medium-pressure mercury lamp with Pyrex filters (>280 nm). Microcrystalline samples were degassed, sealed, and irradiated for 48 h in Pyrex tubes. In order to obtain a uniform exposure to light the sample tubes were rotated periodically. The conversions both in solution and in solid-state irradiations were less than 20%. Under such conditions the photoproducts were stable as analyzed by GLC. The products were extracted with a chloroform–water mixture and gas chromatographically analyzed. Among the photoproducts benzaldehyde, benzil, and deoxybenzoin were identified by comparison with authentic samples (Aldrich), and the other product pinacol ether was characterized by its spectral properties (IR and ^{1}H NMR) and compared with those pinacol ethers isolated from 1–3. The IR and ^{1}H NMR spectra of diastereomeric pinacol ethers derived from 4–6 are provided here.

4. IR (neat): 2900, 1600, 1340 cm^{-1}. ^{1}H NMR ($CDCl_3$): (a) δ 0.95 (6 H, t); 1.0–1.60 (8 H, m); 3.20 (4 H, m); 4.05 (2 H, s); 6.80–7.20 (10 H, m); (b) δ 0.95 (6 H, t); 1.01–1.60 (8 H, m), 3.20 (4 H, m); 4.25 (2 H, s); 6.80–7.20 (10 H, m).

5. IR (neat): 2900, 1600, 1345 cm^{-1}. ^{1}H NMR ($CDCl_3$): (a) δ 0.95 (6 H, t); 1.0–1.65 (12 H, m); 3.20 (4 H, m); 4.05 (2 H, s); 6.9–7.20 (10 H, m); (b) δ 0.95 (6 H, t); 1.0–1.70 (12 H, m); 3.0–3.25 (4 H, m); 4.05 (2 H, s); 7.0–7.25 (10 H, m).

6. IR (neat): 2900, 1600, 1340 cm^{-1}. ^{1}H NMR ($CDCl_3$): (a) δ 0.90 (6 H, t); 1.0–1.70 (16 H, m); 3.0–3.25 (4 H, m); 4.05 (2 H, s); 7.0–7.20 (10 H, m); (b) δ 0.90 (6 H, t); 1.0–1.70 (16 H, m); 3.03–3.30 (4 H, m); 4.25 (2 H, s); 7.0–7.20 (10 H, m).

Photolysis (>280 nm) of the ketones 4–6 in benzene and methanol were also carried out. The irradiations (1 h) were done in NMR tubes with the initial ketone concentrations of $\sim 1.6 \times 10^{-2}$ M. The samples were analyzed by GLC.

Host/Guest Ratio. Known amounts of β-cyclodextrin complexes of the ketones 4–6 were dried to a constant weight after being washed with cold water and diethyl ether. The guest ketones were extracted with a warm chloroform–water mixture. From the amount of the ketone recovered and the total complex taken the host/guest ratio was calculated. The amount of the extracted ketone was also estimated by GC analysis using an internal standard (benzoin methyl ether). The two values thus obtained are in good agreement. The measured host/guest ratios for all the three β-cyclodextrin complexes are provided in Table I.

Acknowledgment. G.D.R. thanks Council of Scientific and Industrial Research, Government of India, for the award of Senior Research Fellowship.

Registry No. 1, 3524-62-7; 1·β-cyclodextrin, 102979-45-3; 4, 22510-13-0; 4·β-cyclodextrin, 109391-46-0; 5, 36945-04-7; 5·β-cyclodextrin, 109391-47-1; 6, 38482-89-2; 6·β-cyclodextrin, 109391-48-2; PhCHO, 100-52-7; $(PhCH(OMe))_2$, 3962-43-4; PhCOCOPh, 134-81-6; $PhCH_2COPh$, 451-40-1; $PhCO_2H$, 65-85-0; $PhCO_2Me$, 93-58-3; $(Me(CH_2)_5OCH(Ph))_2$, 109391-43-7; $(Me(CH_2)_7OCH(Ph))_2$, 109391-44-8; $(Me(CH_2)_9OCH(Ph))_2$, 109391-45-9; oxetanol, 92549-02-5.

Copper-Catalyzed Double Cyclization Reaction of Azidoquinones: One-Step Synthesis of Dihydropyrroloindoloquinones and Related Quinolinoquinones

Yoshinori Naruta,* Naoshi Nagai, Yoshihiro Arita, and Kazuhiro Maruyama*

Department of Chemistry, Faculty of Science, Kyoto University, Kyoto, 606 Japan

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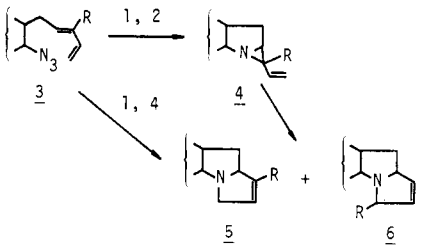
Intramolecular cyclization of 2-azido-3-(2,4-pentadienyl)-1,4-quinone (7) has been examined in the presence of metal catalysts ML_n (L = acetylacetonato). Copper or $Cu(acac)_2$ catalysts exhibited the highest catalytic activity both to the decomposition of the azide and to the formation of the corresponding dihydropyrroloindoloquinone (8), which was obtained in 58% yield in one step. The related 2-azido-3-(3,5-hexadienyl)-1,4-quinones gave the corresponding quinolinoquinone derivatives in moderate yields. The double cyclization reaction proceeds in extremely high regio- and stereoselectivities, and the generality was established. Quinonoid structure and the presence of a conjugated dienyl side chain at the proximal position to an azide group are essential factors for the completion of this double cyclization reaction. The role of the copper catalyst to the cyclization reaction is also discussed.

Cycloaddition reactions of organic azides or nitrenes to an unsaturated double bond have been studied directed toward the synthesis of nitrogen heterocycles,[1] such as aziridines,[2] pyrroles,[3] indoloquinones,[4] etc.[5] Decomposition of organic azides have been performed under pyrolytic,[3,5a-f] photolytic,[2a,4,5q] and acidic[6] conditions. By

Scheme I



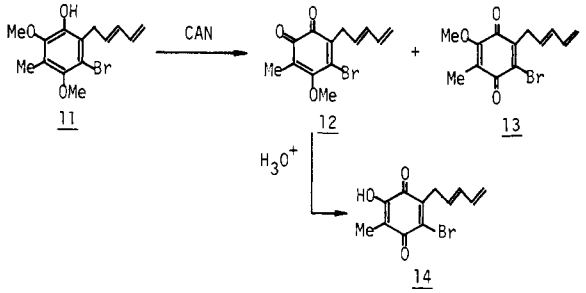
(1) For reviews, see: (a) Abramovitch, R. A.; Kyba, E. P. *The Chemistry of the Azide Group*; Patai, S., Ed.; Wiley: London, 1971; pp 221–329. (b) Supplement D of ref 1a, 1983; Chapters 7 and 8. (c) Lewis, F. D.; Saunders, W. H., Jr. *Nitrenes*; Lwowski, W., Ed.; Wiley: New York, 1970. (d) Wentrup, C. *Adv. Heterocycl. Chem.* **1981**, *28*, 231. (e) Scriven, E. F. V., *Reactive Intermediates*; Abramovitch, R. A., Ed.; Plenum: New York, 1982; Vol. 2, pp 1–54. (f) *Azides and Nitrenes, Reactivity and Utility*; Scriven, E. F. V., Ed.; Academic: New York, 1984.

(2) (a) Scheiner, P. *Tetrahedron* **1968**, *24*, 2757. (b) Hassner, A.; Matthews, G. J.; Fowler, F. W. *J. Am. Chem. Soc.* **1969**, *91*, 5046. (c) Ende, D. V.; Krief, A. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 279. (d) Ittah, Y.; Sasson, Y.; Shahak, I.; Tsaroom, S.; Blum, J. *J. Org. Chem.* **1978**, *43*, 4271. (e) Hassner, A.; Galle, J. E. *J. Am. Chem. Soc.* **1970**, *92*, 3733.

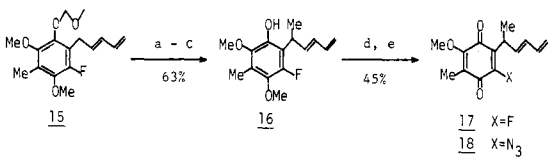
(3) Sundberg, R. J.; Pearce, B. C. *J. Org. Chem.* **1982**, *47*, 725.

0022-3263/87/1952-3956$01.50/0

Scheme II

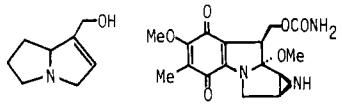


Scheme III[a]



[a] (a) *n*-BuLi; (b) MeI; (c) H_3O^+; (d) CAN; (e) NaN_3.

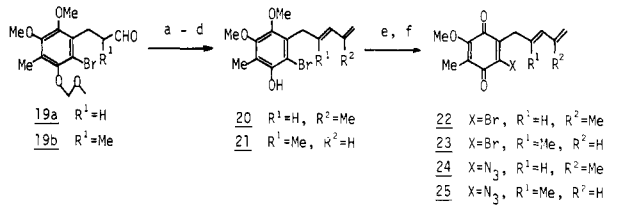
analogy with the reaction of organic diazo compounds,[7] metal-catalyzed decomposition of organic azides is expected to be a promising route to the cycloaddition of nitrenes to olefins under mild conditions with high product selectivity. However, due to the difficulty of cycloaddition of intermediate organoimido transition-metal complex[8] to olefins, reports on this subject were limited to the decomposition of simple azides.[9] From the synthetic point of view, the intramolecular cyclization of an azide group to a dienyl moiety gives a pyrrolizidine, the key structure of pyrrolizidine alkaloids, e.g., supinidine (**1**), and mitomycins, e.g., mitomycin A (**2**). Recently the noncatalyzed pyrolytic



1 Supinidine 2 Mitomycin A

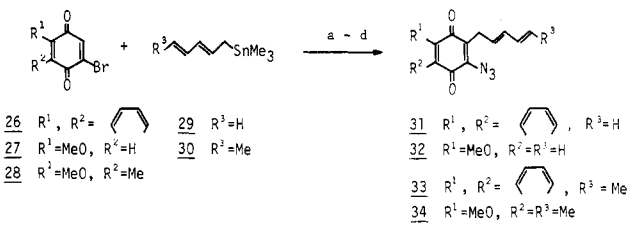
method was applied to the key fragment synthesis of pyrrolizidine alkaloids from activated azido diene **1** (R = CO_2Et),[10] but low regioselectivity was observed at the stage of the vinylic rearrangement of an intermediate aziridine (**4**, **5**, and/or **6**, Scheme I). The 1,3-dipolar cycloaddition pathway is unfavorable for azido dienes with a less activated dienyl moiety, and pyrolytic decomposition of these azido dienes gave only a complex mixture, presumably because of nitrene formation.[10b,c]

Scheme IV[a]



[a] (a) isopropenylmagnesium bromide (or vinylmagnesium bromide); (b) H_3O^+; (c) Tf_2O/2,6-lutidine; (d) H_3O^+; (e) CAN; (f) NaN_3.

Scheme V[a]



[a] (a) $AlCl_3$·OEt_2; (b) H_3O^+; (c) Ag_2O; (d) NaN_3.

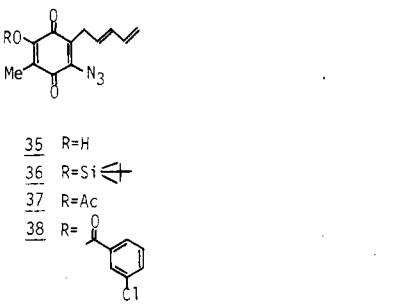


Figure 1.

We explored pyrrolizidine ring formation by copper-catalyzed reaction of 2-azido-3-(2,4-pentadienyl)-1,4-quinones.[11] Here, we will disclose the details of the reaction and the application of this reaction to the synthesis of pyrroloindoloquinones and the homologous quinolinoquinones in excellent regio- and stereoselectivity.

Results and Discussion

Azidoquinone Synthesis. The azidoquinones **7** with a conjugated dienyl side chains (all trans configuration except noted) were synthesized as shown in Scheme II.

3-Bromo-2-(2,4-pentadienyl)phenol (**11**)[12] was oxidized with ceric ammonium nitrate (CAN)[29] to give the corresponding *o*- (**12**) and *p*-quinones (**13**) (**12**/**13** = 3:2). The *o*-quinone **12** was converted to **13** by the two-step sequence: acid hydrolysis to hydroxyquinone **14** followed by methylation with diazomethane. The combined yield of **13** was 69% from **11**. The quinone **13** was converted to azidoquinone **7** by treatment with NaN_3 in 90% yield.

1′-Methyl derivative **18** was prepared by the regioselective methylation at this position of the corresponding pentadienyl anion (Scheme III). The protected fluorophenol **15**[12] was treated with *n*-BuLi in THF at −75° C, and subsequently the generated dienyl anion was meth-

(4) (a) Germeraad, P.; Weyler, W., Jr.; Moore, H. W. *J. Org. Chem.* **1974**, *39*, 781. (b) Naruta, Y.; Yokota, T.; Nagai, N.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1986**, 972. (c) Naruta, Y.; Nagai, N.; Yokota, T.; Maruyama, K. *Chem. Lett.* **1986**, 1185.

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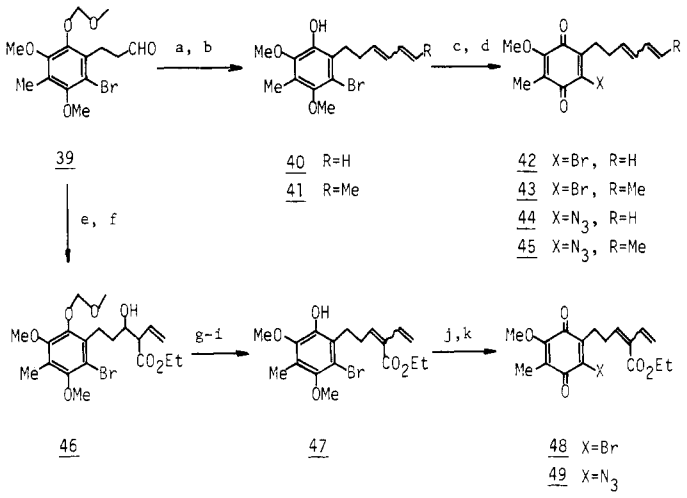
(10) (a) Hudlicky, T.; Frazier, J. O.; Kwart, L. D. *Tetrahedron Lett.* **1985**, *26*, 3523. (b) Pearson, W. H. *Ibid.* **1985**, *26*, 3527. (c) Hudlicky, T.; Frazier, J. O.; Seoane, G.; Tiedje, M.; Seoane, A.; Kwart, L. D.; Beal, C. *J. Am. Chem. Soc.* **1986**, *108*, 3755. (d) Pearson, W. H.; Celebuski, J. E.; Poon, Y.-F.; Dixon, B. R.; Glans, J. H. *Tetrahedron Lett.* **1986**, *27*, 6301.

