid-state organic conductors; the most widely used π acceptors to date have all been derived from benzenoid quinones, e.g., **3** and **4**.[20]



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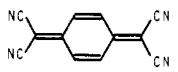

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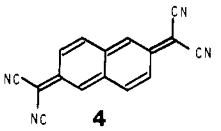

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Methods and Results

Hückel theory[21] is a venerable method for comparison of properties of conjugated molecules, while MINDO/3[22] is a reasonably reliable method for the prediction of heats of formation

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Table III. Results of Calculations on the Naphthoquinones in Figure 2

compd	ΔH_f MINDO/3, kcal/mol	π-DE MINDO/3, kcal/mol	REPE Hückel, β	π-HOMO/LUMO gap MINDO/3, eV	π-HOMO/LUMO gap Hückel, β	π-LUMO MINDO/3, eV	π-HOMO MINDO/3, eV
			"Classical"				
12-NQ	−16.9	+13.1	0.028	8.16	0.708	−0.77	−8.93
14-NQ	−22.7	+14.9	0.028	8.46	0.718	−0.80	−9.26
15-NQ	−9.4	+1.6	0.008	7.67	0.328	−1.26	−8.93
17-NQ	−7.3	−0.5	0.007	7.64	0.344	−1.32	−8.96
23-NQ	−0.4	−7.4	0.007	7.29	0.322	−1.26	−8.55
26-NQ	−7.1	−0.7	0.006	8.01	0.377	−1.41	−9.42
			"Nonclassical"				
13-NQ	+27.0			5.55	0.066	−2.56	−8.11
16-NQ	+29.5			4.99	0.052	−2.76	−7.75
18-NQ	+25.3			5.35	0.079	−2.49	−7.84
27-NQ[a]					0.014		

[a] The MINDO/3 calculation on this quinone did not converge.

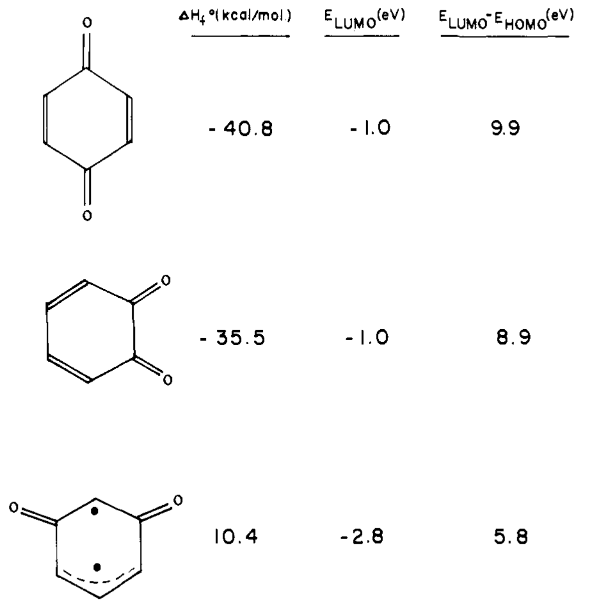


Figure 3. Geometries and properties of benzoquinones (BQs) according to MINDO/3. Geometries shown are those obtained by MINDO/3 optimizations.[46]

of CHNO molecules. We have used both methods, along with ab initio techniques using the STO-3G basis set,[23] to assess the stabilities and reactivities of azuloquinones. We have recently reported[24] that MINDO/3 and STO-3G techniques give excellent predictions of reactivities of substituted benzoquinones and naphthoquinones.

The results for azuloquinones are given in Tables I and II. From these data, predictions can be made about relative values of physical and chemical properties. To place these predictions on a more absolute scale, however, we have also carried out calculations on benzoquinones (BQs) and naphthoquinones (NQs). Results for BQs are given in Figure 3, and those for NQs in Table III.

Standard Hückel calculations, using the Hess and Schaad parameters for oxygen, were employed.[17] The MINDO/3 calculations were performed with optimization of all geometrical parameters with no assumptions whatsoever.[22] In several cases, the MINDO/3 optimized geometries were significantly nonplanar, and these structures are all shown in Figure 4. A major source of nonplanarity is the relief of eclipsing that can occur with

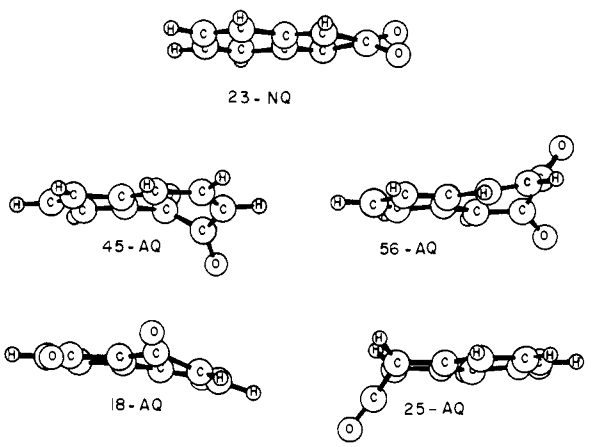
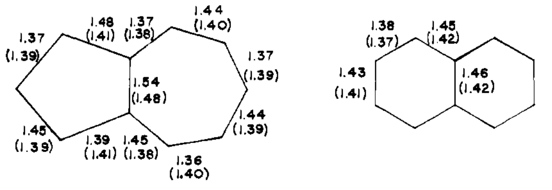


