Substituent effect on the energy barrier for σ-bond formation from π-single-bonded species, singlet 2,2-diakloxyoxycyclopentane-1,3-diyls

Jianhuai Ye¹, Yoshihisa Fujiwara² and Manabu Abe*¹,³

Full Research Paper

Address:
¹Department of Chemistry, Graduate School of Science, Hiroshima University, Japan, ²Department of Mathematical and Life Sciences, Graduate School of Science, Hiroshima University, Japan, and ³Institute for Molecular Science (IMS), Okazaki, Aichi 444-8787, Japan

Email:
Manabu Abe* - mabe@hiroshima-u.ac.jp

* Corresponding author

Keywords:
laser flash photolysis; lifetime; singlet diradicals (biradicals); substituent effect; π-single bond

Beilstein J. Org. Chem. 2013, 9, 925–933.
doi:10.3762/bjoc.9.106
Received: 14 March 2013
Accepted: 22 April 2013
Published: 14 May 2013

This article is part of the Thematic Series “New reactive intermediates in organic chemistry”.

Guest Editor: G. Bucher

© 2013 Ye et al; licensee Beilstein-Institut.
License and terms: see end of document.

Abstract

Background: Localized singlet diradicals are in general quite short-lived intermediates in processes involving homolytic bond-cleavage and formation reactions. In the past decade, long-lived singlet diradicals have been reported in cyclic systems such as cyclobutane-1,3-diyls and cyclopentane-1,3-diyls. Experimental investigation of the chemistry of singlet diradicals has become possible. The present study explores the substituents and the effect of their substitution pattern at the C(1)–C(3) positions on the lifetime of singlet octahydropentalene-1,3-diyls to understand the role of the substituents on the reactivity of the localized singlet diradicals.

Results: A series of singlet 2,2-diakloxy-1,3-diaryloctahtydralene-1,3-diyls DR were generated in the photochemical denitrogenation of the corresponding azoalkanes AZ. The ring-closed products CP, i.e., 3,3-diakloxy-2,4-diphenyltricyclo[3.3.0.0²⁻⁴]octanes, were quantitatively obtained in the denitrogenation reaction. The first-order decay process (k = 1/τ) was observed for the fate of the singlet diradicals DR (λ_max ≈ 580–590 nm). The activation parameters, ΔH‡ and ΔS‡, for the ring-closing reaction (σ-bond formation process) were determined by the temperature-dependent change of the lifetime. The energy barrier was found to be largely dependent upon the substituents Ar and Ar’. The singlet diradical DRf (Ar = 3,5-dimethoxyphenyl, OCH₂Ar’ = OCH₂(3,5-dimethoxyphenyl)) was the longest-lived, τ₂₉₃ = 5394 ± 59 ns, among the diradicals studied here. The lifetime of the parent diradical DR (Ar = Ph, OCH₂Ar’ = OCH₃) was 299 ± 2 ns at 293 K.

Conclusion: The lifetimes of the singlet 1,3-diyls are found to be largely dependent on the substituent pattern of Ar and Ar’ at the C(1)–C(3) positions. Both the enthalpy and entropy effect were found to play crucial roles in increasing the lifetime.
Introduction
Localized singlet diradicals are key intermediates in processes involving the homolytic bond-cleavage and formation reactions (Figure 1) [1,2]. The singlet diradicals are, in general, quite short-lived species due to the very fast radical–radical coupling reaction [3]. However, in the past decade, the singlet diradicals have been observed or even isolated in cyclic systems such as cyclobutane-1,3-diyls [4-20] and cyclopentane-1,3-diyls [17,21-26]. Detailed experimental study of singlet diradical chemistry is thus now possible using the long-lived localized singlet diradicals.

Figure 1: Localized singlet diradicals.

So far, we have studied singlet diradical chemistry using long-lived 2,2-dialkoxy-1,3-diphenyloctahydropentalene-1,3-diyls DR with a singlet ground state, which can be cleanly generated by the photochemical denitrogenation of the corresponding azoalkanes AZ (Scheme 1). The 2,2-electron-withdrawing-group-substituted singlet 1,3-diradicals are categorized as Type-1 diradicals [1,27], which possess a π-single-bonding character (–π–, closed-shell character) between the two radical sites. The role of the alkoxy group (OR) on the lifetime (τ = 1/k) was investigated by combined studies of experiments and quantum chemical calculations [26,28].

In the present study, the effect of the bulky 3,5-dimethoxyphenyl group substituent was investigated on the lifetime of the localized singlet diradicals. Thus, the aryl substituent was introduced at C(1), C(2), or/and C(3) positions of the diradicals DRd–g, and the substituent effects on the lifetime of the singlet diradicals were compared with the lifetime of a phenyl-group-substituted diradical DRc and the parent diradical DRa. The laser flash photolysis technique was used for the generation of DRc–g from the corresponding azoalkanes AZc–g (Scheme 2).