(11) Copper powder was used after activation under H_2 stream at 200 °C. Naruta, Y.; Arita, Y.; Nagai, N.; Uno, H.; Maruyama, K. *Chem. Lett.* **1982**, 1859.

(12) Maruyama, K.; Nagai, N.; Naruta, Y. *J. Org. Chem.* **1986**, *51*, 5083.

Scheme VI[a]



[a] (a) allyl- or crotyltriphenylphosphonium bromide/*n*-BuLi; (b) H_3O^+; (c) CAN; (d) NaN_3; (e) ethyl crotonate/LDA; (f) H_3O^+; (g) Ac_2O/pyridine/DMAP; (h) DBU; (i) H_3O^+; (j) CAN; (k) NaN_3.

ylated with MeI. After hydrolysis, the corresponding 2-(1-methyl-2,4-pentadienyl)-3-fluorophenol (**16**) was obtained in 63% yield. The phenol **16** was oxidized to the corresponding quinone (**17**) without formation of the corresponding ortho isomer[30] and then converted to the azidoquinone **18** in 45% overall yield from **16**.

The analogous azidoquinones **24** and **25** were prepared by side chain elongation of compounds **19a** and **19b**, respectively (Scheme IV). The aldehyde **19a** was treated with 2-propenylmagnesium bromide, and the resultant allyl alcohol was converted to diene **20**, followed by hydrolysis (36% from **19a**). The diene **20** was converted to the corresponding azidoquinone **24** in the usual manner in 60% overall yield from **20**. The azidoquinone **25** was obtained in the same manner in 10% overall yield from **19b**.

The direct introduction of 2,4-pentadienyl or 2,4-hexadienyl group was attained by Lewis acid mediated dienylation with the corresponding stannyl reagents[13] (Scheme V). 2-Bromonaphthoquinone (**26**) was treated with trimethyl-2,4-pentadienylstannane (**29**) in the presence of $AlCl_3$·OEt_2. After hydrolysis, oxidation with Ag_2O,[31] and treatment with NaN_3, the azidoquinone **31** was obtained in 40% overall yield. In the similar manner, azidoquinone **32** was obtained in 58% yield from quinone **27**. Azidoquinones **33** and **34** were obtained by similar reactions in 30% and 35% yields, respectively.

5-Alkoxy derivatives **35–38** were prepared for an examination of a substituent effect on the quinonoid moiety (Figure 1). The bromohydroxyquinone **14** was converted to the corresponding azidoquinone (**35**) in 80% yield with NaN_3. The pentadienyl quinone **35** was converted to the [(*tert*-butyldimethylsilyl)oxy]quinone **36** (45%), the acetoxyquinone **37** (66%), and [(3-chlorobenzoyl)oxy]quinone **38** (48%).

The azidoquinones **44** and **45** with various 3,5-hexadienyl side chains were prepared according to Scheme VI. The resultant quinone (**42**, 50%)[32] and azidoquinone (**44**, 80%) were a 1:1 mixture of cis/trans stereoisomers. Azidoquinone **45** (Δ^3,Δ^5; cis,trans/trans,trans = 44:56) was obtained analogously in 14% yield.

Aldehyde **39** was treated with ethyl crotonate/LDA to afford **46** in 65% yield. Alcohol **46** was converted to 2-[4-(ethoxycarbonyl)-3,5-hexadienyl]phenol **47** by acetylation, followed by hydroacetoxy elimination in 68% yield from **46**. Quinone **49** (E/Z = 1.7:1) was obtained in 61% yield from **47** by the usual oxidation[32] followed by azidation.

Scheme VII

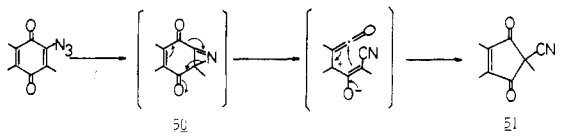


Table I. Effect of Metal Catalyst in Pyrolytic Decomposition of Azidoquinone 7 in Benzene under Reflux[a]

		isolated yield, %			
entry	catalyst	8	9	10	7
1	none	0	0	69	9
2	$V(acac)_3$[d]	0	30	30	34
3	$VO(acac)_2$[e]	0	7	46	6
4	$Cr(acac)_3$[f]	6	0	55	13
5[b]	$Cr(acac)_3$	14	3	44	10
6	$Mn(acac)_2$[g]	0	9	6	1
7	$Mn(acac)_3$[h]	0	0	19	8
8	$Fe(acac)_3$[i]	0	0	48	0
9	$Co(acac)_2$[j]	0	23	7	4
10	$Co(acac)_3$[k]	0	13	12	9
11	$Ni(acac)_2$[i]	3	12	9	0
12	$Cu(acac)_2$[l]	35	1	3	0
13[c]	$Cu(acac)_2$	58	6	0	0
14	$Zn(acac)_2$[m]	0	17	12	11
15	CuCl	25	2	24	35
16	CuBr	22	0	31	33
17	CuCN	16	0	28	16
18	Cu_2O	17	0	51	29
19	CuOTf[n]	0	0	4	0

[a] All reactions were performed according to the general procedure (see Experimental Section). [b] [7] = 0.015 M. [c] [7] = 0.005 M. Two equivalents of the catalyst to **7** was used. [d] Grdenić, D.; Korpar-Čolig, B. *Inorg. Chem.* **1964**, *3*, 1328. [e] *Inorg. Synth.* **1957**, *5*, 114. [f] *Inorg. Synth.* **1957**, *5*, 130. [g] *Inorg. Synth.* **1960**, *6*, 164. [h] *Inorg. Synth.* **1963**, *7*, 183. [i] Charles, R. G.; Pawlikowski, M. A. *J. Phys. Chem.* **1958**, *62*, 440. [j] *Inorg. Synth.* **1968**, *11*, 84. [k] *Inorg. Synth.* **1957**, *5*, 188. [l] See Table II, footnote *n*. [m] *Inorg. Synth.* **1967**, *10*, 74. [n] See ref 18.

Metal Catalysts and Reaction Conditions. Initially, to accomplish the cyclization reaction, various procedures were examined. Photochemical ($\lambda > 360$ nm) decomposition was not suitable.[14] Pyrolytic decomposition of azidoquinone led to the formation of ring-contracted cyclopentenedione derivative **51**, whose reaction course was thought to proceed by attack of the quinone by an intermediate nitrene (Scheme VII[15]). Without copper catalyst, a similar reaction product (**10**) was obtained by pyrolysis of **7** in refluxing benzene (eq 1, Table I, entry 1). Metal salts such as $AgBF_4$,[16] $RhCl_3$,[17] and $Rh_2(OAc)_4$,[17] which are known to be active for carbenoid formation from diazo compounds, were not effective. However, the reaction of **7** in the presence of copper powder afforded **8** (53%) and **9** (25%) (eq 2).[11] Copper(II) salt $Cu(acac)_2$ was equally suitable for our purpose. To explore the optimization of this cyclization, we surveyed acetylacetonato complexes of first-row transition metals as catalysts (Table I, entries 2–14). With $Cr(acac)_3$ (Table I, entries 4 and 5), the formation of the double cyclized product **8** was observed but in lower yield than with the copper catalysts. With other

(13) This Lewis acid mediated dienylation method with tin reagent affords a dienylquinone without formation of Diels–Alder adduct. In this case, $AlCl_3$·OEt_2 gave optimum yield. Naruta, Y.; Nagai, N.; Arita, Maruyama, K. *Chem. Lett.* **1983**, 1683.

(14) **8** was obtained in 16% yield.

(15) Weyler, W., Jr.; Pearse, D. S.; Moore, H. W. *J. Am. Chem. Soc.* **1973**, *95*, 2603.

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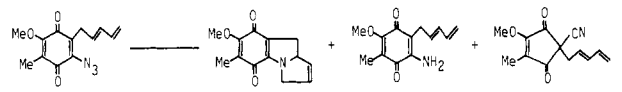
(17) Paulissen, R.; Reimlinger, H.; Hayez, E.; Hubert, A. J.; Teyssie, P. *Tetrahedron Lett.* **1973**, *14*, 2233.



7 8 9 10

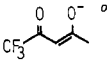
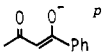
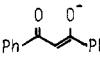
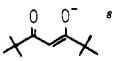
Conditions				
Benzene, reflux, 4 h.	-	-	69%	(1)
Copper powder, benzene, reflux, 4 h.	53%	25%	-	(2)

metal complexes, no cyclization products were obtained. Among copper catalysts, copper(I) salts were less effective in the cyclization reaction than copper(0) or -(II) derivatives, partly due to the low solubility of most of the copper(I) salts in benzene (Table I, entries 15–19). With copper(I) salts, the active catalysts might be copper(0) or copper(II) salts, both of which might be expected to be produced from copper(I) salts by disproportionation under the reaction conditions.[18] CuOTf, in which the Cu(I) ion possesses highly electrophilic character, can coordinate to an olefin to form an olefin–copper(I) complex,[18] which would be expected to react intramolecularly with the nearby azide group. This salt, however, was not effective (Table I, entry 19). In short, copper(0) or -(II) salts were the most effective. Because of the ease of treatment and the high reproducibility, we used copper(II) catalysts thereafter.

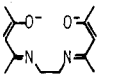
Next, several benzene-soluble copper(II) salts were examined to determine the most effective catalyst (Table II). Complexes having imino-type or salicylaldehyde ligands gave 8 in lower yields because of their low solubility to benzene[19] (Table II, entries 1–5). (*meso*-Tetraphenylporphyrinato)copper (Cu(tpp)) has no effect for the formation of 8 (Table II, entry 6). For the comparison of the effect of ligand basicity, instability of the complex, and steric hindrance of ligand, copper(II) complexes which structurally resemble β-diketone ligands were examined. In the copper complexes examined, the acid dissociation constants log K_d[20] of the corresponding metal-free β-diketones are within a narrow range (–log K_d = 9.5–10.3) except that of (trifluoroacetyl)acetone (–log K_d = 6.7). The copper complex with the latter acidic ligand (Table II, entry 8) was less effective both for the decomposition and for the double cyclization than the complexes with more basic ligands. On the other hand, the stability constants log K_{av}[20a] of the copper(II) complexes examined are in a range from 10.0 (for Cu(*t*-BuCOCHCO-*t*-Bu)$_2$) to 7.0 (for Cu(MeCOCHCO$_2$Et)$_2$), while the catalytic activities of these copper complexes were independent of the K_{av} value (Table II, entries 11 and 13). The bulkiness[20b,c] of ligands did not greatly effect this reaction (Table II, entries 10 and 12).

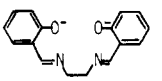
Since this cyclization reaction was sensitive to reaction conditions, i.e., concentration both of the substrate and of the catalyst, solvent, and reaction temperature, the formation of the cyclized product 8 from 7 in a standard reaction was optimized by use of Cu(acac)$_2$ catalyst.

Table II. Pyrolysis of Azidoquinone 7 with Copper Salts in Benzene under Reflux[a]

		isolated yield, %		
entry	catalyst	8	9	7
1	Cu(acacen)[b,h]	31	4	0
2	Cu(salad)$_2$[c,i]	25	5	0
3	Cu(salen)[d,j]	trace	trace	21
4	Cu(dmg)$_2$[e,k]	11	19	21
5	Cu(oxin)$_2$[f,l]	17	trace	23
6	Cu(tpp)[g,m] CuL$_2$, L	0	0	32
7	 [n]	58	6	0
8	 [o]	17	trace	35
9	 [p]	33	trace	0
10	 [q]	43	trace	0
11	 [r]	55	0	0
12	 [s]	33	0	0
13	 [t]	37	0	0

[a] All reactions were performed according to the general procedure (see Experimental Section).

[b] acacen =  [c] salad = 

[d] salen =  [e] dmg =  [f] oxin = 

[g] tpp = *meso*-tetraphenylporphyrin. [h] McCarthy, P. J.; Hovey, R. J.; Uno, K.; Martell, A. E. *J. Am. Chem. Soc.* **1955**, *77*, 5820. [i] Tyson, G. N., Jr.; Adams, S. D. *J. Am. Chem. Soc.* **1940**, *62*, 1228. [j] Pfeiffer, P.; Breith, E.; Lubbe, E.; Tsumaki, T. *Justus Liebigs Ann. Chem.* **1933**, *503*, 84. [k] Tschgaeff, L. *Z. Anorg. Chem.* **1905**, *46*, 144. [l] Nakatsuka, Y. *Bull. Chem. Soc. Jpn.* **1936**, *11*, 45. [m] *Inorg. Synth.* **1976**, *16*, 214. [n] Jones, M. M. *J. Am. Chem. Soc.* **1959**, *81*, 3188. [o] Belford, R. L.; Martell, A. E.; Calvin, M. *J. Inorg. Nucl. Chem.* **1956**, *2*, 11. [p] Hon, P. K.; Pfluger, C. E.; Belford, R. L. *Inorg. Chem.* **1966**, *5*, 516. [q] Holtzclaw, H. F., Jr.; Johnson, K. W. R.; Hengeweld, F. W. *J. Am. Chem. Soc.* **1952**, *74*, 3776. [r] Shugaw, E. A. *Dokl. Akad. Nauk. SSSR* **1951**, *81*, 853. [s] Fackler, J. P., Jr.; Cotton, F. A. *Inorg. Chem.* **1963**, *2*, 97. [t] Fackler, J. P., Jr.; Cotton, E. A. *Inorg. Chem.* **1963**, *2*, 102.

