(±)-CI-TMI (**7**) and (±)-*seco*-CI-TMI (**16**) displayed a DNA covalent alkylation profile strikingly similar to that of duocarmycin A (Figure 1), substantially more selective than racemic (±)-*N*-BOC-CI (Figure 2) or optically active (+)- and (−)-*N*-BOC-CI[17,23] (not shown), and remarkably similar to that of (+)-CC-1065 (Figure 2). The selectivity of the covalent alkylation of **7** (CI-TMI) and **16** (*seco*-CI-TMI) proved virtually indistinguishable, and the intensity of the DNA alkylation exhibited by **16** proved comparable to that of duocarmycin A but greater than that of **7** (CI-TMI, ca. 10–100×). Presumably this may be attributed to the relative instability of **7** to the conditions of assay.[13]

Selectivity: duocarmycin A ≅ (±)-CI-TMI (**7**) = (±)-**16** ≫ (±)-*N*-BOC-CI (**8**) = (±)-**15**. Intensity: (+)-CC-1065 (ca. 1–0.1×) ≥ duocarmycin A ≅ (±)-**16** (ca. 1–10×) ≥ (±)-CI-TMI (**7**, ca. 10–100×) ≫ (±)-**15** (ca. 10^3–10^4×) ≅ (±)-*N*-BOC-CI (**8**, ca. 10^4×).

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Supplementary Material Available: Full experimental details for the preparation of **14**, **16–17**, and **7** and a summary of the DNA binding studies (6 pages). Ordering information is given on any current masthead page.

Reaction of Bicyclo[6.3.0]undeca-2,4,6,8,11-pentaen-10-ylidene in Oxygen-Doped Matrices: Characterization of the First Carbonyl Oxide with a π-Donating Ring System[†]

Shigeru Murata, Hideo Tomioka,* Takeshi Kawase,[‡] and Masaji Oda*[,‡]

Department of Industrial Chemistry, Faculty of Engineering, Mie University, Tsu, Mie 514, Japan, and Department of Chemistry, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan

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Summary: The first carbonyl oxide with a π-donating ring system, which is generated by the reaction of the title carbene with O_2 in an Ar matrix, exhibits a considerably long wavelength UV absorption and remarkable photochemical stability.

Carbonyl oxides are established as reactive intermediates in many oxidation reactions. In recent years, carbonyl oxides have been characterized spectroscopically by the use of the matrix isolation technique[1,2] and laser flash photolysis.[3] However, the studies have been limited to carbonyl oxides with aryl groups or π-accepting ring systems, all of which have the UV–vis absorption maxima in the range of 380–460 nm. Recent semiempirical calculations suggested that strong π-electron donors cause significant perturbation to properties of the parent carbonyl oxide: an increase of zwitterionic character, an increase of nucleophilicity, and a considerable red shift of the $\pi \rightarrow \pi^*$ transition maximum.[4] In this paper we report the spectroscopic characterization of the carbonyl oxide formed from the title carbene (**1**) in O_2-doped Ar matrix. This is the first direct observation of a carbonyl oxide with a π-electron-donating ring system,[5] revealing the validity of theoretical predictions on this class of carbonyl oxides.

Photolysis (λ > 350 nm, 1 h) of the 10-diazobicyclo[6.3.0]undeca-2,4,6,8,11-pentaene (**2**)[6] matrix isolated in Ar at 12 K afforded the title carbene **1**, which showed IR absorptions at 800 and 687 cm^{-1}. The matrix containing **1** had a light red color, the UV–vis spectrum of which showed absorption with maxima at 546 and 506 nm. The characterization of **1** was confirmed by the ESR measurement. Irradiation of **2** in 2-methyltetrahydrofuran at 17 K gave intense signals characteristic of a triplet species, the zero-field splitting parameters of which were evaluated to be $D = 0.2401$ cm^{-1} and $E = 0.0044$ cm^{-1}. The spec-