Results and Discussion
Synthesis of AZc–g and their steady-state photolyses. The precursor azoalkanes AZc–g were prepared in an analogous method to the synthesis of AZa,b [28] (Scheme 3). Pyrazoles 3c–f were synthesized in the reaction of tetrazines 1 (Ar = Ph or 3,5-dimethoxyphenyl) with 2,2-dialkoxy-5,5-dimethyl-Δ3-1,3,4-oxadiazolines 2 [29], which are the precursor of the dialkoxycarbene (Scheme 3a). Azoalkanes AZc–f (λmax ≈ 360 nm with ε ≈ 100) were obtained by a cycloaddition reaction with cyclopentadienes, and followed by a hydrogenation reaction [30,31]. The synthesis of AZg (Ar = 3,5-dimethoxyphenyl, Ar′ = H) was performed from the corresponding 1,3-diketone 4 (Scheme 3b). 2,2-Dimethoxy-1,3-diylylpropane-1,3-dione 5g was prepared from 1,3-dione 4 (R = 3,5-dimethoxybenzene) according to the method of Tiecco [32]. Pyrazole 3g was then synthesized by the reaction with hydrazine hydrate. AZg was obtained by the Diels–Alder [4 + 2]-cycloaddition with cyclopentadiene and hydrogenation using PtO2 as a cata-
Scheme 2: Generation of singlet diradicals DRc–g and their reactivity in the photochemical denitrogenation of AZc–g.

Detection of singlet diradicals DRc–g. The detection of singlet diradicals DRc–g was examined by the photochemical denitrogenation of azoalkanes AZc–g in a glassy matrix of 2-methyltetrahydrofurane (MTHF) at 80 K, [AZ] ≈ 4 × 10⁻³ mol/L, and by the laser flash photolysis experiments of AZc–g at room temperature in benzene solution. First of all, the MTHF matrix solution of AZc–g was irradiated with a 500 W Xenon lamp through a monochromator (λirr = 360 ± 10 nm). A strong absorption band, which corresponds to DRc–g, was observed in the visible region at 80 K (570–590 nm, Table 1), as exemplified for the photoirradiation of AZe–g in Figure 2a. The strong absorption bands are quite similar to those of singlet diradicals DRa,b with λmax = 574 nm and 572 nm [1,28], respectively. The assignment of the strong band to the singlet diradical is...
further supported by the following facts: (a) The absorptions obtained on photolysis in a MTHF glass were thermally persistent at 80 K and resembled that of the transient absorption spectra in solution (for example, DRe, $\lambda_{\text{max}} = 590$ nm, Figure 2b); (b) the species were ESR-silent in the MTHF-matrix at 80 K; (c) the lifetime of the transient was insensitive to the presence of molecular oxygen (decay trace at 580 nm, Figure 2c); and (d) the activation parameters (Table 1) are similar to those for the decay process of DRe, in particular, the high (ca. 10$^{12}$ s$^{-1}$) pre-exponential Arrhenius factors (log $A$) are indicative of a spin-allowed reaction to the ring-closed products CPc–g [34].

The lifetime of the singlet diradical was largely dependent on the substituents Ar and Ar’. The activation parameters, $\Delta H^\ddagger$, $\Delta S^\ddagger$, $E_a$, log $A$ were determined from the Eyring plots and Arrhenius plots, which were obtained from the temperature-dependent change of the lifetime (Table 1). For comparison, the lifetime of diradical DRe (Table 1, entry 1) was also measured under similar conditions, and determined to be 299 ns at 293 K. The obtained lifetime was nearly the same as that obtained previously by us (292 ns) [28].