Even if dioxane[21] or tetrachloroethylene,[21] both of which effectively stabilize singlet nitrene, were used as a solvent or an additive (Table III, entries 11, 13, and 14), no improvement in the yield of 8 was observed. When bromobenzene, which accelerates intersystem crossing of the nitrene from singlet to triplet,[22] was used as solvent, a yield of 8 comparable to that obtained when the reaction was run in benzene was obtained (Table III, entry 15). These results suggest that the free nitrene may not be responsible for the formation of the cyclized product 8.

The copper-catalyzed reaction is sensitive to the reaction temperature. Below 60 °C the decomposition of the azidoquinone 7 is slow (Table III, entry 7), and no reaction was observed at 25 °C. On the other hand, since the decomposition of 8 to unassignable products was accelerated

(18) (a) Jenkins, C. L.; Kochi, J. K. *J. Am. Chem. Soc.* **1972**, *94*, 843, 856. (b) Salomon, R. G.; Kochi, J. K. *Ibid.* **1973**, *95*, 3300.

(19) Maximum solubilities (mol/L) in dry benzene at 80 °C are as follows: Cu(acac)$_2$, 0.015; Cu(eacac)$_2$, 0.18; Cu(salad)$_2$, 0.005.

(20) (a) Averaged stability constant K_{av} is shown in the following equation.

$$\log K_{av} = \tfrac{1}{2}\log K_{CuL}K_{CuL}$$

$$Cu^{II}L_2 \underset{+L}{\overset{-L}{\rightleftharpoons}} Cu^{II}L \underset{+L}{\overset{-L}{\rightleftharpoons}} Cu^{II}$$

Calvin, M.; Wilson, K. W. *J. Am. Chem. Soc.* **1945**, *67*, 2003. (b) Guter, G. A.; Hammond, G. S. *Ibid.* **1959**, *81*, 4686.

(21) (a) Takeuchi, H.; Igura, T.; Mitani, M.; Tsuchida, T.; Koyama, K. *J. Chem. Soc., Perkin Trans. 2* **1978**, 783. (b) Breslow, D. S.; Edwards, E. I. *Tetrahedron Lett.* **1967**, *22*, 2123.

(22) Anastassiou, A. G. *J. Am. Chem. Soc.* **1967**, *89*, 3184.

Table III. Pyrolytic Decomposition of Azidoquinone 7 with Copper(II) Salts[a]

entry	mol ratio of catalyst/7	solvent	[7], M	isolated yield, % 8	9	7
1	0.1	benzene	0.1	43	12	0
2	0.5	benzene	0.02	31	0	0
3	0.5	benzene	0.005	38	11	0
4	1	benzene	0.01	35	1	0
5	2	benzene	0.01	31	0	0
6	2	benzene	0.005	58	6	0
7[b]	2	benzene	0.005	20	6	17
8	2	benzene	0.002	23	10	17
9	4	benzene	0.005	38	1	0
10	4	benzene	0.0025	25	0	0
11	2	dioxane	0.01	46	1	5
12[c]	2	toluene	0.01	23	1	0
13	2	benzene + dioxane[d]	0.005	50	13	8
14	2	benzene + $Cl_2C{=}CCl_2$[d]	0.005	25	4	0
15	2	bromobenzene	0.008	46	0	0
16	2	benzene	0.02	56	0	0

[a] All reactions were performed according to the general procedure (see Experimental Section). Reactions were performed at 80 °C unless otherwise noted. Bis(acetylacetonato)copper(II) was used as the catalyst in entries 1–15, and bis(ethyl acetoacetate)copper(II) was used in entry 16. [b] Yield obtained at 60 °C. [c] The reaction was performed at 110 °C. [d] Ten equivalents of an additive to 7 were used.

at higher temperature (110 °C, Table III, entry 12), the reaction in refluxing benzene was most suitable for the formation of 8. When the amount of the copper catalyst $Cu(acac)_2$ was decreased to 0.1 equiv, the decomposition of 7 proceeded similarly, and the double cyclized product 8 was obtained in 43% yield without loss of efficiency (Table III, entry 1), suggesting a catalytic role of the copper complex. This reaction was also influenced by the concentration both of the quinone 7 and of the catalyst. Generally, the dilute reaction mixtures gave the better results. In the reactions that use $Cu(acac)_2$ as a catalyst, this fact might be related to the solubility of metal salt.[19] Therefore, with $Cu(acac)_2$, the most effective concentration (0.01 M) of the copper salt at 80 °C is close to the saturated concentration (0.016 M) in benzene. Under these conditions increasing the stoichiometry of the catalyst to 2 equiv showed little improvement in the product 8 formation (Table III, entry 6).

Generality of the Reaction. To establish the generality of this reaction and to observe the effect of substituents on the dienyl side chain or on the quinone nucleus, several dienylazidoquinone derivatives were examined. Most of azidoquinones gave the corresponding pyrrolizidinoquinones in modest to good yield in one step. Characteristically the cyclization proceeded in extremely high regio- and stereoselectivity. The 1′-methyl derivative 18 afforded exclusively the corresponding β-isomer (Table IV, entry 1).[23] Presumably, the transition state leading to the 9β-product (A) is thought to be more stable than that giving 9α-product (B) because of less steric repulsion between the methyl group at the 1′-position and the olefin at the 2′-position (Figure 2). *trans,trans*-2,4-Hexadienyl derivatives also gave the corresponding cyclized products with the 3α-methyl configuration in a regio- and stereoselective manner (Table IV, entries 4 and 6).[24] A methyl group at the 2′-position inhibited the cyclization reaction to afford only the complex mixture (Table IV, entry 2). 2-Azido-3-(3,5-hexadienyl)-1,4-quinone derivatives showed the similar cyclization reaction to afford the double cyclized products (Table IV, entries 12–14). An electron-withdrawing group on the dienyl side chain had no effect on product yield (Table IV, entry 14).

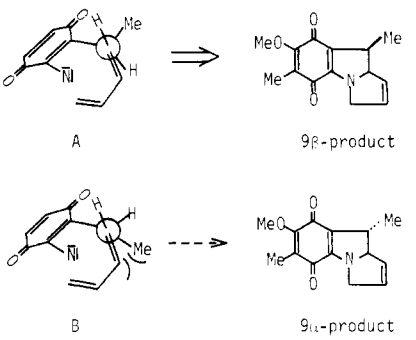
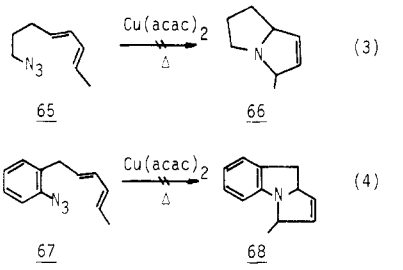


Figure 2.

Possible Mechanism. To clarify the function of the copper catalyst in the reaction mechanism, we examined the Cu-catalyzed decomposition of simple olefinic acids, i.e., *trans,trans*-4,5-azidooctadiene (**65**)[25] and 1-azido-2-(*trans,trans*-2,4-hexadienyl)benzene (**67**).



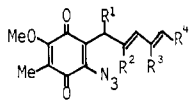
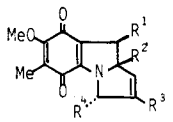
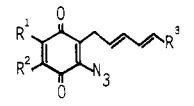
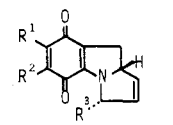
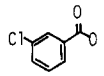
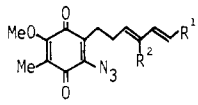
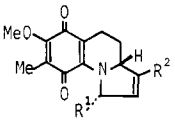
In the presence of $Cu(acac)_2$, both azides gave only complex mixtures instead of the corresponding double cyclized products (**66** or **68**). Thus, the quinonoid nucleus is playing a key role in the cyclization. In the uncatalyzed reaction of the azidoquinone 7, intramolecular triazoline formation between a deactivated azide group and a nonpolarized diene is unlikely. Furthermore, under the copper-catalyzed reaction conditions, the starting azidoquinone 7 was completely consumed within 2 h, while in the uncatalyzed reaction the azidoquinone 7 was recovered even after 4 h (Table I, entry 1) accompanied with the

(23) The stereochemistry at the 9-position was determined by the coupling constant $J_{9\alpha\text{-}9a}$ = 5.2 Hz, in comparison with those of the unsubstituted compound,[11] $J_{9\alpha\text{-}9a}$ = 6.9 Hz, $J_{9\beta\text{-}9a}$ = 11.5 Hz.

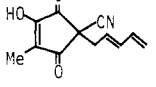
(24) The stereochemistry of the C-3 position was determined by the CF_3CO_2H-induced ^1H NMR shift values in comparison with those of the C-3 unsubstituted compound, see: Laszlo, P. *Progress in Nuclear Magnetic Resonance Spectroscopy*; Emsley, J. W.; Feeney, J.; Sutcliff, L. H. Ed.; Pergamon; Oxford, 1967; Vol. 3, pp 231–402.

(25) This type of acyclic azide gave complex mixture under uncatalyzed pyrolytic conditions.[10c]

Table IV. Pyrolysis of Alkadienylazidoquinones with $Cu(acac)_2$[a]

entry	azidoquinone[b]					product	isolated yield, %
		R^1	R^2	R^3	R_4		
1	**18**	Me	H	H	H	**52**	27 (16)[c]
2	**25**	H	Me	H	H		0[d]
3	**24**	H	H	Me	H	**53**	48
4	**34**	H	H	H	Me	**54**	22
		R^1	R^2	R^3			
5	**31**			H		**55**	47 (43)[e]
6	**33**			Me		**56**	41
7	**32**	MeO	H	H		**57**	32 (45)[e]
8	**36**	*t*-$BuMe_2SiO$	Me	H		**58**	35
9	**37**	AcO	Me	H		**59**	8
10	**38**		Me	H		**60**	8
11	**35**	HO	Me	H			0[f]
		R^1	R^2				
12	**44**	H	H[g]			**61**	21
13	**45**	Me	H[h]			**62**	21
14	**49**	H	CO_2Et[i]			**63**	25

[a] All reactions were performed by the general procedure (see Experimental Section). [b] Stereochemistry of the conjugated double bond in the azidoquinone was assigned to be trans or trans,trans except noted otherwise. [c] [Azidoquinone] = 0.005 M, see Experimental Section. [d] A complex mixture was obtained. [e] Yield obtained with copper powder as the catalyst. [f] 1-Cyano-3-hydroxy-4-methyl-1-(2,4-pentadienyl)-3-cyclopentene-2,5-dione (**64**) was obtained in 20% yield. [g] trans/cis = 50:50. [h] Δ^3,Δ^5; trans,trans/cis,trans = 56:44. The Δ^5-cis isomer was not obtained. [i] E/Z = 63:37.



64

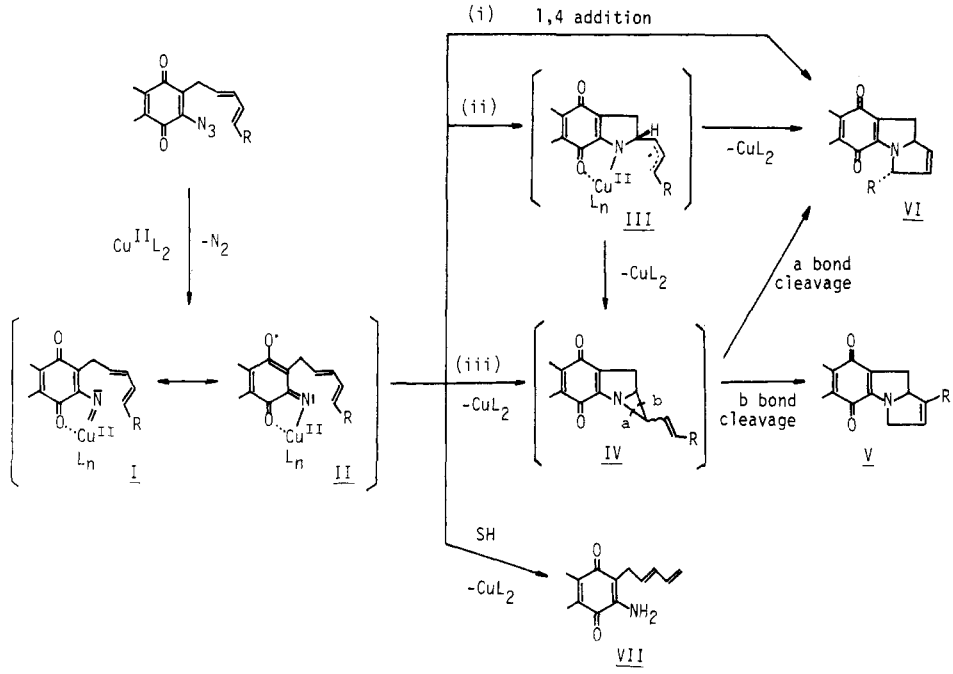
ring-contracted product. These results suggest that the copper salt promotes the extrusion of nitrogen from the azidoquinone and prevents the formation of an azirine intermediate (such as **50** via a free nitrene as shown in Scheme VII) by the coordination of copper ion to the nitrene. The presence of a quinonoid carbonyl group at the vicinal position to azide group would be effective for the stabilization of the nitrene-coordinated copper complex. Actually, the reaction of *o*-quinone **12** under the copper-catalyzed conditions resulted only the formation of complex mixture. This result supports the above argument.

The functional group at the 5-position of the azidoquinones **35–38** had a marked effect on the double-cyclization. 5-Hydroxy derivative **35**, which can preferentially coordinate to copper ion by its carbonyl and hydroxyl functionalities at the 4- and 5-positions, respectively, gave no cyclized product but the product **64** via a free nitrene (Table IV, entry 11). Similarly, an electron-withdrawing group at this position decreased the formation of the cyclized product (Table IV, entries 9 and 10). These results are in accord with the decrease in the ability of the conjugated quinone carbonyl group to coordinate with the nitrene-complexes copper ion. The possible structures (I and II)[26] of the copper-coordinated nitrene are shown in Scheme VIII. Concerning the mechanism of the successive cyclization to pyrroloindoloquinones (V) or the related quinolinoquinones, at least three options present themselves[27] (Scheme VIII): (i) direct 1,4-addition of the nitrene–copper complex I to the diene, (ii) stepwise radical cyclization via a radical intermediate III, and (iii) vinylaziridine IV formation followed by vinylic rearrangement. While the exact mechanism cannot be clarified without further study, the radical process would be more likely to occur, since the double cyclization products (**54**, **56**, and **62** in Table IV) had exclusively the α-Me configuration regardless of their original stereochemistry of the conjugated double bond. If one assumes the radical process including III as an intermediate, the observed stereochemistry can be well explained by the final ring formation via a less hindered geometry, which minimizes the steric interaction between the terminal Me group and the coordinated copper complex. The other cyclization processes (i and iii) may give two possible stereoisomers, both of which have no steric preference by means of space-filling model study. Formation of the aminoquinone (VII) can also be explained reasonably by hydrogen abstraction of intermediate I and II from some hydrogen donors in the reaction mixture.