Figure 4. ORTEP plots of the quinones predicted to be nonplanar.[46]

1,2-diketones. Thus, 23-NQ, 45-AQ, and 56-AQ are significantly nonplanar. The slight nonplanarity of the tropone ring in 18-AQ also relieves peri interactions between oxygens. Finally, the nonclassical 2,5-azuloquinone is not an energy minimum but collapses to the highly strained cyclopropanone. This species is stabilized somewhat by the formation of a tropone ring upon cyclization to the tricyclic cyclopropanone, whereas the other nonclassical AQs can only form strained species without aromatic (tropone) stabilization.

The tendency of MINDO/3 to produce bond alternation in aromatic systems is manifested in calculations on azulene and naphthalene. In the drawings shown below, MINDO/3 and experimental bond lengths[25a] (in parentheses) are shown for these species.



Azulene is predicted to have only C_s symmetry,[25b] with alternating double and single (sp^2–sp^2) bonds, while the bond locali-

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(23) Hehre, W. J.; Stewart, R. F.; Pople, J. A. *J. Chem. Phys.* **1969**, *51*, 2657.

(24) Rozeboom, M. D.; Tegmo-Larsson, I.-M.; Houk, K. N. *J. Org. Chem.*, in press.

(25) (a) X-ray structure of azulene: Robertson, J. M.; Shearer, H. M. M.; Sim, G. A.; Watson, D. G. *Acta Crystallogr.* **1962**, *15*, 1. X-ray structure of naphthalene: Cruickshank, D. W. J.; Sparks, R. A. *Proc. R. Soc. London, Ser. A* **1960**, *258*, 270. (b) Dewar, M. J. S. *Pure Appl. Chem.* **1975**, *44*, 767. (c) Kollmar, H. *J. Am. Chem. Soc.* **1979**, *101*, 4832. (d) Bastiansen, O.; Derissen, J. L. *Acta Chem. Scand.* **1966**, *20*, 1319. (e) Tobler, H. J.; Bauder, A.; Günthard, Hs. H. *J. Mol. Spectrosc.* **1965**, *18*, 239. (f) Hanson, A. W. *Acta Crystallogr.* **1962**, *19*, 19. (g) Cox, J. D.; Pilcher, G. "Thermochemistry of Organic and Organometallic Compounds"; Academic Press: New York, 1970.

zation in naphthalene is slightly overestimated.

There is some doubt as to the actual structure of azulene. Kollmar recently found better agreement between the experimental dipole moment of azulene and that predicted by SCF calculations assuming C_s symmetry than obtained with calculations assuming C_{2v} symmetry.[25c] X-ray,[25a] electron diffraction,[25d] and microwave spectra[25e] have not provided definitive evidence for aromatic or bond-alternating structures, whereas a crystal structure of the azulene–trinitrobenzene complex indicates that all peripheral bonds of azulene have lengths of 1.395 ± 0.009 Å.[25f]

Classical Quinones

Thermodynamic Stabilities (ΔH_f and Delocalization Energies). The azuloquinones can be ranked in order of their MINDO/3 heats of formation from the lowest (most stable) to the highest as follows:

$$\text{AQs}\quad \Delta H_f\quad \text{MINDO/3:}\ 15 < 17 < [14,16,18,12] < [24,26] < [45,47] < 56$$

To the extent that the chemical reactivities of similar coupounds depend on their relative thermodynamic stabilities, the 1,5- and 1,7-azuloquinones are thus predicted to enjoy the greatest "chemical stability". The range of stabilities is rather large, with a gap of 16 kcal/mol separating the most stable from the least. It is interesting to note that all the 1,*n*-azuloquinones have $\Delta H_f < 0$, whereas all the *m*,*n*-azuloquinones ($m \neq 1$) have $\Delta H_f > 0$.

Other structural trends also emerge. The azuloquinones which contain a tropone ring (15- and 17-AQ) are more stable than those which contain a cyclopentadienone ring (24- and 26-AQ), whereas those which contain both types of annulenone rings (14-, 16-, and 18-AQ) fall in between. This agreement of the MINDO/3 calculations with our chemical intuition is most satisfying.[17] The stabilization due to a tropone unit (5.3–5.5 kcal/mol, e.g., conversion of 24-AQ to 14-AQ) is similar in magnitude to the destabilization caused by a cyclopentadienone unit (4.7–5.8 kcal/mol, e.g., conversion of 17-AQ to 18-AQ). Equally reasonable is the prediction that those azuloquinones bearing an electron-withdrawing group on the "exocyclic" double bond of a pentafulvene subunit should be relatively unstable (45-, 47-, and 56-AQ), while that with a carbonyl group on a heptafulvene unit is relatively stable (12-AQ). That is, the calculations confirm that tropylium-like species are preferred (aromatic), while cyclopentadienyl-cation-like species are disfavored (antiaromatic).