Table I. IR Data of Carbonyl Oxide 3 Matrix-Isolated in Ar at 12 K

3	$^{18}O_2$-3	Δ[a]
1463 (m)	1462 (m)	1
1417 (w)	1415 (w)	2
1406 (m)	1405 (m)	1
1369 (m)	1362 (w)	7
1326 (m)	1325 (w)	1
1132 (m)	1124 (m)	8
971 (s)	961 (m)	10
931 (s)	889 (s), 882 (s)	42, 49
905 (m)	*b*	-
849 (w)	845 (m)	4
842 (m)	838 (m)	4
700 (w)	699 (w)	1
692 (w)	680 (w)	12

[a] ^{18}O isotopic shifts in cm^{-1}. [b] This peak cannot be assigned, probably due to overlapping with strong peaks.

[†] This work is respectfully dedicated to Professor W. Kirmse on the occasion of his 60th birthday.

[‡] Osaka University.

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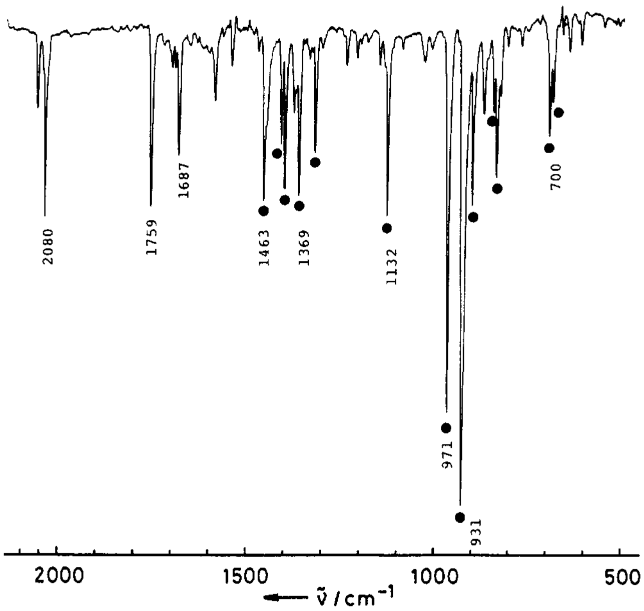


Figure 1. IR spectrum obtained by irradiation of 2 for 35 min at $\lambda > 350$ nm in O_2-doped Ar matrix (20% O_2) at 12 K. The peaks marked with full circles are assigned to the bands due to 3. The peaks at 2080, 1759, 1687 cm^{-1} are assigned to the bands due to 2, 4, and 6, respectively.

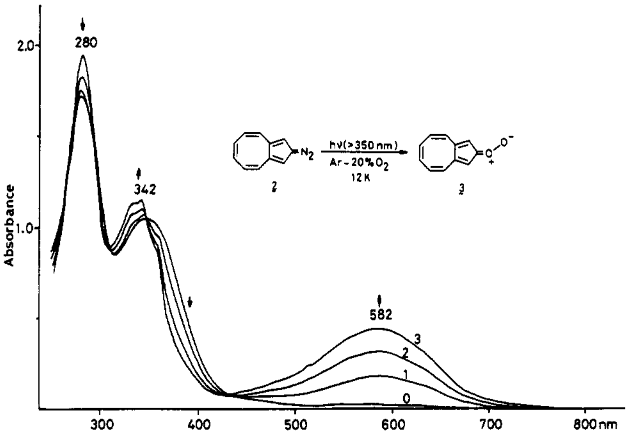
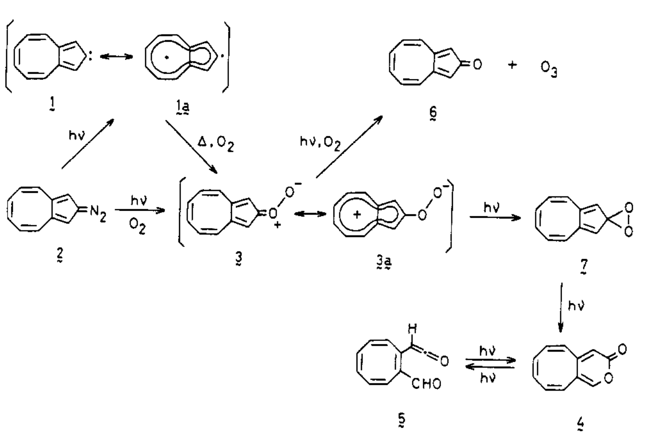