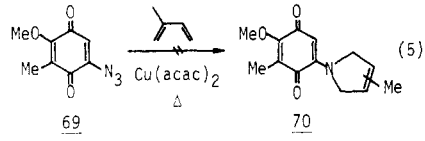
(26) These structures were considered by analogy to carbenoid chemistry: (a) Reference 7. (b) Wulfman, D. S. *Tetrahedron* **1976**, *32*, 1231.

(27) (a) Scheiner, P. *J. Am. Chem. Soc.* **1968**, *90*, 988. (b) Borel, D.; Gelas-Mialhe, Y.; Vessieve, R. *Can. J. Chem.* **1976**, *54*, 1590. (c) Pommelet, J. C.; Chuche, J. *Ibid.* **1976**, *54*, 1571. (d) Scheiner, P. *J. Org. Chem.* **1967**, *32*, 2628.

Scheme VIII



Finally, we examined the copper-catalyzed intermolecular cyclization of a simple azidoquinone (**69**) in isoprene,[28] but only a complex mixture was obtained instead of the expected 5-(3-pyrrolinyl)quinone **70**. It is concluded that the double cyclization can only be realized when a conjugated diene is present close to the azide group.



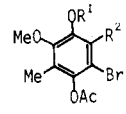
Conclusions

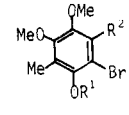
The copper-catalyzed cycloadditions of azidoquinones bearing a conjugated diene at the proximal position have been shown to give the corresponding dihydropyrroloindoloquinones and related quinolinoquinones directly. This pyrrolizidine ring formation in one step can be applicable to a variety of substituted derivatives, which might otherwise be difficult to obtain by other routes. $Cu(acac)_2$ is concluded to be the best catalyst among many other metal catalysts and copper(II) derivatives. For the completion of the formal 1,4-addition of the azido dienes, quinonoid structure is shown to play an essential role for stabilization presumably by bidentative coordination to copper(II) ion and by delocalization of an unpaired electron.

This methodology opens a convergent route to the synthesis of mitomycins and related homologous heterocyclic quinones. The continuing efforts toward these unique antibiotics are in progress in our laboratory.

Experimental Section

General Methods. Melting points were measured with a micromelting point apparatus and are uncorrected. Proton magnetic resonance spectra were observed with JEOL JNM-PS-100 and JNM-FX400 spectrometers with tetramethylsilane as an internal standard. Infrared spectra were measured with a JASCO IRA-1 spectrometer. Mass spectra were measured with a JEOL JMS-DX 300 mass spectrometer. Column chromatography was performed with Wakogel C-200. Microanalyses were performed by the Microanalytical Laboratory of Kyoto University. All solvents were freshly distilled and stored under a nitrogen atmosphere. Dichloromethane was distilled from calcium hydride. Ether and THF were distilled from benzophenone ketyl and stored over sodium wire. Benzene was stored over 4A molecular seives after distillation. Unless otherwise noted, other solvents were used after simple distillation. All metal salts were synthesized and purified according to the literatures listed in the footnotes of Tables I and II. Microanalyses of azidoquinones could not be performed due to their instability. Unless otherwise noted, the standard workup procedure of the reaction mixture was as follows: after the reaction mixture was poured into water and extracted a few times with ether, the combined organic phase was washed with water and then brine, dried over $MgSO_4$, and evaporated in vacuo.





71 $R^1 = H$, $R^2 = H$
72 $R^1 = CH_2CH{=}CH_2$, $R^2 = H$
73 $R^1 = H$, $R^2 = CH_2CH{=}CH_2$
74 $R^1 = Me$, $R^2 = CH_2CH{=}CH_2$
78 $R^1 = CH_2\underset{Me}{C}{=}CH_2$, $R^2 = H$

75 $R^1 = H$, $R^2 = CH_2CH{=}CH_2$
76 $R^1 = MOM$, $R^2 = CH_2CH{=}CH_2$
77 $R^1 = MOM$, $R^2 = CH_2CH_2CH_2OH$
$(MOM = CH_2OCH_3)$

2-Bromo-5-methoxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (13). To a solution of 5-bromo-2,4-dimethoxy-3-methyl-6-(2,4-pentadienyl)phenol (**11**, 206 mg, 0.66 mmol)[12] in CH_3CN (2 mL) was added a solution of ceric ammonium nitrate (CAN, 1.0 g, 2.0 mmol) in water (2 mL) during 3 min at 0 °C. To the reaction mixture were added water and ether, and the ethereal phase was washed with water and evaporated to give a crude mixture of the *o*-quinone **12** and the *p*-quinone **13**. To this residue were added aqueous 6 N HNO_3 (0.5 mL) and CH_3CN (10 mL). After being stirred for 1 h in the dark, the mixture was concentrated in vacuo, and ether and water were added. The organic phase was washed with water twice and then brine, dried over $MgSO_4$, and evaporated to give a crude mixture of **13** and **14**. To

(28) Photochemical reaction of the azidoquinone **69** in the presence of excess amount of diene gave the corresponding indoloquinone derivatives. See ref 4.

(29) Jacob, P., III; Callery, P. S.; Shulgin, A. T.; Castagnoli, N., Jr. *J. Org. Chem.* **1976**, *41*, 3627.

the residue was added ether, and the solution was cooled to 0 °C. The solution was treated with a 0.15 M ether solution of CH_2N_2 (6.6 mL) and stirred at 0 °C for 1 h. The mixture was evaporated and purified through a short column on silica gel (hexane–ether as eluent) to give 131 mg (0.44 mmol, 67%) of **13**: yellow oil; NMR (CCl_4) δ 1.92 (s, 3 H), 3.38 (d, 2 H, J = 7 Hz), 4.00 (s, 3 H), 4.90–5.26 (m, 2 H), 5.36–5.76 (m, 1 H), 5.96–6.42 (m, 2 H); IR (NaCl) 1665 (vs), 1005 (s), 950 (w), 905 cm^{-1} (w); high-resolution MS, calcd for $C_{13}H_{13}O_3Br$ 296.0049, found 296.0054.

Physical and spectral data of **4-bromo-5-methoxy-6-methyl-3-(2,4-pentadienyl)-1,2-benzoquinone (12)** and **2-bromo-5-hydroxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (14)** were as follows.

12: red crystals, mp 74–78 °C; NMR (CCl_4) δ 3.94 (s, 3 H), 3.32 (d, 2 H, J = 7 Hz), 3.86 (s, 3 H), 4.94–5.14 (m, 2 H), 5.38–5.46 (m, 1 H), 5.98–6.28 (m, 2 H); IR (KBr) 1650 (vs), 1000 (s), 940 (m), 900 cm^{-1} (s).

14: yellow crystals; mp 110–113 °C; NMR ($CDCl_3$) δ 2.00 (s, 3 H), 3.48 (d, 2 H, J = 7 Hz), 5.00–5.30 (m, 2 H), 5.47–5.76 (m, 1 H), 6.08–6.36 (m, 2 H), 7.00 (br, 1 H, OH); IR (KBr) 3380 s), 1630 (s), 1000 (m), 950 (w), 900 cm^{-1} (m).

2-Azido-5-methoxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (7). Standard Azidation Method. To an EtOH (10 mL) solution of the quinone **13** (416 mg, 1.4 mmol) was added an aqueous solution (2 mL) of NaN_3 (455 mg, 7 mmol). After being stirred for 1 h at room temperature in the dark, the mixture was concentrated in vacuo, and water/$CHCl_3$ was added to the residue. The aqueous layer was extracted with $CHCl_3$, and the combined organic phase was washed with water and brine, dried over $MgSO_4$, and evaporated. After purification by column chromatography on silica gel, 330 mg (1.27 mmol, 91%) of **7** was obtained: red oil; NMR (CCl_4) δ 1.76 (s, 3 H), 3.00 (d, 2 H, J = 7 Hz), 3.94 (s, 3 H), 4.74–5.12 (m, 2 H), 5.24–5.64 (m, 1 H), 5.76–6.28 (m, 2 H); IR (NaCl) 2110 (vs), 1650 cm^{-1} (vs); UV (MeOH) λ_{max} (log ϵ) 305 (3.79), 502 (2.60).

3-Fluoro-4,6-dimethoxy-5-methyl-2-(1-methyl-2,4-pentadienyl)phenol (16). To a THF (5 mL) solution of 3-fluoro-4,6-dimethoxy-1-(methoxymethoxy)-5-methyl-2-(2,4-pentadienyl)benzene (**15**, 458 mg, 1.6 mmol) was added n-BuLi (1.3 M, 1.78 mL, 2.3 mmol) at −75 °C under N_2. After the mixture was stirred for 0.5 h at −40 to −70 °C, MeI (1 mL) was added at −75 °C. Then the mixture was allowed to warm to 0 °C, quenched with water, and extracted with ether. The ethereal solution was evaporated, and the residue was treated with 5% HCl solution (0.5 mL) in acetone (5 mL) and refluxed for 1 h. After the usual workup and chromatographic purification on silica gel, 261 mg (0.98 mmol, 63%) of **16** was obtained: colorless oil; NMR (CCl_4) δ 1.43 (d, 3 H, J = 7 Hz), 1.15 (s, 3 H), 3.73 (s, 3 H), 3.77 (s, 3 H), 3.95 (m, 1 H), 4.94 (d, 1 H, J = 10 Hz), 5.13 (d, 1 H, J = 14 Hz), 5.73 (br, 1 H, OH), 5.95–6.54 (m, 3 H). Anal. Calcd for $C_{15}H_{19}O_3F$: C, 67.64; H, 7.19; F, 7.13. Found: C, 67.43; H, 6.92; F, 7.42.

2-Azido-5-methoxy-6-methyl-3-(1-methyl-2,4-pentadienyl)-1,4-benzoquinone (18). To **16** (261 mg, 0.98 mmol) in CH_3CN (2.5 mL) was added CAN (1.18 g, 2.2 mmol) in water (2.5 mL) at 0 °C with stirring for 3 min. The mixture was poured into water and after the usual workup, 114 mg of the corresponding quinone **17** (0.46 mmol, 47%) was obtained. In this oxidation, the corresponding ortho isomer of **17** was not obtained.[30] **17** was converted to the azidoquinone **18** in 90% by the standard azidation method.

17: yellow oil; NMR (CCl_4) δ 1.39 (d, 3 H, J = 7 Hz), 1.92 (s, 3 H), 3.80 (m, 1 H), 4.05 (s, 3 H), 5.00–5.24 (m, 2 H), 5.80–6.41 (m, 3 H); IR (NaCl) 1650 (s), 1000 (m), 950 cm^{-1} (m); high-resolution MS, calcd for $C_{14}H_{15}O_3F$ 250.1005, found 250.1008.

18: red oil; NMR (CCl_4) δ 1.41 (d, 3 H, J = 7 Hz), 1.81 (s, 3 H), 3.50 (m, 1 H), 4.03 (s, 3 H), 5.00–5.27 (m, 2 H), 5.75–6.40 (m, 3 H); IR (NaCl) 2100 (vs), 1640 cm^{-1} (s).

3-Allyl-2-bromo-4,5-dimethoxy-6-methylphenol (75). A dry acetone (30 mL, dried over $CaSO_4$) suspension of **71** (7.73 g, 28 mmol),[12] K_2CO_3 (4.64 g, 34 mmol), and allyl bromide (3 mL, 34 mmol) was refluxed overnight under nitrogen. After filtration and evaporation, the residue was purified by a short column on silica gel to give 7.03 g (22 mmol, 80%) of **72**: NMR (CCl_4) δ 2.04, (s, 3 H), 2.30 (s, 3 H), 3.83 (s, 3 H), 4.50 (d, 2 H, J = 6 Hz), 5.27 (d, 1 H, J = 10 Hz), 5.42 (d, 1 H, J = 14 Hz), 6.03 (m, 1 H), 6.94 (s, 1 H); IR (NaCl) 2950 (m), 1750 (vs), 1480 (m), 1190 (s), 1090 (s), 1000 cm^{-1} (m).

A diethylaniline (22 mL) solution of **72** (7.03 g, 22 mmol) was heated at 200 °C under argon for 3 h. After it cooled to room temperature, the solution was poured into 10% HCl solution and ether. The ethereal layer was washed with 10% HCl solution, water, and then brine, dried over $MgSO_4$, and evaporated to give crude **73**: colorless crystals; mp 109–111 °C; NMR (CCl_4) δ 2.09 (s, 3 H), 2.31 (s, 3 H), 3.79 (d, 2 H, J = 7 Hz), 3.82 (s, 3 H), 5.00–5.16 (m, 2 H), 5.81 (br, 1 H, OH), 5.66–6.14 (m, 1 H); IR (KBr) 1740 (vs), 1400 (s), 1360 (m), 1200 cm^{-1} (s); MS, m/e (relative intensity) 316 (9), 314 (M^+, 9), 274 (91), 272 (100), 178 (70).

A dry acetone (50 mL) solution of this crude **73**, K_2CO_3 (4.1 g, 30 mmol), and MeI (1.9 mL, 30 mmol) was refluxed overnight under nitrogen. After the usual workup, crude **74** was obtained. To a MeOH (30 mL) solution of the crude **74** was added a MeOH (30 mL) solution of KOH (2.52 g, 45 mmol) at 0 °C under nitrogen. After the mixture was stirred for 1 h at this temperature, neutralization with 10% HCl and evaporation gave a residue, which was purified by column chromatography on silica gel to give 5.17 g (18 mmol, 82% from **72**) of **75**: colorless oil; NMR (CCl_4) δ 2.15 (s, 3 H), 3.42 (d, 2 H, J = 7 Hz), 3.71 (s, 3 H), 3.74 (s, 3 H), 4.80–5.00 (m, 2 H), 5.56–6.00 (m, 1 H); IR (NaCl) 3450 (s), 2950 (m), 1470 (m), 1410 (s), 1300 (m), 1230 (m), 1110 (s), 1030 (m), 1000 cm^{-1} (m); MS, m/e (relative intensity) 288 (26), 286 (M^+, 100), 271 (67), 192 (53).