Confidence in these MINDO/3 values of ΔH_f is bolstered by the moderate agreement between calculation and experiment for 1,4-benzoquinone ($\Delta H_f^{\text{exptl}} = -29.3$ kcal/mol,[25g] cf. Figure 3) and 1,4-naphthoquinone ($\Delta H_f^{\text{exptl}} = -26.5$ kcal/mol,[25g] cf. Table III). The large negative ΔH_f for 14-NQ and for 12-NQ undoubtedly reflects the stabilizing contribution of the intact benzene ring present in these quinones. Of the "extended" naphthoquinones, 26-NQ has been known for many years,[26a] and the 3,7-di-*tert*-butyl derivative of 15-NQ was also reported recently,[26b] although the parent quinone has resisted characterization. The others remain unknown.

As an additional check on the validity of MINDO/3 relative energies, ab initio calculations using the STO-3G basis set[23] were performed for three of the quinones. For economic reasons, the MINDO/3-optimized geometries were adopted. Energies of 26-NQ, 15-AQ, and 26-AQ are −525.110 76, −525.095 32, and −525.077 59 au, respectively, i.e., relative energies of 0, +9.7, and +20.8 kcal/mol. MINDO/3 predicts the same order (ΔH_f^{rel} = 0, +0.7, +11.8 kcal/mol), although a somewhat smaller range.

The reactivities of the known naphthoquinones do indeed correlate roughly with their MINDO/3 ΔH_f values, which range from −22.7 to −7.1 kcal/mol. The azuloquinones predicted to be most stable lie just outside this range, although direct comparisons of ΔH_f values between the two sets of quinones are probably misleading, since chemical reactions of the AQs and NQs lead to very different products. A more meaningful comparison might be that of π-delocalization energies, since differences in strain energies of the carbon skeletons will not be part of these delocalization energies.

Delocalization energies are defined as the difference in energy between the ΔH_f of a compound and some reference value (ΔH_f^{ref}), the latter generally being obtained from an additivity scheme which ignores only the contribution of cyclic conjugation. For the MINDO/3 delocalization energies (π-DE) in Tables I and III, we have used ΔH_f^{ref} values obtained from the bond energy additivity scheme of Dewar and deLlano,[18a] which was extended to the quinones by Gleicher et al.[18b] To the reference heats of formation obtained from these bond-energy increments, an estimated correction for strain was added.[27] The Dewar and deLlano energy terms do not strictly give the appropriate reference energies, since they are obtained from empirical σ bond energy estimates, and SCF calculations for π energies. Bond energies from MINDO/3 for nondelocalized systems would be more appropriate. Nevertheless, we feel that this simple procedure gives a good qualitative indication of delocalization energies, except that the prediction of slight aromaticity for some of the azuloquinones may not be accurate. "Nonclassical" quinones cannot be treated by any simple additivity scheme, since the appropriate bond strengths are not available. The ranking of azuloquinones according to π-DE follows the same order as for ΔH_f, with the exception that all *o*-quinones move up slightly in the stability rankings (see below). The positive values of π-DE indicate a net stabilization resulting from cyclic conjugation in the azuloquinones, i.e., aromaticity, a feature not shared by the extended naphthoquinones.

Hückel calculations can also be used to predict delocalization energies. The resonance energy per electron (REPE) is taken as 1/12 the difference between the total Hückel π energy and a reference value obtained from the additivity scheme of Hess and Schaad.[17] This procedure predicts relatively small, negative REPEs in the range −0.001 to −0.009β for all the azuloquinones (cf. REPE = +0.007β for tropone and −0.016β for cyclopentadienone).[17] The relative ordering of azuloquinones according to Hückel REPEs differs very little from the MINDO/3 π-DE ordering, except for the *o*-quinones (12-, 45-, and 56-AQ), which rank higher in relative stability in the Hückel treatment.

$$\text{AQs}\quad \begin{array}{lll} \pi\text{-DE} & \text{MINDO/3} & [15,17,12] > [14,16,18] > 45 > [24,26,56] > 47 \\ \text{REPE} & \text{Hückel} & [12,45,17,15,16] > [14,56] > 18 > 47 > 26 > 24 \end{array}$$

This discrepancy most likely arises from a failure of the Hess and Schaad additivity scheme to differentiate among single bonds of the type C–C, C–CO, and OC–CO.