Figure 2. UV–vis spectra obtained by irradiation of 2 at $\lambda > 350$ nm in O_2-doped Ar matrix (20% O_2) at 12 K. The spectra were recorded at (0) 0, (1) 0.5, (2) 1, and (3) 2 min after continuous irradiation. The thickness of the matrix for UV–vis spectroscopy was about one-tenth of that used for IR spectroscopy.

troscopic properties of 1,[7] namely the red shift of the maxima in the UV–vis spectrum and the considerably small D value in the ESR spectrum compared to cyclopentadienylidene,[8] imply the large contribution of the biradical character 1a to the electronic structure of 1.

Scheme I



When 2 was photolyzed ($\lambda > 350$ nm, 35 min, 12 K) in an O_2-doped matrix (20% O_2), we could observe no IR peaks assigned to 1. The irradiation caused, instead, the appearance of intense bands at 971 and 931 cm^{-1} (Figure 1) and a deep blue coloration of the matrix. In the UV–vis spectrum, on photolysis of 2, an intense transition with maxima at 582 and 342 nm appeared with isosbestic points at 422 and 348 nm (Figure 2). Further irradiation ($\lambda > 350$ nm, 4 h) resulted in the disappearance of the colored species and the formation of oxidation products, identified tentatively from the IR spectrum as lactone 4 (1759 cm^{-1}), ketene 5 (2124 and 1706 cm^{-1}), ketone 6 (1689 cm^{-1}), and ozone (1032 cm^{-1}).[9]

The colored intermediate could be identified as the carbonyl oxide 3 on the basis of the very intense O–O stretching vibrations at 931 cm^{-1}. Isotopic labeling supports this assignment for 3. With use of $^{18}O_2$ (98% doubly labeled), the intense band at 931 cm^{-1} was split and shifted to 889 and 882 cm^{-1}. The large isotopic shifts of 42 and 49 cm^{-1} are in fair agreement with the values reported for the absorptions assigned to the O–O stretching mode of carbonyl oxides.[1,2] The IR data of the carbonyl oxide 3 are given in Table I. The facile observation of the carbonyl oxide 3 formed in the photochemical process is particularly surprising because all carbonyl oxides in the literature have been reported to be very sensitive to irradiation.[1,2]

The carbonyl oxide 3 could be obtained, of course, in a thermal process. Warming the Ar matrix containing the carbene 1 and O_2 to 35 K, which was prepared by the irradiation ($\lambda > 350$ nm, 1 h, 12 K) of 2 at 0.5% O_2 content, caused a complete disappearance of the bands of 1 and a simultaneous increase in the absorptions due to 3. The matrix took on a deep blue color. When the colored matrix was irradiated with long-wavelength light ($\lambda > 480$ nm, 6 h, 12 K), a new species 7 with IR bands at 1343, 1327, 874, and 700 cm^{-1} appeared slowly with a simultaneous decrease in the bands of 3. Shorter wavelength irradiation ($\lambda > 350$

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[5] Dibenzotropone oxide, which is the carbonyl oxide with a π-electron-donating ring system, has been reported to have the nucleophilic character in the oxygen-transfer reaction in fluid solutions: Adam, W.; Dürr, H.; Haas, W.; Lohray, B. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 101.

[6] The diazo compound 2 was prepared in a 30% yield by the reaction of bicyclo[6.3.0]undecapentaene with tosyl azide in the presence of diethylamine, followed by the chromatographic separation from 9-diazo isomer. 2: dark red viscous oil; ^1H NMR ($CDCl_3$) δ 5.55 (2 H, m), 5.68 (2 H, m), 6.15 (2 H, d, $J = 12$ Hz), 6.41 (2 H, s); ^{13}C NMR ($CDCl_3$) δ 75.5, 120.2, 127.7, 127.8, 127.9, 130.3; IR (Ar, 12 K) 2080 (vs), 1480 (m), 1337 (s), 944 (m), 813 (m), 649 (m), 556 (w) cm^{-1}; UV (Ar, 12 K) λ_{max} 280, 346, 556 nm.