1-Bromo-3,4-dimethoxy-6-(methoxymethoxy)-5-methyl-2-(2-formylethyl)benzene (19a). To a DMF (20 mL) suspension of NaH (60 wt %, washed with dry ether twice, 864 mg, 21 mmol) was added a DMF (20 mL) solution of **75** (5.17 g, 18 mmol) at 0 °C under nitrogen over 10 min. After the mixture was stirred for 1 h at 0 °C, chloromethyl methyl ether (1.6 mL, 21 mmol) was added to the solution, which was stirred for 1 h. The solution was poured into water and extracted twice with ether. The combined organic phase was washed with water three times and then brine, dried over $MgSO_4$, and evaporated to give crude **76**. To a THF (14 mL) solution of crude **76** was added a THF (6.3 mL) solution of BH_3·SMe_2 (5.8 mmol) over 20 min at 0 °C. After the mixture was stirred for 1 h at room temperature, H_2O (1.52 mL) was added to decompose excess borane, and 3 M NaOH (3.5 mL) was then added at 0 °C for a few minutes. After addition of 30% H_2O_2 (2 mL), the mixture was heated at 50 °C for 0.5 h. The solution was cooled to room temperature, brine and ether were added, and the organic phase was washed with water, dried over $MgSO_4$, and evaporated. After a purification by column chromatography on silica gel, 4.3 g (12.3 mmol, 72%) of **77** was obtained: colorless oil; NMR (CCl_4) δ 1.74 (m, 2 H), 2.14 (s, 3 H), 2.85 (t, 2 H, J = 7 Hz), 3.48 (t, 2 H, J = 7 Hz), 3.60 (s, 3 H), 3.80 (s, 3 H), 3.85 (s, 3 H), 4.94 (s, 3 H); IR (NaCl) 2950 (m), 1400 (m), 1400 (s), 1240 (m), 1160 (m), 1000 (s), 970 (m), 920 cm^{-1} (m).

To pyridinium chlorochromate (PCC, 3.2 g, 15 mmol) in dry CH_2Cl_2 (18 mL) was added a CH_2Cl_2 (3 mL) solution of **77** (4.3 g, 12.3 mmol) and stirred for 3 h. After the mixture was stirred for 3 h, filtration through a silica gel column provided 3.56 g (10.2 mmol, 83%) of **19a**: colorless oil; NMR (CCl_4) δ 2.20 (s, 3 H), 2.60 (t, 2 H, J = 7 Hz), 3.05 (t, 2 H, J = 7 Hz), 3.60 (s, 3 H), 3.80 (s, 3 H), 3.82 (s, 3 H), 4.93 (s, 2 H), 9.60 (br, 1 H); IR (NaCl) 2950 (m), 1730 (s), 1460 (m), 1400 (s), 1240 (m), 1160 (m), 1100 (s), 1025 (m), 960 cm^{-1} (m); MS, m/e (relative intensity) 348 (64), 346 (M^+, 40), 267 (100), 195 (93). Anal. Calcd for $C_{14}H_{19}O_5Br$: C, 48.43; H, 5.52; Br, 23.01. Found: C, 48.44; H, 5.78; Br, 22.64.

2-Bromo-4,5-dimethoxy-6-methyl-3-(4-methyl-2,4-pentadienyl)phenol (20). To an ether solution of **19a** (580 mg, 1.7 mmol) was added a 1 M ether solution of 2-isopropenylmagnesium bromide (1.9 mL) at 0 °C under nitrogen. After being stirred for 1 h, the reaction was quenched with saturated NH_4Cl solution. And after the usual workup and purification, 590 mg of the corresponding allyl alcohol (1.50 mmol, 88%) was obtained: colorless oil; NMR (CCl_4) δ 1.74 (s, 3 H), 1.59–1.80 (m, 2 H), 2.20

(30) The corresponding o-quinone form was not formed, presumably because the higher electronegativity of fluoride group than bromide enhanced the attack of OH^-[29] to the nearby carbon atom, resulting in the exclusive formation of the p-quinone.

(31) Kloetzel, M. C.; Dayton, R. P.; Abadir, B. Y. *J. Org. Chem.* **1955**, *20*, 38. Ansell, M. F.; Nash, B. W.; Wilson, D. A. *J. Chem. Soc.* **1963**, 3028.

(s, 3 H), 2.69–2.86 (m, 2 H), 3.64 (s, 3 H), 3.79 (s, 3 H), 3.82 (s, 3 H), 3.96 (t, 1 H, J = 6 Hz), 4.72 (br, 1 H), 4.92 (s, 2 H), 4.95 (br, 1 H). Then to a CH_2Cl_2 solution of this allyl alcohol (590 mg, 1.5 mmol) was added 2,6-lutidine (0.77 mL, 6.9 mmol) and Tf_2O (0.38 mL, 1.5 mmol) at −10 °C under nitrogen and the mixture was stirred for 15 min. After the usual workup, the obtained substrate was treated with 5% HCl solution (0.5 mL) and acetone (5 mL), and the solution was refluxed for 1 h. After the usual workup, 196 mg of **20** (0.6 mmol, 40%) was obtained: colorless oil; NMR (CCl_4) δ 1.78 (s, 3 H), 2.15 (s, 3 H), 3.55 (d, 2 H, J = 7 Hz), 3.78 (s, 3 H), 3.80 (s, 3 H), 4.81 (br, 2 H), 5.38 (br, 1 H, OH), 5.60 (dt, 1 H, J = 7, 15 Hz), 6.13 (d, 1 H, J = 15 Hz); IR (NaCl) 2950 (m), 1460 (s), 1420 (s), 1230 (m), 1110 (s), 970 cm^{-1} (m). Anal. Calcd for $C_{15}H_{19}O_3Br$: C, 55.05; H, 5.85; Br, 24.42. Found: C, 55.23; H, 5.77; Br, 24.40.

2-Azido-5-methoxy-6-methyl-3-(4-methyl-2,4-pentadienyl)-1,4-benzoquinone (24). With the method described, **20** was converted stepwise to the bromoquinone **22** (69%) and the azidoquinone **24** (87%).

22: yellow oil; NMR (CCl_4) δ 1.83 (s, 3 H), 2.01 (s, 3 H), 3.52 (d, 2 H, J = 7 Hz), 4.12 (s, 3 H), 5.00 (br, 2 H), 5.62 (dt, 1 H, J = 7, 15 Hz), 6.40 (d, 1 H, J = 15 Hz); IR (NaCl) 2920 (m), 1660 (vs), 1590 (s), 1450 (m), 1240 (m), 960 cm^{-1} (w); MS, m/e (relative intensity) 312 (18) 310 (M^+, 26), 231 (100), 227 (90); high-resolution MS, calcd for $C_{14}H_{15}O_3Br$ 310.0205, found 310.0208.

24: red oil; NMR (CCl_4) δ 1.75 (s, 3 H), 1.95 (s, 3 H), 3.40 (d, 2 H, J = 7 Hz), 4.10 (s, 3 H), 5.05 (br, 2 H), 5.75 (dt, 1 H, J = 7, 15 Hz), 6.35 (d, 1 H, J = 15 Hz); IR (NaCl) 2100 (vs), 1650 cm^{-1} (s).

4-Acetoxy-5-bromo-2-methoxy-3-methyl-1-(2-methyl-2-propenyloxy)benzene (78). To an ether (15 mL) solution of **71** (2.76 g, 10 mmol) and $EtCO_2N{=}NCO_2Et$ (1.6 mL, 10 mmol) was added an ether (15 mL) solution of 2-methyl-2-propenyl alcohol (0.84 mL, 10 mmol) and PPh_3 (2.6 g, 10 mmol) and stirred for 24 h. After filtration and evaporation, the residue was purified by column chromatography on silica gel to give 1.9 g (5.7 mmol, 57%) of **78**: NMR (CCl_4) δ 1.82 (s, 3 H), 2.01 (s, 3 H), 2.26 (s, 3 H), 3.80 (s, 3 H), 4.34 (s, 2 H), 4.93 (br, 1 H), 5.08 (br, 1 H), 6.94 (s, 1 H); IR (NaCl) 2920 (m), 1760 (vs), 1480 (s), 1180 (s), 1080 cm^{-1} (s); MS, m/e (relative intensity) 330 (M^+, 10), 328 (10), 288 (37), 286 (38), 233 (98), 231 (100).

1-Bromo-3,4-dimethoxy-6-(methoxymethoxy)-5-methyl-2-(2-formylpropyl)benzene (19b). By the same procedure applied for the conversion of **19a** from **72**, **78** was converted to **19b** in 10% yield: colorless oil; NMR (CCl_4) δ 1.05 (d, 3 H, J = 7 Hz), 2.26 (s, 3 H), 2.80–3.20 (m, 3 H), 3.64 (s, 3 H), 3.84 (s, 3 H), 3.88 (s, 3 H), 5.00 (s, 2 H), 9.73 (br, 1 H); MS, m/e (relative intensity) 362 (16), 360 (M^+, 18), 318 (20), 316 (35), 260 (46), 77 (100); high-resolution MS, calcd for $C_{15}H_{21}O_5Br$ 360.0572, found 360.0576.

2-Azido-5-methoxy-6-methyl-3-(2-methyl-2,4-pentadienyl)-1,4-benzoquinone (25). From **19b** bromoquinone **23** and azidoquinone **25** was obtained by the similar method as the syntheses of **22** and **24**.

23: yellow oil; NMR (CCl_4) δ 1.63 (s, 3 H), 2.04 (s, 3 H), 3.48 (br, 2 H), 4.07 (s, 3 H), 5.05 (d, 1 H, J = 10 Hz), 5.12 (d, 1 H, J = 15 Hz), 5.88 (d, 1 H, J = 10 Hz), 6.41–6.80 (m, 1 H); IR (NaCl) 1670 (vs), 1600 (m), 1255 (m), 1130 cm^{-1} (w); high-resolution MS, calcd for $C_{14}H_{15}O_3Br$ 310.0205, found 310.0209.

25: red oil; NMR (CCl_4) δ 1.70 (s, 3 H), 1.97 (s, 3 H), 3.35 (br, 2 H), 4.00 (s, 3 H), 5.00 (d, 1 H, J = 10 Hz), 5.15 (d, 1 H, J = 15 Hz), 5.80 (d, 1 H, J = 10 Hz), 6.45–6.77 (m, 1 H); IR (NaCl) 2120 (vs), 1660 (vs), 1600 (s), 1280 (m), 1150 cm^{-1} (m).

The azidoquinones **31** and **32** were prepared according to the literature.[11]

2-Azido-3-(2,4-hexadienyl)-1,4-naphthoquinone (33) and 2-azido-5-methoxy-6-methyl-3-(2,4-hexadienyl)-1,4-benzoquinone (34) were synthesized from **26** and **28** with stannyl reagent **30** and $AlCl_3{\cdot}OEt_2$ by the similar method as in preparation of **31**.

2-Bromo-3-(2,4-hexadienyl)naphthoquinone: yellow oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.70 (d, 3 H, J = 6.4 Hz), 3.59 (d, 2 H, J = 7.0 Hz), 5.62 (dt, 1 H, J = 14.3, 7.0 Hz), 5.78 (dq, 1 H, J = 14.3, 6.4 Hz), 5.95 (dd, 1 H, J = 10.3, 14.3 Hz), 6.20 (dd, 1 H, J = 10.3, 14.3 Hz), 7.71–7.77 (m, 2 H), 8.02–8.16 (m, 2 H); IR (NaCl) 2950 (w), 1660 (vs), 1600 (s), 1300 (s), 960 (w), 780 cm^{-1} (s); MS, m/e (relative intensity) 318 (60), 316 (M^+, 55), 263 (100), 234 (26); high-resolution MS, calcd for $C_{16}H_{13}O_2Br$ 316.010, found 316.011.

33: red oil; NMR (CCl_4) δ 1.65 (d, 3 H, J = 6 Hz), 3.40 (d, 2 H, J = 7 Hz), 5.73 (m, 1 H), 5.62 (dd, 1 H, J = 10, 14 Hz), 5.93 (dd, 1 H, J = 10, 14 Hz), 6.15 (dd, 1 H, J = 10, 14 Hz), 7.65–7.70 (m, 2 H), 8.00–8.16 (m, 2 H); IR (NaCl) 2950 (w), 2120 (vs), 1670 (vs), 1600 (s), 1350 (s), 1280 (s), 780 cm^{-1} (s).

2-Bromo-5-methoxy-6-methyl-3-(2,4-hexadienyl)-1,4-benzoquinone (32): yellow oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.67 (d, 3 H, J = 6.7 Hz), 1.97 (s, 3 H), 3.38 (d, 2 H, J = 7.0 Hz), 3.97 (s, 3 H), 5.41 (dt, 1 H, J = 7.0, 14.6 Hz), 5.62 (dq, 1 H, J = 6.7, 14.3 Hz), 5.92 (dd, 1 H, J = 10.4, 14.3 Hz), 6.15 (dd, 1 H, J = 10.4, 14.6 Hz); MS, m/e (relative intensity) 312 (31), 310 (M^+, 20), 218 (100), 203 (80), 119 (51); high-resolution MS, calcd for $C_{14}H_{15}O_3Br$ 310.0204, found 310.0201.

2-Azido-5-methoxy-6-methyl-3-(2,4-hexadienyl)-1,4-benzoquinone (34): red oil; NMR (CCl_4) δ 1.65 (d, 3 H, J = 6 Hz), 1.85 (s, 3 H), 3.25 (d, 2 H, J = 7 Hz), 3.93 (s, 3 H), 5.41 (dt, 1 H, J = 7, 14 Hz), 5.60 (m, 1 H), 5.85 (dd, 1 H, J = 10, 14 Hz), 6.13 (dd, 1 H, J = 10, 14 Hz); IR (NaCl) 2940 (m), 2120 (vs), 1650 (vs), 1600 (s), 1360 (m), 1280 (m), 1150 cm^{-1} (m).