The order of stabilities of the naphthoquinones is approximately the same according to both MINDO/3 and Hückel calculations. For the least stable naphthoquinone, 2,7-NQ, according to the Hückel calculations, convergence was not obtained in the MINDO/3 calculations.

Electron Affinities, Reduction Potentials, and Charge-Transfer Complexes (LUMO Energies). In the spirit of Koopmans' theorem,[28] the electron affinity (EA) of a compound should equal the negative of its π LUMO energy (E_{LUMO}). Thus, the order of the electron affinities of azuloquinones should parallel the order of LUMO energies, those quinones with the highest E_{LUMO} having the lowest EA. Both MINDO/3 and Hückel predict that the three most stable AQs (15, 17, and 12) should have the highest LUMO energy, that is lowest EA, or lowest propensity to act as an electron acceptor.

$$\text{AQs}\quad E_{\text{LUMO}}\quad \begin{array}{ll} \text{MINDO/3} & [15,17,12] > [18,45,56] > 14 > [47,24,16] > 26 \\ \text{Hückel} & [12,15,17] > [18,16,14] > [26,24,47,56,45] \end{array}$$

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(26) (a) Willstatter, R.; Parnas, J. *Chem. Ber.* **1907**, *40*, 1406–1415. (b) Schmand, H. L. K.; Boldt, P. *J. Am. Chem. Soc.* **1975**, *97*, 447–448.

(27) A strain energy of 18.7 kcal/mol was assumed for the azuloquinones and 2.6 kcal/mol for the naphthoquinones. These values were estimated from Allinger's potentials for bending strain [Allinger, N. L.; Tribble, M. T.; Miller, M. A.; Werz, D. H. *J. Am Chem. Soc.* **1971**, *93*, 1637–1648] applied to MINDO/3-optimized geometries of 26-AQ and 26-NQ, respectively, and seem in line with the previously quoted value of 16 kcal/mol for the strain energy of azulene [Streitwieser, A., Jr. "Molecular Orbital Theory for Organic Chemists"; Wiley: New York, 1961; p 244].

(28) Koopmans, T. *Physica* (*Utrecht*) **1934**, *1*, 104–113.

Prior theoretical work on quinones has shown that electrochemical reduction potentials ($E_{1/2}$) correlate well with EAs, and several empirical linear relationships have been derived.[29] This correlation, together with Koopmans' theorem, leads to the prediction that the order of reduction potentials of azuloquinones should parallel the E_{LUMO} ordering, those quinones with the highest E_{LUMO} (15, 17-, and 12-AQ) being the least easily reduced.

On an absolute scale, the azuloquinones ($E_{\text{LUMO}} = -0.63$ to -1.28 eV) are actually predicted to be less easily reduced than the extended naphthoquinones ($E_{\text{LUMO}} = -1.26$ to 1.41 eV). The classical benzoquinones, which have $E_{\text{LUMO}} = -1.0$ eV, are similar to the azuloquinones in this regard. From the reported reduction potential for BQ and 26-NQ,[29] we predict that azuloquinones should all have reduction potentials ($E_{1/2}°$) below about 0.8 V.[47] This seems reasonable in light of the greater delocalization energy of the azuloquinones and the smaller delocalization energy of azulene[30] with respect to the naphthalene counterparts.

STO-3G calculations on representative quinones, using MINDO/3 optimized geometries, give the same E_{LUMO} ordering as obtained by MINDO/3; as usual, however, the STO-3G values are all too high by about 4.5 eV.[32]

	15-AQ >	26-AQ >	26-NQ
E_{LUMO} (STO-3G)	(4.27 eV)	(3.21 eV)	(3.08 eV)

From LUMO energies and Koopmans' theorem, vertical electron affinities are approximated. To obtain adiabatic electron affinities, one must determine the difference in ΔH_f between the quinone and its radical anion. We have calculated ΔH_f for representative radical anions both by MINDO/3 and by STO-3G, using MINDO/3-optimized geometries. The calculated values for EA^{vert} and EA^{adiab} do differ quantitatively, but the orderings are the same for several quinones. We therefore have some confidence that predictions based on E_{LUMO} do give the correct order of EA^{vert} or EA^{adiab}.

		15-AQ <	26-AQ <	26-NQ
EA^{adiab}	MINDO/3		1.78 eV	1.98 eV
	STO-3G	−2.74 eV	−1.75 eV	−1.75 eV

The ability of quinones to form charge-transfer complexes with a given π base has also been shown to correlate nicely with EA.[29] For the reasons presented above, then, the charge transfer acceptor ability of the azuloquinones should follow the LUMO order; the quinones with the highest E_{LUMO} (15-, 17-, and 12-AQ) should form the weakest complexes.