[7] The spectral data of 1 are as follows: IR (Ar, 12 K) 1438 (w), 1359 (w), 1034 (w), 800 (s), 687 (s), 554 (w) cm^{-1}; UV (Ar, 12 K) λ_{max} 268, 283, 295, 318, 356, 506, 546 nm; ESR (2-methyltetrahydrofuran, 17 K) Z_1 770, X_1 1639, X_2 4347, Y_2 4510, Z_2 5842 G, microwave frequency = 9.332 GHz.

[8] The UV–vis absorption maximum of cyclopentadienylidene was reported to be 296 nm in the N_2 matrix: Baird, M. S.; Dunkin, I. R.; Poliakoff, M. *J. Chem. Soc., Chem. Commun.* **1974**, 904. Baird, M. S.; Dunkin, I. R.; Hacker, N.; Poliakoff, M.; Turner, J. J. *J. Am. Chem. Soc.* **1981**, *103*, 5190. The zero-field splitting parameters of this carbene were reported to be $D = 0.4089$ cm^{-1} and $E = 0.0120$ cm^{-1}; Wasserman, E.; Barash, L.; Trozzolo, A. M.; Murray, R. W.; Yager, W. A. *J. Am. Chem. Soc.* **1964**, *86*, 2304.

[9] The IR data of the oxidation products are as follows. The relative intensities and ^{18}O isotopic shifts in cm^{-1} are designated in parentheses. 4: 1759 (s, 27), 1216 (m, 16), 1096 (w, 12), 879 (m, 0), 776 (w, 1), 648 (m, 1) cm^{-1}. 5: 2124 (s, 28), 1706 (w, 34) cm^{-1}. 6: 1687 (m, 28), 1384 (m, 2), 910 (w, 1) cm^{-1}. The lactone 4 was revealed to be in equilibrium photochemically with the ketene 5. Shorter wavelength irradiation ($\lambda > 200$ nm) shifted the equilibrium toward 5.

nm, 30 min) of **7** rapidly produced lactone **4** and ketene **5**, but no absorptions assigned to ketone **6** and ozone grew at all. The photolabile intermediate **7**, which was a precursor of **4** and **5**, should be reasonably identified as the corresponding dioxirane.[10] The photochemical conversion of dioxirane to ester in matrices has been well established.[1,2]

The reaction of bicyclo[6.3.0]undeca-2,4,6,8,11-pentaen-10-ylidene (**1**) with O_2 is summarized in Scheme I. Though this scheme is apparently consistent with that of the reaction between cyclopentadienylidene and O_2,[1,11] there are some important differences in the properties of the intermediates. The transition of cyclopentadienone oxide occurs at 420 nm,[1c] while the maximum of the $\pi \rightarrow \pi^*$ transition of **3** is recorded at 582 nm. This considerable red shift is explained in terms of not only the extension of the conjugated π-system, but the π-electron-donating ability of the bicyclo[6.3.0]undecapentaenyl skeleton owing to the contribution of the stable bicyclic 10π cation, as shown in the canonical structure **3a**. This finding is in accord with CNDO/S predictions, where the $\pi \rightarrow \pi^*$ transition of tropone oxide was calculated to occur at 546 nm.[4] In the IR spectrum of **3**, the O–O stretching vibration is found at 931 cm^{-1}, which is in the range of the O–O stretchings reported for other carbonyl oxides.[1,2] This result is also in line with the prediction that the O–O bond lengths are little affected by the substitution of π-donating ring system.[4]

No simple explanation for the photochemical stability of **3** can be offered at the present time.[12] If the zwitterionic structure **3a** contributes largely to the electronic structure of **3**, this species is expected to be highly nucleophilic and to react as a 1,3-dipole. Experiments to reveal the reactivity of **3** are planned in our laboratories.