2-Azido-5-hydroxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (35). The azidoquinone **35** was obtained from hydroxyquinone **14** by the usual azidation method: red needles; mp 98 °C dec; NMR (CCl_4) δ 2.00 (s, 3 H), 3.28 (d, 2 H, J = 7 Hz), 5.13 (d, 1 H, J = 10 Hz), 5.25 (d, 1 H, J = 14 Hz), 5.60–5.82 (m, 1 H), 6.08–6.58 (m, 2 H), 7.37 (br, 1 H, OH); IR (KBr) 3320 (s), 2100 (vs), 1630 (vs), 1590 (vs), 1320 (s), 1280 (s), 1200 (m), 1130 (m), 1080 (m), 1000 (m), 750 cm^{-1} (m).

2-Azido-5-[(*tert*-butyldimethylsilyl)oxy]-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (36). To a CH_2Cl_2 (4 mL) solution of **35** (99 mg, 0.4 mmol) were added 2,6-lutidine (118 μL, 1 mmol) and *tert*-butyldimethylsilyl trifluoromethanesulfonate (92 μL, 0.4 mmol) at 0 °C under N_2, and the mixture was stirred for 15 min at 0 °C. After the usual workup and chromatographic purification, 65 mg of **36** (0.18 mmol, 45%) was obtained: yellow oil; NMR (CCl_4) δ 0.26 (s, 6 H), 0.93 (s, 9 H), 1.86 (s, 3 H), 3.02 (d, 2 H, J = 7 Hz), 4.80–5.11 (, 2 H), 5.25–5.66 (m, 1 H), 5.76–6.28 (m, 2 H); IR (NaCl) 2100 (vs), 1650 cm^{-1} (s).

2-Azido-5-acetoxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (37). To a CH_2Cl_2 (3.5 mL) solution of **35** (86 mg, 0.35 mmol) were added Et_3N (49 μL, 0.53 mmol) and AcCl (30 μL, 0.42 mmol) at 0 °C under N_2, and the mixture was stirred for 15 min. After the usual workup, 48 mg of **37** (0.17 mmol, 48%) was obtained: red oil; NMR (CCl_4) δ 1.95 (s, 3 H), 2.33 (s, 3 H), 3.20 (d, 2 H, J = 7 Hz), 5.03 (d, 1 H, J = 10 Hz), 5.15 (d, 1 H, J = 14 Hz), 5.56 (dt, 1 H, J = 7, 14 Hz), 5.98–6.45 (m, 2 H); IR (NaCl) 2100 (vs), 1770 (s), 1655 (s), 1640 (s), 1600 (s), 1350 (m), 1270 (m), 1170 (s), 1115 cm^{-1} (m).

2-Azido-5-[(3-chlorobenzoyl)oxy]-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (38). **38** was obtained in 48% yield from **35** with *m*-chlorobenzoyl chloride and Et_3N in a similar manner to the synthesis of **37**. **38**: red oil; NMR (CCl_4) δ 2.00 (s, 3 H), 3.20 (d, 2 H, J = 7 Hz), 5.00 (d, 1 H, J = 10 Hz), 5.15 (d, 1 H, J = 14 Hz), 5.55 (dt, 1 H, J = 7, 14 Hz), 5.97–6.44 (m, 2 H), 7.40–8.12 (m, 4 H); IR (NaCl) 2100 (vs), 1750 (vs), 1660 (vs), 1600 (s), 1420 (m), 1350 (s), 1265 (s), 1220 (s), 1160 (m), 1140 (m), 780 cm^{-1} (m).

3-Bromo-2-(3-formylethyl)-4,6-dimethoxy-1-(methoxymethoxy)-5-methylbenzene (39). In a similar manner to the synthesis of **19a**, **39** was prepared: colorless oil; NMR (CCl_4) δ 2.22 (s, 3 H), 2.67 (t, 2 H, J = 7 Hz), 3.13 (t, 2 H, J = 7 Hz), 3.52 (s, 3 H), 3.76 (s, 6 H), 5.04 (s, 2 H), 9.87 (br, 1 H); IR (NaCl) 2950 (m), 1720 (vs), 1450 (s), 1160 (s), 1110 (s), 1010 (s), 950 cm^{-1} (m); MS, m/e (relative intensity) 348 (8), 346 (M^+, 8), 302 (42), 277 (79), 261 (100); high-resolution MS, calcd for $C_{14}H_{19}O_5Br$ 346.0417, found 346.0422.

3-Bromo-4,6-dimethoxy-5-methyl-2-(3,5-hexadienyl)phenol (40). To a dry ether (15 mL) solution of allyltriphenylphosphonium bromide (582 mg, 1.5 mmol) was added *n*-BuL (1.33 M, 1.1 mL, 1.5 mmol) at 0 °C under N_2, and the mixture was stirred for 1 h. A dry ether (5 mL) solution of **39** (524 mg, 1.5 mmol) was added to the mixture and stirred for 1 h. The mixture was poured into water and extracted with ether twice. The organic phase was evaporated, and to the residue were added 3% HCl

solution and acetone (10 mL). The solution was refluxed for 1 h. After the usual workup and purification, 162 mg of **40** (0.5 mmol, 25%) was obtained, which was the mixture of stereoisomers; cis/trans = 50:50.

cis-**40**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 1.26 (s, 3 H), 1.40–1.50 (m, 2 H), 1.89–1.93 (m, 2 H), 2.74 (s, 3 H), 4.08 (d, 1 H, J = 16.8 Hz), 4.05 (d, 1 H, J = 10.1 Hz), 4.15 (d, 1 H, J = 16.8 Hz), 4.59 (dt, 1 H, J = 10.7, 7.3 Hz), 5.01 (dd, 1 H, J = 10.7, 10.7 Hz), 5.68 (ddd, 1 H, J = 16.8, 10.7, 10.7 Hz).

trans-**40**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 1.26 (s, 3 H), 1.30–1.36 (m, 2 H), 1.89–1.93 (m, 2 H), 2.74 (s, 3 H), 3.95 (d, 1 H, J = 10.1 Hz), 4.08 (d, 1 H, J = 16.0, 8.0 Hz), 4.85 (dt, 1 H, J = 7.3, 15.0 Hz), 5.09 (dd, 1 H, J = 15.0, 10.1 Hz), 5.31 (ddd, 1 *H*, J = 10.1, 10.1, 16.8 Hz).

The mixture: white solid; mp 58–59 °C; IR (KBr) 2920 (m), 1450 (m), 1090 (m), 1000 cm^{-1} (m).

2-Azido-5-methoxy-6-methyl-3-(3,6-hexadienyl)-1,4-benzoquinone (44). The bromoquinone **42**[32] and the azidoquinone **44** were obtained from **40** in the same manner as in the synthesis of **7** from **11**.

42: yellow oil; NMR (CCl_4) δ 1.98 (s, 3 H), 2.04–2.47 (m, 2 H), 2.74–2.86 (m, 2 H), 4.03 (s, 3 H), 4.93–5.27 (m, 2 H), 5.58–6.80 (m, 3 H); IR (NaCl) 2920 (w), 1650 (vs), 1580 (s), 1440 (w), 1240 (m), 1000 cm^{-1} (w); high-resolution MS, calcd for $C_{14}H_{15}O_3Br$ 310.0205, found 310.0209.

44: red oil; IR (NaCl) 2950 (m), 1450 (m), 1410 (m), 1110 (m), 1090 (m), 1020 (m), 780 cm^{-1} (s).

3-Bromo-4,6-dimethoxy-5-methyl-2-(3,5-heptadienyl)phenol (41). **41** was obtained from **39** with crotyltriphenylphosphonium bromide in the same manner as in the synthesis of **40**.

41: colorless oil; NMR (CCl_4) δ 1.76 (d, 3 H, J = 6 Hz), 2.25 (s, 3 H), 2.16–2.52 (m, 2 H), 2.80–2.97 (m, 2 H), 3.76 (s, 3 H), 3.81 (s, 3 H), 5.26–6.12 (m, 4 H); IR (NaCl) 2950 (m), 1450 (m), 1410 (m), 1110 (m), 1090 (m), 1020 (m), 780 cm^{-1} (s); MS, m/e (relative intensity) 342 (19), 340 (M^+, 21), 251 (100), 259 (99).

2-Azido-5-methoxy-6-methyl-3-(3,5-heptadienyl)-1,4-benzoquinone (45). The bromoquinone **43**[32] and the azidoquinone **45**, both of which were a mixture of two stereoisomers, Δ^3,Δ^5, cis, trans/trans,trans = 44:56, were obtained as **42** and **44**, respectively.

cis-**43**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 1.72 (d, 3 H, J = 6.7 Hz), 1.98 (s, 3 H), 2.36 (d, 2 H, J = 7.6, 7.6 Hz), 2.77 (t, 2 H, J = 7.6 Hz), 3.99 (s, 3 H), 5.29 (dt, 1 H, J = 10.1, 7.6 Hz), 5.66 (dd, 1 H, J = 7.0, 14.7 Hz), 5.98 (m, 2 H).

trans-**43**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 1.70 (d, 3 H, J = 6.7 Hz), 1.98 (s, 3 H), 2.25 (dt, 2 H, J = 7.6, 7.6 Hz), 2.77 (t, 2 H, J = 7.6 Hz), 3.97 (s, 3 H), 5.53 (dd, 1 H, J = 14.0, 7.3 Hz), 5.59 (dd, 1 H, J = 7.0, 14.0 Hz), 5.98 (m, 2 H).

The mixture: red oil; IR (NaCl) 2950 (w), 1660 (vs), 1600 (m), 1450 (m), 1245 (s), 990 cm^{-1} (m); MS, m/e (relative intensity) 326 (9), 324 (M^+, 7), 245 (100), 213 (38); high-resolution MS, calcd for $C_{15}H_{17}O_3Br$ 324.0361, found 324.0364.

45, the mixture: red oil; NMR (CCl_4) δ 1.85 (s, 3 H), 2.01–2.45 (m, 2 H), 2.72–2.83 (m, 2 H), 4.01 (s, 3 H), 4.92–5.18 (m, 2 H), 5.53–6.77 (m, 3 H); IR (NaCl) 2950 (w), 2120 (vs), 1650 (vs), 1600 (s), 1450 (m), 1360 (s), 1280 (s), 1150 cm^{-1} (m).

3-Bromo-2-[4-(ethoxycarbonyl)-3-hydroxy-5-hexenyl]-4,6-dimethoxy-1-(methoxymethoxy)-5-methylbenzene (46). To a THF (10 mL) solution of diisopropylamine (0.67 mL, 4.8 mmol) and HMPA (1.5 mL) was added *n*-BuLi (1.4 M, 2.9 mL) at −75 °C under nitrogen and stirred for 15 min. Then to the solution was added ethyl crotonate (0.5 mL, 3.96 mmol), and the mixture was stirred for 30 min. To this mixture was added a THF (3 mL) solution of **39** (1.16 g, 3.3 mmol) and stirred for 1 h. The reaction was quenched with saturated NH_4Cl solution, and after the usual workup and chromatographic purification, crude **46** was obtained: colorless oil; NMR (CCl_4) δ 1.68 (d, 3 H, J = 7 Hz), 2.05–2.39 (m, 2 H), 1.92 (s, 3 H), 2.68–2.80 (m, 2 H), 3.56 (s, 3 H), 3.87 (s, 3 H), 5.00–5.30 (m, 1 H), 5.59–5.69 (m, 1 H), 5.99 (m, 2 H).

3-Bromo-2-[4-(ethoxycarbonyl)-3,5-hexadienyl]-4,6-dimethoxy-5-methylphenol (47). **46** (696 mg, 1.5 mmol), pyridine (1.6 mL), acetic anhydride (0.22 mL, 2.4 mmol), and 4-(dimethylamino)pyridine (32 mg) were stirred for 12 h at 0 °C. The reaction was quenched with saturated $NaHCO_3$ solution, and after the usual workup, the acetate of **47** was obtained. To a dry DME (8 mL) solution of this acetate was added DBU (0.24 mL, 1.58 mmol) at 0 °C under nitrogen and stirred for 4 min. The reaction was quenched with saturated NH_4Cl solution and extracted with ether. The organic phase was evaporated, the residue was treated with 5% HCl solution (0.5 mL) and acetone (5 mL), and the solution was refluxed for 1 h. After the usual workup and purification, 408 mg (1.02 mmol, 68%) of **47** was obtained: colorless oil; NMR (CCl_4) δ 1.28 (t, 3 H, J = 7 Hz), 2.27 (s, 3 H), 2.45–2.78 (m, 2 H), 2.88–3.14 (m, 2 H), 3.27 (s, 3 H), 3.76 (s, 3 H), 4.40 (q, 2 H, J = 7 Hz), 5.00–5.76 (m, 2 H), 5.98–6.96 (m, 2 H); IR (NaCl) 1700 (s), 1450 (s), 1400 (m), 1230 (s), 1100 cm^{-1} (m); MS, m/e (relative intensity) 400 (11), 398 (M^+, 11), 259 (21), 119 (100).

2-Azido-3-[4-(ethoxycarbonyl)-3,5-hexadienyl]-5-methoxy-6-methyl-1,4-benzoquinone (49). In the same manner as the synthesis of **7**, **47** was converted stepwise to the bromoquinone **48** (76%)[32] and the azidoquinone **49** (80%), both of which were the mixture of stereoisomers; E/Z = 1.7:1.

The mixture: yellow oil; IR (NaCl) 2930 (m), 1720 (s), 1660 (vs), 1450 (m), 1250 (s), 730 cm^{-1} (m); MS, m/e (relative intensity) 384 (39), 382 (M^+, 24), 303 (100), 257 (94), 229 (79), 149 (75); high-resolution MS, calcd for $C_{17}H_{19}O_5Br$ 382.0415, found 382.0417.

(*E*)-**48**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 0.90 (t, 3 H, J = 7.3 Hz), 2.00 (s, 3 H), 2.53 (m, 2 H), 3.85 (m, 2 H), 4.01 (s, 3 H), 4.22 (q, 2 H, J = 7.3 Hz), 5.38 (dd, 1 H, J = 11.6, 1.5 Hz), 5.60 (dd, 1 H, J = 17.7, 1.5 Hz), 6.44 (dd, 1 H, J = 11.6, 17.7 Hz), 6.71 (t, 1 H, J = 7.9 Hz).