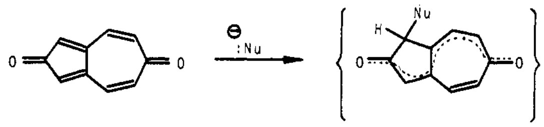
Michael Additions (LUMO Energies and Coefficients). Quinones share with many other electron-deficient π systems a susceptibility to Michael additions. In molecular orbital terms, such reactions can be viewed as an interaction between the LUMO of the acceptor molecule (quinone) and the HOMO of the nucleophile.[33] In the absence of other factors, the closer together these two orbitals lie in energy, the faster the reaction should be. It follows that the reactivities of the azuloquinones toward a given nucleophile should then correlate with their LUMO energies, those with the lowest lying LUMO being the most reactive. The azuloquinones of greatest thermodynamic stability (15- and 17-AQ) are thus predicted to enjoy also the greatest kinetic stability with respect to nucleophilic attack. The azuloquinones should all be less reactive in this respect than the extended naphthoquinones.

Table IV.[a] Comparison of PPP Predictions and Spectral Properties of Two NQs

12-NQ		14-NQ	
PPP λ_{max} (f)	obsd ($CHCl_3$) λ_{max} (log ϵ)	PPP λ_{max} (f)	obsd ($CHCl_3$) λ_{max} (log ϵ)
	520 (1.81)		425 (1.7)
377 (0.20)	400 (3.4)	335 (0.02)	
322 (0.06)	345 (3.4)	331 (0.11)	330 (3.5)
250 (0.71)		268 (0.76)	250 (4.3)
240 (0.09)		245 (0.25)	

[a] λ_{max} in nm.

Nucleophilic attack on a quinone should be favored at the atom with the largest LUMO coefficient.[24,23] We have recently shown that LUMO coefficients do, indeed, correctly predict sites of reaction of nucleophiles with substituted benzoquinones and naphthoquinones.[24] In Table II, the LUMO coefficients are given for the AQs. On 26-AQ, for example, attack should occur in the 1 position (eq 1). This example illustrates a special feature of the azuloquinones which benzenoid quinones do not share, viz., that nucleophilic addition can lead to an anionic intermediate wherein the negative charge is delocalized over both oxygen atoms. For those azuloquinones which contain a tropone unit (14-, 15-, 16-, 17-, and 18-AQ), MINDO/3 predicts preferential attack at the ring junction. The largest LUMO coefficients for the extended naphthoquinones are all predicted by MINDO/3 to be about 0.400, which is somewhat smaller than that for most azuloquinones.



(1)

Dimerization, Polymerization, and Color (π-HOMO/LUMO Gap). Bimolecular reactions involving identical molecules may also be analyzed in terms of the interaction between the HOMO of one partner and the LUMO of the other;[33] other factors being equal, the rate of dimerization (and polymerization) should be greatest for those compounds having the smallest HOMO/LUMO gap.[34] The HOMO for all azuloquinones is a π orbital according to MINDO/3.

AQs π-HOMO/LUMO GAP	MINDO/3	15 > 17 > 47 > 18 > 26 > 45 > [24,56,14] > [12,16]
	Hückel	[15,45,17,47,26] > 12 > [18,56,24,16,14]

As before, 15- and 17-AQ rank among the highest in kinetic stability; however, the other azuloquinones are not grouped in any obvious pattern. The Hückel treatment predicts a modest gap in the range of 0.40–0.53β, whereas the MINDO/3 results (7.70–8.64 eV) compare favorably with those for the naphthoquinones (7.29–8.46 eV). It is probably not accidental that the four known naphthoquinones are those with the largest π-HOMO/LUMO gaps. It is also amusing to note that they were prepared and characterized in order of the magnitude of their π-HOMO–LUMO gaps: 14-NQ (1873, 8.46 eV),[35] 12-NQ (1877, 8.16 eV),[36] 26-NQ (1907, 8.01 eV),[25] di-*t*-Bu-15-NQ (1975, 7.67 eV).[26]

The π-HOMO/LUMO gap is also related to the energy of the $\pi \rightarrow \pi^*$ electronic transition[37] and therefore to the color of these quinones. The naphthoquinones range in color from canary yellow for 14-NQ to orange for 12-NQ to red for the extended quinones (26- and 15-NQ),[38] in agreement with the ordering according to the π-HOMO/LUMO gap. While it is not necessarily correct

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[29] (a) Briegleb, G. *Agnew. Chem., Int. Ed. Engl.* **1964**, *3*, 617–632. (b) Davis, K. N. C.; Hammond, P. R.; Peover, M. E. *Trans. Faraday Soc.* **1965**, *61*, 1516–1522. (c) Chen, E. C. M.; Wentworth, W. E. *J. Chem. Phys.* **1975**, *63*, 3183–3191.

[30] Dewar, M. J. S. "The Molecular Orbital Theory of Organic Chemistry"; McGraw-Hill: New York, 1969; p 177.

[31] Wallenfels, K.; Mohle, W. *Chem. Ber.* **1943**, *76*, 924–936.

[32] Strozier, R. W.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1979**, *101*, 1340–1343.