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[10] The IR data of **7** are as follows. The relative intensities and ^{18}O isotopic shifts in cm^{-1} are designated in parentheses. **7**: 1537 (w, 1), 1399 (w, 4), 1386 (w, 18), 1343 (s, 9), 1327 (m, 9), 1135 (w, 4), 915 (w, 1), 874 (m, 2), 700 (m, 0).

[11] Chapman, O. L.; Hess, T. C. *J. Am. Chem. Soc.* **1984**, *106*, 1842.

[12] Calculations suggest that π-donor substituents increase zwitterionic character of carbonyl oxide, which favors thermal isomerization to dioxirane: Gauss, J.; Cremer, D. *Chem. Phys. Lett.* **1987**, *133*, 420. Cremer, D.; Schmidt, T.; Gauss, J.; Radhakrishnan, T. P. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 427.

Synthesis and Reactions of Ester-Substituted Fulvenes. A New Route to $\Delta^{9(12)}$-Capnellene

Ying Wang, Debabrata Mukherjee,[1a] David Birney,[1b] and K. N. Houk*

Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, California 90024

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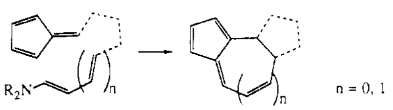
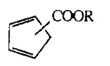
Summary: The condensation of cyclopentadienecarboxylic acid ester with aldehydes produces ester-substituted fulvenes regioselectively. The products undergo both intermolecular and intramolecular [6 + 2] cycloadditions to give the synthetically useful linearly fused tricyclopentanoids. A formal synthesis of $\Delta^{9(12)}$-capnellene is reported.

We previously reported the use of intermolecular and intramolecular cycloadditions of dienamines[2] and enamines[3] to fulvenes. The latter is a useful method for the synthesis of tricyclopentanoids, as shown below.

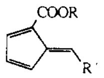


One drawback to this method is that the fulvene ring is always derived from cyclopentadiene. Consequently, three of the positions of the ring are unsubstituted in the product, so that the elaboration of these tricyclic intermediates into natural products presents difficulties which hinder the generality of this approach. One apparent solution to this is the use of a substituted cyclopentadiene as a starting material. Among the cyclopentadienes, cyclopentadienecarboxylic ester from cracking of Thiele's ester is cheap and easily available.[4] However, the regioselectivity of condensation of a substituted cyclopentadiene with an aldehyde is a potential complication. Ficini and co-workers reported earlier the reaction of ynamines with methyl cyclopentadienecarboxylate.[5] Two regioisomeric aminofulvenes were obtained in a 6:1 ratio. We have found that it is possible to prepare fulvenes from aldehydes regioselectively with the ester substituent at C-2 of the fulvene. These new types of fulvenes undergo cycloadditions regioselectively to give synthetically useful tricyclopentanoids. From one of these, a formal synthesis of $\Delta^{9(12)}$-capnellene was achieved.

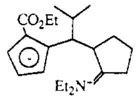
When ester **2** was treated with isobutyraldehyde in THF at −30 °C in the presence of aqueous methylamine and a buffer solution consisting of methylamine and acetic acid (pH 8–9), fulvene **3** was obtained in 60% yield after chromatography on silica gel. These reaction conditions gave the fulvene in moderate yield, whereas use of strong bases or preformed cyclopentadienide gave only poor yields of product. Similarly, fulvenes **4** and **5** were prepared from pivalaldehyde in 40% and 55% yields, respectively.[6]



1 R = Me
2 R = Et



3 R = Et, R'= isopropyl
4 R = Me, R'= tert-butyl
5 R = Et, R'= tert-butyl



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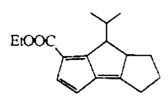

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[1] (a) Present address: Indian Association for the Cultivation of Science, Calcutta, India. (b) Present address: Department of Chemistry, Texas Tech University.

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