(*Z*)-**48**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 0.90 (t, 3 H, J = 7.3 Hz), 2.00 (s, 3 H), 2.84 (m, 2 H), 3.85 (m, 2 H), 4.01 (s, 3 H), 4.22 (q, 2 H, J = 7.3 Hz) 5.10 (d, 1 H, J = 11.0 Hz), 5.24 (d, 1 H, J = 17.7 Hz), 5.93 (t, 1 H, J = 8.2 Hz), 6.29 (dd, 1 H, J = 11.0, 17.7 Hz).

The azidoquinone **49**: red oil; IR (NaCl) 2110 (vs), 1720 (s), 1650 (vs), 1600 (vs), 1260 cm^{-1} (m).

(*E*)-**49**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 0.90 (t, 3 H, J = 7.3 Hz), 1.84 (s, 3 H), 2.48 (m, 2 H), 3.55 (m, 2 H), 3.95 (s, 3 H), 4.22 (q, 2 H, J = 7.3 Hz), 5.28 (dd, 1 H, J = 11.6, 1.5 Hz), 5.50 (dd, 1 H, J = 17.7, 1.5 Hz), 6.43 (dd, 1 H, J = 11.6, 17.7 Hz), 6.70 (t, 1 H, J = 7.9 Hz).

(*Z*)-**49**: 400-MHz ^{1}H NMR ($CDCl_3$) δ 0.90 (t, 3 H, J = 7.3 Hz), 1.84 (s, 3 H), 2.75 (m, 2 H), 3.55 (m, 2 H), 3.95 (s, 3 H), 4.22 (q, 2 H, J = 7.3 Hz), 5.00 (d, 1 H, J = 10.0 Hz), 5.14 (d, 1 H, J = 17.7 Hz), 5.81 (t, 1 H, J = 8.2 Hz), 6.20 (dd, 1 H, J = 11.0, 17.7 Hz).

Metal-Catalyzed Pyrolysis of 2-Azido-5-methoxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (7) (Tables I–III). General Procedure. To a refluxing dry benzene (27 mL) solution of metal salt (0.3 mmol in Table I and 0.6 mmol in Tables II and III) was added a dry benzene (3 mL) solution of **7** (78 mg, 0.3 mmol). The solution was refluxed until the starting quinone (**7**) disappeared on TLC, or when the reaction was slow, reflux was ceased after 4 h. The mixture was cooled to room temperature, filtered, and evaporated. The products were separated by column chromatography or PLC on silica gel. The resulting yield of each product was shown in each table and equation. Physical properties and spectral data were as follows.

9,9a-Dihydro-7-methoxy-6-methyl-3*H*-pyrrolo[1,2-*a*]-indole-5,8-dione (8): purple crystals; mp 119–121 °C; 270-MHz ^{1}H NMR ($CDCl_3$) δ 1.87 (s, 3 H), 2.85 (dd, 1 H, J = 16.8, 6.9 Hz), 2.99 (dd, 1 H, J = 16.8, 11.5 Hz), 4.01 (dddd, 1 H, J = 16.1, 1.3, 2.6, 4.2 Hz), 4.04 (s, 3 H), 4.30 (ddd, 1 H, J = 16.1, 1.9, 1.6, 3.6 Hz), 4.93 (m, 1 H), 5.82 (m, 1 H), 5.87 (m, 1 H); ^{13}C NMR ($CDCl_3$) δ 8.28, 30.89, 56.66, 61.23, 71.23, 119.23, 124.64, 128.35, 130.89, 154.10, 157.61, 179.78, 183.32; IR (KBr) 1660 (s), 1630 (s), 1590 (s), 1410 (s), 1300 (m), 1260 (s), 1130 (s), 1010 cm^{-1} (s); MS, m/e (relative intensity) 231 (M^+, 62), 132 (77), 104 (47), 83 (100); UV (MeOH) λ_{max} (log ϵ) 220 (4.10), 324 (3.90), 5.36 (3.11). Anal. Calcd for $C_{13}H_{13}NO_3$: C, 67.52; H, 5.67; N, 6.06. Found: C, 67.30; H, 5.55; N, 5.80.

2-Amino-5-methoxy-6-methyl-3-(2,4-pentadienyl)-1,4-benzoquinone (9): red oil; NMR (CCl_4) δ 1.84 (s, 3 H), 3.16 (s, 2 H, J = 6 Hz), 4.10 (s, 3 H), 4.90–5.13 (m, 2 H), 4.93 (br, 2 H, NH_2), 5.44–5.70 (m, 1 H), 5.95–6.33 (m, 2 H); IR (NaCl) 3340 (m),

(32) The corresponding *o*-quinone isomer was converted to the para form according to the same procedure as in Scheme II without isolation of the ortho form, and the overall yield was indicated.

1640 (m), 1600 (s), 1000 (m), 780 (m), 740 cm^{-1} (m); MS, *m/e* (relative intensity) 233 (M^+, 4), 232 (3), 231 (4), 217 (12), 199 (16), 119 (100); high-resolution, MS calcd for $C_{13}H_{15}O_3N$ 233.1051, found 233.1055.

1-Cyano-3-methoxy-4-methyl-1-(2,4-pentadienyl)-3-cyclopentene-2,5-dione (10): colorless oil; NMR (CCl_4) δ 1.92 (s, 3 H), 2.78 (d, 2 H, J = 8 Hz), 4.34 (s, 3 H), 5.04–5.28 (m, 3 H), 5.96–6.40 (m, 2 H); IR (NaCl) 2230 (w), 1690 (vs), 1610 (vs), 1000 (m), 950 cm^{-1} (w); MS, *m/e* (relative intensity) 231 (M^+, 29), 203 (100). Anal. Calcd for $C_{13}H_{13}O_3N$: C, 67.52; H, 5.67; N, 6.06. Found: C, 67.74; H, 5.65; N, 6.06.

$Cu(acac)_2$-Catalyzed Double Cyclization Reaction (Table III). The reaction was done according to the general procedure shown above. Physical properties and spectral data of new products were as shown.

9,9a-Dihydro-7-methoxy-6,9β-dimethyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (52): 400-MHz ^1H NMR ($CDCl_3$) δ 1.36 (d, 3 H, J = 7.0 Hz), 1.87 (s, 3 H), 3.31 (dq, 1 H, J = 7.0, 5.2 Hz), 3.98 (dddd, 1 H, J = 15.6, 3.0, 1.5, 1.5 Hz) 4.01 (s, 3 H), 4.28 (dddd, 1 H, J = 15.6, 3.0, 1.5, 1.5 Hz), 4.40 (m, 1 H), 5.83 (m, 1 H), 5.86 (m, 1 H); ^{13}C NMR ($CDCl_3$) δ 8.07, 20.19, 39.20, 56.18, 69.59, 80.04, 119.91, 125.72, 127.83, 130.26, 167.50, 176.20, 177.52, 187.07; IR (KBr) 1630 (s), 1650 (s), 1580 (s), 1450 (m), 1400 (m), 1300 (m), 1050 (m), 760 (s), 730 cm^{-1} (s); MS, *m/e* (relative intensity) 245 (M^+, 100), 230 (65), 202 (77), 83 (78); UV (MeOH) λ_{max} (log ϵ) 218 (4.37), 269 (3.86, sh), 322 (3.98), 531 (3.30); high-resolution MS, calcd for $C_{14}H_{15}O_3N$ 245.1051, found 245.1052.

9,9a-Dihydro-7-methoxy-2,6-dimethyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (53): dark purple crystals; mp 151–153 °C; 400-MHz ^1H NMR ($CDCl_3$) δ 1.76 (s, 3 H), 1.87 (s, 3 H), 2.79 (dd, 1 H, J = 16.7, 6.8 Hz), 2.93 (dd, 1 H, J = 16.7, 12.0 Hz), 3.94 (dd, 1 H, J = 15.8, 1.3 Hz), 4.05 (s, 3 H), 4.11 (d, 1 H, J = 15.8 Hz), 4.94 (m, 1 H), 5.41 (d, 1 H, J = 1.3 Hz); ^{13}C NMR ($CDCl_3$) δ 8.0, 14.0, 30.7, 59.6, 61.0, 71.4, 124.1, 124.7, 138.1, 153.7, 161.0, 179.7, 183.2; IR ($CHCl_3$) 1640 (m), 1620 (s), 1570 (vs), 1440 (m), 1400 (s), 1300 (s), 1260 (s), 1230 (s), 1130 (s), 1000 (s), 800 cm^{-1} (m); UV (MeOH) λ_{max} (log ϵ) 219 (4.16), 313 (3.88), 596 (2.19); high-resolution MS, calcd for $C_{14}H_{15}O_3N$ 245.1051, found 245.1051.

9,9a-Dihydro-7-methoxy-3α,6-dimethyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (54): purple oil: 400-MHz ^1H NMR ($CDCl_3$) δ 1.18 (d, 3 H, J = 6.4 Hz), 1.88 (s, 3 H), 2.88 (dd, 1 H, J = 6.8, 16.7 Hz), 2.94 (dd, 1 H, J = 12.1, 16.7 Hz), 4.06 (s, 3 H), 4.41 (m, 1 H), 5.10 (m, 1 H), 5.78 (m, 1 H), 5.86 (m, 1 H); IR ($CHCl_3$) 1705, 1610, 1600, 1560, 1360, 1190, 980 cm^{-1}; MS, *m/e* (relative intensity) 245 (M^+, 100), 230 (70); high-resolution MS, calcd for $C_{14}H_{15}O_3N$ 245.1051, found 245.1053.

11,11a-Dihydro-3*H*-pyrrolo[1,2-*a*]benzo[*f*]indole-5,10-dione (55): red purple crystals; mp 135–136 °C; NMR ($CDCl_3$) δ 2.96 (dd, 1 H, J = 18, 8 Hz), 3.18 (dd, 1 H, J = 18, 11 Hz), 4.06 (dd, 1 H, J = 16, 3.5 Hz), 4.42 (dd, 1 H, J = 16, 4.5 Hz), 4.92 (m, 1 H, J = 11, 8, 4.5, 3.5 Hz), 5.85 (br, 2 H), 7.58 (m, 2 H), 7.95 (m, 2 H); IR (KBr) 1665 (vs), 1625 cm^{-1} (vs); MS, *m/e* (relative intensity) 237 (M^+); high-resolution MS, calcd for $C_{15}H_{11}O_2N$ 237.0789, found 237.0785.

11,11a-Dihydro-3α-methyl-3*H*-pyrrolo[1,2-*a*]benzo[*f*]indole-5,10-dione (56): red purple oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.17 (d, 3 H, J = 6.4 Hz), 2.78 (dd, 1 H, J = 17.1, 12.2 Hz), 3.02 (dd, 1 H, J = 17.1, 11.0 Hz), 4.51 (m, 1 H), 5.05 (m, 1 H), 5.68 (m, 1 H), 5.79 (m, 1 H), 7.57 (m, 2 H), 7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 20.8, 32.6, 62.5, 73.7, 122.9, 125.4, 126.0, 127.2, 128.8, 131.9, 133.7, 135.5, 141.5, 152.3, 173.0, 182.0; IR ($CHCl_3$) 1670, 1620, 1590, 1560, 1400, 1265, 1245, 1190, 950, 905 cm^{-1}; MS, *m/e* (relative intensity) 251 (M^+, 67), 249 (100), 236 (48), 222 (11); UV (MeOH) λ_{max} (log ϵ) 207 (3.68), 280 (3.65), 498 (2.50); high-resolution MS, calcd for $C_{16}H_{13}O_2N$ 251.0946, found 251.0948.

9,9a-Dihydro-7-methoxy-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (57): purple crystals; mp 112 °C dec; NMR (CCl_4) δ 2.85 (dd, 1 H, J = 17, 11.5 Hz), 3.09 (dd, 1 H, J = 17, 10.5 Hz), 5.85 (br, 2 H), 5.60 (s, 1 H); IR (KBr) 1655 (vs), 1630 cm^{-1} (vs); MS, *m/e* 217 (M^+); high-resolution MS, calcd for $C_{12}H_{11}O_3N$ 217.0738, found 217.0737.

9,9a-Dihydro-7-[(*tert*-butyldimethylsilyl)oxy]-6-methyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (58): purple oil; 400-MHz ^1H NMR ($CDCl_3$) δ 0.25 (s, 6 H), 0.94 (s, 9 H), 1.86 (s, 3 H), 4.01 (m, 1 H), 4.33 (m, 1 H), 4.89–4.96 (m, 1 H), 5.79–5.82 (m, 1 H), 5.84–5.87 (m, 1 H); IR (NaCl) 1650 (s), 1400 (m), 1190 cm^{-1} (m); MS, *m/e* (relative intensity) 331 (M^+, 50), 216 (100); high-resolution MS, calcd for $C_{18}H_{25}O_3NSi$ 331.1603, found 331.1601.

7-Acetoxy-9,9a-dihydro-6-methyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (59): purple oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.89 (s, 3 H), 2.24 (s, 3 H), 2.89 (dd, 1 H, J = 6.4, 17.0 Hz), 3.05 (dd, 1 H, J = 12.3, 17.0 Hz), 4.05 (m, 1 H), 4.33 (m, 1 H), 4.99 (m, 1 H), 5.82 (m, 1 H), 5.90 (m, 1 H); IR (NaCl) 1750 (s), 1640 cm^{-1} (s); high-resolution MS, calcd for $C_{14}H_{13}O_4N$ 259.0844, found 259.0845.

9,9a-Dihydro-7-[(3-chlorobenzoyl)oxy]-6-methyl-3*H*-pyrrolo[1,2-*a*]indole-5,8-dione (60): purple oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.95 (s, 3 H), 2.89 (dd, 1 H, J = 6.4, 17.0 Hz), 3.04 (dd, 1 H, J = 12.2, 17.0 Hz), 4.05 (d, 1 H, J = 16.5 Hz), 4.31 (d, 1 H, J = 16.5 Hz), 4.99 (m, 1 H), 5.84 (m, 1 H), 5.90 (m, 1 H), 7.26 (s, 1 H), 7.45 (t, 1 H, J = 7.3 Hz), 7.62 (d, 1 H, J = 7.3 Hz), 8.03 (d, 1 H, J = 7.3 Hz); IR (NaCl) 1650 cm^{-1} (s); high-resolution MS, calcd for $C_{18}H_{14}O_3NCl$ 327.0662, found 327.0665.