[33] Houk, K. N. *Acc. Chem. Res.* **1975**, *8*, 361. Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: New York, 1976.

[34] Fukunaga, T. Third International Symposium on Novel Aromatic Compounds, San Francisco, Calif., Aug 1977.

[35] Groves, C. E. *J. Chem. Soc.* **1873**, *26*, 209–211.

[36] Stenhouse, J.; Groves, C. E. *J. Chem. Soc.* **1877**, *32*, 47–54.

[37] Laszlo, P.; Stang, P. J. "Organic Spectroscopy"; Harper and Row: New York, 1971; p 80.

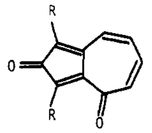
[38] (a) Fieser, L. F. "Organic Syntheses"; Wiley: New York, 1932; Collect. Vol. I, pp 383–385. (b) *Ibid.*, Collect. Vol. II; **1943**; pp 430–432. See also ref 23 and 24.

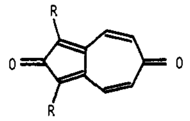
to compare HOMO–LUMO gaps in alternant hydrocarbons (e.g., naphthalene or NQs) to those in nonalternant hydrocarbons (e.g., azulene and AQs),[39] there should be a qualitative relationship between HOMO–LUMO gap size and color. Thus, using the colors of NQs for calibration, the data in Tables I and III lead to the prediction that the azuloquinones should also range in color from yellow to orange to red in the order shown above (decreasing π-HOMO/LUMO gap).

Since the HOMO-LUMO gap differs from the transition energy by the change in electron repulsion upon electron promotion, we have also calculated the transition energies for some of the AQs by the PPP π-electron method.[40] The MINDO/3 geometries were used as initial input, and a π-bond order, bond length criterion was used to reoptimize geometries. These calculations give reasonable predictions for the $\pi\pi^*$ transition energies in 12- and 14-NQ, as shown in Table IV.

The colors of these quinones are due to the long-wavelength $n\pi^*$ transitions, which were not calculated by these π-electron calculations. However, the reasonable agreement of the calculated $\pi\pi^*$ transition energies with the experimental values leads to some confidence in predictions made for the azuloquinones. These are summarized in Table V. The two AQs with the largest HOMO–LUMO gaps, 15- and 17-AQ, are predicted to have $\pi\pi^*$ λ_{max} of 371 and 394 nm, respectively, and, assuming some tailing into the visible, as well as the presence of lower energy $n\pi^*$ transitions, these compounds are expected to be light yellow in color. The remaining planar "classical" AQs are predicted to have λ_{max} of 529–596 nm (Table V), suggesting that these compounds will have intense purple to blue-green colors.[47] For comparison, the deep blue azulene has a λ_{max} of 580 nm.

Substituent Effects (LUMO Coefficients). Incorporation of donor substituents on an electron-deficient azuloquinone framework should raise the LUMO energy, with the greatest effect resulting from substitution on the position with the largest π-LUMO coefficient.[33,34] Since those positions are also predicted to be the most likely site for nucleophilic attack, a judicious placement of alkyl groups could impede Michael additions to the azuloquinones both by raising the LUMO energy and by simple steric hindrance. The positions at which alkyl substitution should have the most "stabilizing" effect can be read directly from Table II. For example, MINDO/3 and Hückel theory both predict that donor substituents on the cyclopentadienone ring of 24- and 26-AQ should be most effective in protecting these quinones from nucleophilic attack:





Chemical "instability" might also arise from dimerization or polymerization. As discussed above, these, too, are tied to the LUMO energy via the HUMO/LUMO gap. Donor substituents which raise the LUMO energy relative to the HOMO energy should widen the gap and retard dimerization conversely. Electron-withdrawing substituents at the same position should *lower* the π-LUMO energy, thereby enhancing the rates of bimolecular reactions. In light of this analysis, it is not surprising that attempts to prepare a 2,6-azuloquinone bearing carboethoxy substituents at the 1 and 3 positions gave only the corresponding dimer.[15]

Ionization Potentials (n_O and π-HOMO Energies). The first IP_V for all of the azuloquinones should be associated with electron loss from the π HOMO, which lies higher in energy than the nonbonding orbitals on oxygen according to MINDO/3 (Table I). The first ionization potentials for the azuloquinones (8.41–9.40 eV) are predicted to fall in the same range as those for the isomeric naphthoquinones (8.55–9.42 eV, Table V). For comparison, the highest π orbital of 14-BQ is calculated to lie at −10.91 eV by MINDO/3, whereas the experimental lowest π IP is 10.93 eV by photoelectron spectroscopy.[41]

Table V. Summary of Spectral Properties Predicted by PPP Calculations

compd	ϵ HOMO, eV	ϵ LUMO, eV	λ_{max} (f)
15-AQ	−9.65	−3.60	371 (0.38), 347 (0.00), 341 (0.14)
17-AQ	−9.50	−3.59	394 (0.31), 349 (0.19), 314 (0.03)
47-AQ	−9.93	−4.21	529 (0.05), 344 (0.13), 304 (0.62)
26-AQ	−9.70	−4.25	597 (0.02), 350 (0.60), 304 (0.03)
12-AQ	−8.89	−3.50	572 (0.04), 397 (0.40), 309 (0.13)
16-AQ	−9.43	−4.06	549 (0.05), 332 (0.07), 321 (0.23)
24-AQ	−9.42	−4.13	596 (0.07), 367 (0.22), 316 (0.08)

Geometries. In agreement with experimental data on known quinones,[42] the $C_{10}H_6O_2$ quinones are all predicted to show strong bond alternation. In the azulo- and naphthoquinones, the formal double bonds are all 1.35–1.40 Å, except for the C-4a, C-8a bonds in 12- and 14-NQ, which are 1.46 Å. The C–C single bonds are all 1.45–1.55 Å, the C–C(O) bonds are 1.48–1.54 Å, the C(O)–C(O) bonds are 1.53–1.55 Å, and the CO double bonds are 1.20–1.21 Å. Although most of the calculated bond lengths appear normal, one clear peculiarity stands out. In every case, for both sets of quinones, the bond shared by the two rings is longer than normal. For example, an elongated C=C of 1.40 Å is predicted for the azuloquinones having a formal double bond between positions 3a and 8a (14-, 16-, and 18-AQ). Both 24- and 26-AQ have an sp^2–sp^2 C–C bond length of 1.55 Å at that position. Similar patterns can be seen in the naphthoquinones. We interpret these data to imply that π,π interaction along the central bond is not especially favorable (cf. azulene[43]). However, MINDO/3 does systematically overestimate such bond lengths. For example, the central bond in naphthalene is predicted to be 1.441 Å, rather than the 1.419 Å found experimentally,[22] and the central bond of pentalene is predicted to be 1.553 Å, rather than 1.43 Å, as found experimentally[44] in the 1,3,5-tri-*tert*-butyl derivative.

Summary

Which of the azuloquinones will be the most stable? MINDO/3 clearly predicts 1,5-azuloquinone to have the most favorable ΔH_f and π-DE and also to be the least susceptible to dimerization, polymerization, Michael addition, and reduction. The closely related 1,7-azuloquinone probably ranks second overall, but beyond that no reliable "order of stability" can be constructed. Although 12-AQ ranks high in ΔH_f, π-DE, and resistance to reduction and Michael addition, it should dimerize rapidly. Precisely the reverse hold for 47-AQ. These examples illustrate the difficulties associated with further predictions of an "overall order of stability", although certain trends are clear. In general, the 1,*n*-azuloquinones have the most favorable MINDO/3 ΔH_f, π-DE, and $E_{1/2}$ and the highest Hückel π-LUMO energies; their susceptibility to dimerization, however, varies considerably.

The presence of certain subunits within an azuloquinone also correlates with predicted properties. By *all* measures, those azuloquinones which contain a tropone ring (15- and 17-AQ) appear more "stable" than those which contain a cyclopentadienone ring (24- and 26-AQ), while those which contain both ring systems (14-, 16-, and 18-AQ) lie in between. A pentafulvene subunit

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[39] Michl, J.; Thulstrup, E. W *Tetrahedron* **1976**, *32*, 205.

[40] See, for example, Borden, W. T. "Modern Molecular Orbital Theory for Organic Chemists"; Prentice-Hall: Englewood Cliffs, N.J., 1975; Chapter 7. The program used for these calculations was written by Simmons (Simmons, H. E. *Prog. Org. Chem.* **1970**, *7*, 1) and extensively modified by M. D. Gordon. Two-center integrals were calculated by the method of Nishimoto and Mataga (Nishimoto, K.; Mataga, N. *Z. Phys. Chem.* (*Frankfurt am Main*) **1957**, *12*, 335), and core resonance integrals were calculated by the method of Nishimoto and Forster (Nishimoto, K.; Forster, L. S. *Theor. Chim. Acta* **1965**, *3*, 407). Ionization potentials and one-center electron repulsion integrals were taken as −11.16 and 11.13 eV for carbon and −17.70 and 15.23 eV for oxygen.

[41] Dougherty, D.; McGlynn, S. P. *J. Am. Chem. Soc.* **1977**, *99*, 3234.

[42] Bernstein, J.; Cohen, M. S.; Leiserowitz, L. In ref 2a, pp 37–110.

[43] Dewar, M. J. S. In ref 30, pp 172, 220.

[44] Pentalene X-ray: Kitschke, B.; Lindner, H. J. *Tetrahedron Lett.* **1977**, 2511. See also: Bischof, P.; Gleiter, R.; Hafner, K.; Knauer, K. H.; Spanget-Larsen, J.; Süss, H. U. *Chem. Ber.* **1978**, *111*, 932.