3,9,10,10a-Tetrahydro-7-methoxy-6-methylpyrrolo[1,2-*a*]quinoline-5,8-dione (61): dark purple solid; mp 101–104 °C; 400-MHz ^1H NMR ($CDCl_3$) δ 1.31 (m, 1 H), 1.88 (s, 3 H), 2.25 (m, 1 H), 2.34 (m, 1 H), 2.81 (dd, 1 H, J = 17.4, 4.6 Hz), 4.08 (s, 3 H), 4.24 (m, 1 H), 4.44 (d, 1 H, J = 18.3 Hz), 4.79 (d, 1 H, J = 18.3 Hz), 5.83 (m, 1 H), 5.91 (m, 1 H); IR (KBr) 1620 (s), 1660 (m), 1560 (s), 1430 (s), 1310 (m), 1230 (m), 940 (m), 780 (m), 760 (m); MS, *m/e* (relative intensity) 245 (M^+, 48), 167 (35), 149 (100), 83 (21); UV (MeOH) λ_{max} (log ϵ) 207 (4.36), 2.26 (4.37), 284 (3.90), 318 (3.90), 545 (3.37); high-resolution MS, calcd for $C_{14}H_{15}O_3N$ 245.1051, found 245.1054.

3,9,10,10a-Tetrahydro-7-methoxy-3α,6-dimethylpyrrolo[1,2-*a*]quinoline-5,8-dione (62): purple oil; 400-MHz ^1H NMR ($CDCl_3$) δ 1.13 (d, 3 H, J = 6.4 Hz), 1.24 (dddd, 1 H, J = 12.4, 12.4, 11.5, 5.6 Hz), 1.87 (s, 3 H), 2.18 (dddd, 1 H, J = 12.4, 7.3, 2.6, 1.3 Hz), 2.32 (ddd, 1 H, J = 18.4, 12.4, 7.3 Hz), 2.73 (ddd, 1 H, J = 18.4, 5.6, 1.3 Hz), 4.06 (s, 3 H), 4.08 (m, 1 H), 5.35 (dq, 1 H, J = 6.4, 1.7 Hz), 5.77 (ddd, 1 H, J = 6.4, 1.7, 1.7 Hz), 5.81 (ddd, 1 H, J = 6.4, 1.7, 1.7 Hz); ^{13}C NMR ($CDCl_3$) δ 8.27, 21.31, 23.27, 28.05, 60.95, 63.29, 66.50, 114.49, 123.45, 126.30, 132.74, 144.39, 156.85, 180.00, 185.91; IR ($CHCl_3$) 1620 (m), 1660 (m), 1560 (s), 1400 (m), 1300 (w), 1130 (w), 1000 cm^{-1} (w); MS, *m/e* (relative intensity) 259 (M^+, 100), 244 (80), 230 (30), 216 (25); UV (MeOH) λ_{max} (log ϵ) 225 (4.25), 289 (3.86), 318 (3.86), 551 (3.26); high-resolution MS, calcd for $C_{15}H_{17}O_3N$ 259.1207, found 259.1202.

1-(Ethoxycarbonyl)-3,9,10,10a-tetrahydro-7-methoxy-6-methyl-3*H*-pyrrolo[1,2-*a*]quinoline-5,8-dione (63): 400-MHz ^1H NMR ($CDCl_3$) δ 1.29–1.30 (m, 1 H), 1.31 (t, 1 H, J = 7.0 Hz), 1.86 (s, 3 H), 2.30–2.38 (m, 1 H), 2.59–2.6 (m, 1 H), 2.80 (dd, 1 H, J = 18.3, 5.2 Hz), 4.06 (s, 3 H), 4.20–4.30 (m, 1 H), 4.47 (m, 1 H), 4.53 (d, 1 H, J = 20.1 Hz), 4.98 (d, 1 H, J = 20.5 Hz), 6.84 (m, 1 H); ^{13}C NMR ($CDCl_3$) δ 6.10, 14.1, 20.4, 24.8, 58.1, 60.7, 61.0, 64.8, 111.3, 122.9, 133.3, 134.5, 137.9, 143.1, 179.7, 183.6, 185.6; IR ($CHCl_3$) 2950 (w), 1710 (vs), 1660 (s), 1570 (vs), 1280 (s), 1260 (s), 1110 (s), 910 cm^{-1} (s); MS, *m/e* 317 (M^+, 85), 288 (19), 244 (100), 200 (22), 83 (27); UV (MeOH) λ_{max} (log ϵ) 207 (4.23), 285 (3.89), 6.11 (2.0); high-resolution MS, calcd for $C_{12}H_{11}O_3N$ 317.1262, found 317.1260.

1-Cyano-3-hydroxy-4-methyl-1-(2,4-pentadienyl)-3-cyclopentene-2,5-dione (64): colorless oil; NMR (CCl_4) δ 1.96 (s, 3 H), 2.78 (d, 2 H, J = 7 Hz), 5.00–5.58 (m, 3 H), 5.85–6.44 (s, 3 H); IR (NaCl) 3500 (m), 2240 (w), 1700 (s), 1650 (m), 1410 (s), 1365 (m), 1010 cm^{-1} (m); MS, *m/e* (relative intensity) 217 (M^+, 37), 202 (22), 189 (17), 176 (15), 83 (56), 67 (100); high-resolution MS, calcd for $C_{12}H_{11}O_3N$ 217.0739, found 217.0740.

Registry No. **7**, 109034-88-0; **8**, 84568-13-8; **9**, 84568-16-1; **10**, 109034-89-1; **11**, 109034-90-4; **12**, 109034-91-5; **13**, 84568-10-5; **14**, 109034-92-6; **15**, 109034-93-7; **16**, 109034-94-8; **17**, 109064-62-2; **18**, 109034-95-9; **19a**, 109034-96-0; **19a** (allyl alcohol), 109035-43-0; **19b**, 109035-44-1; **19b** (allyl alcohol), 109035-45-2; **20**, 109034-97-1; **21**, 109034-98-2; **22**, 109034-99-3; **23**, 109035-00-9; **24**, 109035-01-0; **25**, 109064-63-3; **26**, 2065-37-4; **28**, 84568-08-1; **30**, 89131-88-4; **31**, 109035-02-1; **32**, 109035-03-2; **33**, 109035-04-3; **34**, 109035-05-4; **35**, 109035-06-5; **36**, 109035-07-6; **37**, 109035-08-7; **38**, 109035-09-8; **39**, 109035-10-1; (*Z*)-**40**, 109035-11-2; (*E*)-**40**, 109035-48-5; **41**, 109035-12-3; (*E*)-**42**, 109035-60-1; (*Z*)-**42**, 109035-13-4; (*Z*)-**43**, 109035-14-5; (*E*)-**43**, 109035-51-0; (*Z*)-**44**, 109035-15-6; (*E*)-**44**, 109035-61-2; (*Z*)-**45**, 109035-16-7; (*E*)-**45**, 109035-52-1; **46**,

109035-17-8; **47**, 109035-18-9; **47** (acetate), 109035-55-4; (*E*)-**48**, 109035-19-0; (*Z*)-**48**, 109035-56-5; (*E*)-**49**, 109035-20-3; (*Z*)-**49**, 109035-57-6; **52**, 109035-21-4; **53**, 109035-22-5; **54**, 109035-23-6; **55**, 84568-15-0; **56**, 109035-24-7; **57**, 84568-14-9; **58**, 109035-25-8; **59**, 109035-26-9; **60**, 109035-27-0; **61**, 109035-28-1; **62**, 109064-64-4; **63**, 109035-29-2; **64**, 109035-30-5; **71**, 88088-57-7; **72**, 109035-36-1; **73**, 109035-37-2; **74**, 109035-38-3; **75**, 109035-39-4; **76**, 109035-40-7; **77**, 109035-41-8; **77** (R^1 = H, R^2 = $CH_2C(Me)=CH_2$), 109035-33-8; **77** (R^1 = MOM, R^2 = $CH_2C(Me)=CH_2$), 109035-34-9; **77** (R^1 = MOM, R^2 = $CH_2CH(Me)CH_2OH$), 109035-35-0; **78**, 109035-42-9; **78** (R^1 = H, R^2 = $CH_2C(Me)=CH_2$), 109035-31-6; **78** (R^1 = MOM, R^2 = $CH_2C(Me)=CH_2$), 109035-32-7; $V(acac)_3$, 13476-99-8; $VO(acac)_2$, 3153-26-2; $Cr(acac)_3$, 21679-31-2; $Mn(acac)_2$, 14024-58-9; $Mn(acac)_3$, 14284-89-0; $Fe(acac)_3$, 14024-18-1; $Co(acac)_2$, 14024-48-7; $Co(acac)_3$, 21679-46-9; $Ni(acac)_2$, 3264-82-2; $Cu(acac)_2$, 13395-16-9; $Zn(acac)_2$, 14024-63-6; CuCl, 7758-89-6; CuBr, 7787-70-4; CuCN, 544-92-3; Cu_2O, 1317-39-1; CuOTf, 42152-44-3; Cu(acacen), 14263-53-7; $Cu(salad)_2$, 14523-25-2; Cu(salen), 14167-15-8; $Cu(dmg)_2$, 14221-10-4; $Cu(oxin)_2$, 10380-28-6; Cu(tpp), 14172-91-9; $Cu(F_3CCOCH=C(O^-)Me)_2$, 14324-82-4; $Cu(MeCOCH=C(O^-)Ph)_2$, 14128-84-8; $Cu(PhCOCH=C(O^-)Ph)_2$, 14405-48-2; $Cu(EtOCOCH=C(O^-)Me)_2$, 14284-06-1; $Cu(Me_3CCOCH=C(O^-)CMe_3)_2$, 14040-05-2; $Cu(MeCOC(Me)=C(O^-)Me)_2$, 14781-49-8; $Cl_2C=CCl_2$, 127-18-4; $ClCH_2OMe$, 107-30-2; $HOCH_2C(Me)=CH_2$, 513-42-8; $3\text{-}ClC_6H_4COCl$, 618-46-2; Cu, 7440-50-8; 2-bromo-3-(2,4-hexadienyl)naphthoquinone, 109035-46-3; 2-bromo-5-methoxy-6-methyl-3-(2,4-hexadienyl)-1,4-benzoquinone, 109035-47-4; *tert*-butyldimethylsilyl trifluoromethanesulfonate, 69739-34-0; allyltriphenylphosphonium bromide, 1560-54-9; ethyl crotonate, 10544-63-5; 4-bromo-3-(3,5-hexadienyl)-5-methoxy-6-methyl-1,2-benzoquinone, 109035-49-6; 4-bromo-3-(3,5-heptadienyl)-5-methoxy-6-methyl-1,2-benzoquinone, 109035-53-2; 3-bromo-2-(2,4-hexadienyl)-5-methyl-6-hydroxy-1,4-benzoquinone, 109035-50-9; 3-bromo-2-(2,4-heptadienyl)-5-methyl-6-hydroxy-1,4-benzoquinone, 109035-54-3; 4-bromo-3-(4-(ethoxycarbonyl)-3,5-hexadienyl)-5-methoxy-6-methyl-1,2-benzoquinone, 109035-58-7; 2-bromo-3-(4-(ethoxycarbonyl)-3,5-hexadienyl)-5-hydroxy-6-methyl-1,4-benzoquinone, 109035-59-8.

Silver(I)-Catalyzed Isomerization of Water-Soluble Quadricyclanes

Kazuhiro Maruyama* and Hitoshi Tamiaki

Department of Chemistry, Faculty of Science, Kyoto University, Kyoto 606, Japan

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In aqueous ammonia, silver(I)-catalyzed isomerization of quadricyclanes to norbornadienes was investigated. The catalytic action of silver(I) perchlorate induced rapid and clean isomerization of water-soluble quadricyclanes **1b–g** to the corresponding norbornadienes **2b–g** even at room temperature. In the isomerization, the silver(I) catalyst might attack **1** from the five-membered ring, which was different from the directions observed in the cobalt(II)–porphyrin- and rhodium(I)-catalyzed reactions. The present reactions proceed via the formation of the cationic species and the successive cleavage of the highly strained cyclopropane ring of **1** to give **2**.

It is well-known that silver(I) salts are useful for organic synthesis, and especially effective for the ring cleavage of organic molecules.[1] The mechanisms of silver(I)-catalyzed reactions have been discussed, and most of them indicate that the cationic species induced by silver(I) may be the reaction intermediates.[1] Typically, silver(I) accelerated the isomerization of quadricyclanes to norbornadienes,[2] and a cationic species was widely recognized as the intermediate.[3]

In the above reactions, the attacking direction of silver(I) is important but has not been investigated. Recently, it was shown that silver(I) might attack from one of the exo directions of quadricyclanes in bezene.[4] Here, we report first that silver(I) salts are effective for the isomerization of some water-soluble quadricyclanes **1b–g** to norbornadienes **2b–g** in aqueous ammonia and then discuss the reaction pathway.

Results and Discussion

Water-soluble cobalt–porphyrin complexes were effective catalysts for the isomerization of water-soluble quadricyclanes to the corresponding norbornadienes in an aqueous sodium carbonate solution (see ref 5). In this system, however, introduction of a methyl group at the R position in quadricyclanes **1** (see Table I) reduced remarkably the rate of the isomerization induced by cobalt tetrakis(*p*-carboxyphenyl)porphyrin (Co-TPPC). To overcome this disadvantage, we examined several catalysts and found that silver salts were effective for the isomerization. For example, when silver perchlorate (0.1 mg) was added to an aqueous ammonia solution (0.5 mL) of quadricyclane **1b** at room temperature, **1b** isomerized to norbornadiene **2b** suddenly and cleanly, and the half-life of **1b** was about 7 min at 25 °C (see Table I). On the other hand, addition of silver perchlorate to nonsubstituted **1a** in aqueous ammonia induced the formation of undesirable byproducts, water adducts **3a** and other unknowns, in addition to the slow isomerization to **2a**.

Acceleration of the isomerization rate by substitution of a methyl group at the R position could support the theory that the reaction intermediate in aqueous ammonia was the cationic species charged partially on the adjacent carbon of the R position. Taking into consideration the fact that water adducts could not be observed during the isomerization of **1b** to **2b**, water might not have trapped

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