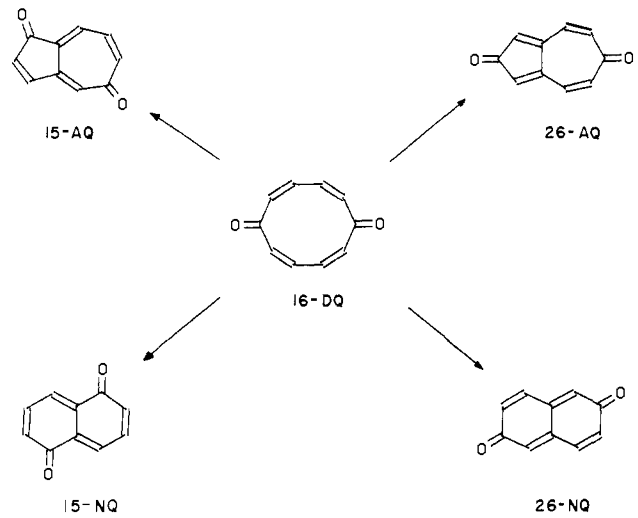


Figure 5. A family of C_{10} quinones having a common perimeter.[46]

(45-, 47-, 56-AQ) correlates with the worst MINDO/3 ΔH_f, the lowest Hückel π LUMOs, and the largest Hückel π-LUMO coefficients. Only 12-AQ contains none of these three subunits.

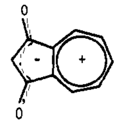
Many of the $C_{10}H_6O_2$ quinones share a common perimeter and may be viewed as perturbed [10]annulene quinones which also remain unknown. Figure 5 illustrates the family which includes both of the known, extended naphthoquinones. By all the measures of chemical stability discussed herein, 15-AQ is predicted to rank not only ahead of the other azuloquinone (26-AQ) but also ahead of the related naphthoquinones (15-NQ and 26-NQ). The π-delocalization energy of 15-AQ is also more positive than that of the other family members in Figure 5. MINDO/3 calculations on planar, all-cis [10]annulene-1,6-quinone give a LUMO energy of −1.12 eV and a HOMO/LUMO gap of 8.65 eV for the monocyclic parent.[45] Introduction of a transannular σ bond as in Figure 5 leads to lower lying LUMOs and significantly smaller HOMO/LUMO gaps for all the bicyclic quinones except 15-AQ (cf. Table I and III). Thus, we conclude that 1,5-azuloquinone represents a very reasonable goal for synthesis and study. A program to prepare several of the azuloquinones is currently underway in one of our laboratories.

Nonclassical Quinones

In this final section we briefly consider the quinones of azulene and naphthalene for which no simple Kekulé structure can be drawn (cf. *m*-benzoquinone). These are illustrated at the bottom of Figures 1 and 3. No such quinones have ever been isolated.

As expected, MINDO/3 calculations predict these nonclassical quinones all to have less favorable heats of formation, smaller HOMO/LUMO gaps, larger LUMO coefficients, lower lying LUMOs, and higher lying HOMOs than the corresponding classical quinones (see Tables I, II, and III). One of these (25-AQ) collapses to a tricyclic system in MINDO/3 (Figure 1). The Hückel treatment likewise reveals a distinct difference, although less dramatic, between the classical and nonclassical azuloquinones. Thus, the nonclassical quinones are all predicted to suffer easy dimerization, polymerization, nucleophilic addition, and reduction.

1,3-Azuloquinone, however, stands out from all the rest as a particularly intriguing compound. Inspection of the MINDO/3 geometry and the Hückel charge density pattern suggests that 13-AQ can be best depicted as



13-AQ

It is difficult to conceive of *any* nonclassical quinone with a more stabilized zwitterionic form than this one. Of the nonclassical azulene and naphthalene quinones, 13-AQ is predicted to have, by far, the most favorable heat of formation, the largest HOMO/LUMO gap, the smallest LUMO coefficients, and the highest lying LUMO. Of all nonclassical quinones, this one should have the best chance for survival.

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(45) Hückel calculations on all the DQs as well as the pentalenequinones and cyclooctatetraenequinones have been carried out by one of use (T.F.), and are available upon request to him.

(46) These drawings were prepared by the PROPHET sytem, a national computer resource sponsored by the NIH through the Chemical/Biological Information-Handling Program, Division of Research.

(47) After completion of this work, we were informed by Dr. Tadayoshi Morita of Tohoku University of the successful synthesis of the parent 1,2-azuloquinone as well as the 3-cyano- and 3-ethoxycarbonyl derivatives: Morita, T.; Karasawa, M.; Takase, K. *Chem. Lett.*, **1980**, 197–200. 12-AQ is a green, crystalline compound with a long wavelength λ_{max} = 600 nm which tails beyond 800 nm in the visible spectrum. The reduction potential of 12-AQ is −0.55 V (vs. SCE) in CH_3CN. We thank Dr. Morita for communicating these results to us prior to publication.