The lifetime of DRe (Ar = Ar’ = Ph) was found to be 1305 ns at 293 K (Table 1, entry 2), which was ca. 4.5 times longer than the parent DRe. On introduction of a 3,5-dimethoxyphenyl ring at C(2) position of the 1,3-diradical, i.e., DRe (Ar = Ph, Ar’ = 3,5-dimethoxyphenyl), a further increase of the lifetime at 293 K was observed to be 1933 ns (Table 1, entry 3). The result clearly indicates that the steric bulkiness plays an important role in increasing the energy barrier for the ring-closing reaction. Indeed, the activation enthalpy ($\Delta H^\ddagger = 36.6$ kJ mol$^{-1}$, Table 1, entry 3) for DRe was found to be higher than that for DRe (Ar = Ar’ = Ph) (Table 1, entry 1). Interestingly, the effect of an aryl group substituent at C(1) and C(3) positions on the lifetime was found to be larger than that at C(2); compare the lifetime of DRe (4001 ns, Ar = 3,5-dimethoxyphenyl, Ar’ = Ph, Table 1, entry 4) with that of DRe (1933 ns, Table 1, entry 3). When the 3,5-dimethoxyphenyl group was introduced at all of the C(1), C(2), and C(3) positions, the lifetime of the diradical DRf ($\Delta G^\ddagger = 42.2$ kJ mol$^{-1}$, Table 1, entry 5) was dramatically increased to 5394 ns at 293 K. The activation entropy ($\Delta S^\ddagger = -27.8$ and $-19.4$ J mol$^{-1}$, Table 1, entries 4 and 5) also plays an important role in increasing the lifetime of the singlet species. A much shorter lifetime was found for the diradical DRe (Ar = 3,5-dimethoxyphenyl, Ar’ = H). Thus, the introduction of the bulky substituents is needed at all positions C(1)–C(3) of the

Table 1: Lifetimes and activation parameters of singlet diradicals DR.

| entry | DR   | $\tau_{293K}$/ns$^a$ | $\lambda_{\text{max}}$ (at 80 K) | $\Delta G^\ddagger_{293K}$/kJ mol$^{-1}$ | $\Delta H^\ddagger$/kJ mol$^{-1}$ | $\Delta S^\ddagger$/kJ mol$^{-1}$ K$^{-1}$ | $E_a$/kJ mol$^{-1}$ | log $A^c$ |
|-------|------|----------------------|-----------------------------------|-------------------------------------|---------------------------------|-------------------------------|-------------------|--------|
| 1     | DRe  | 299                  | 573                               | $35.1 \pm 0.7$                      | $32.7 \pm 0.2$                   | $-8.1 \pm 1.2$                | $35.3 \pm 0.2$ | $12.8 \pm 0.1$ |
| 2     | DRe  | 1305                 | 583                               | $39.1 \pm 0.9$                      | $33.5 \pm 0.6$                   | $-17.9 \pm 1.7$               | $36.2 \pm 0.6$ | $12.3 \pm 0.1$ |
| 3     | DRe  | 1933                 | 584                               | $39.6 \pm 0.6$                      | $36.6 \pm 0.1$                   | $-10.1 \pm 1.1$               | $39.2 \pm 0.1$ | $12.7 \pm 0.1$ |
| 4     | DRe  | 4001                 | 592                               | $40.9 \pm 0.8$                      | $33.3 \pm 0.4$                   | $-27.8 \pm 1.3$               | $35.9 \pm 0.4$ | $11.8 \pm 0.1$ |
| 5     | DRe  | 5394                 | 593                               | $42.2 \pm 0.7$                      | $36.5 \pm 0.3$                   | $-19.4 \pm 1.0$               | $39.1 \pm 0.3$ | $12.2 \pm 0.1$ |
| 6     | DRe  | 580                  | 583                               | $36.7 \pm 0.4$                      | $33.0 \pm 0.2$                   | $-12.9 \pm 1.0$               | $35.6 \pm 0.2$ | $12.2 \pm 0.1$ |

$^a$Experimental errors are ca. 5%.

$^b$In MTHF at 80 K.

$^c$Activation parameters were determined by measurements of the lifetime of the singlet diradicals at five different temperatures in a temperature range from 293 to 333 K.
1,3-diradicals to increase the lifetime. The repulsive steric interactions of the Ar group with the Ar' group are suggested to play important roles in increasing the energy barrier of the reaction from the diradicals to the ring-closed compounds CP. The results clearly indicate that the substituent effect using the sterically bulky group is effective to prolong the lifetime of the singlet diradicals.

Conclusion

We have succeeded in generating long-lived singlet diradical species DRe–g. \( \tau_{293} = 580-5394 \) ns, which were much longer-lived species than DRA \( \tau_{293} = 299 \) ns. It was found that the lifetimes are largely favoured on the substituent pattern of Ar and Ar' at the C(1)–C(3) positions of the 1,3-diyls. Thus, both the enthalpy and entropy effect were found to play crucial roles in increasing the lifetime.

Experimental

All reagents were purchased from commercial sources and were used without additional purification, unless otherwise mentioned. Azoalkanes AZc–g were prepared according to the methods described previously (Scheme 3) and were isolated by silica gel column chromatography and GPC column chromatography. \(^1\)H and \(^{13}\)C NMR spectra were reported in parts per million (δ) by using CDCl\(_3\) or C\(_6\)D\(_6\) as internal standards. Assignments of \(^{13}\)C NMR were carried out by DEPT measurements. IR spectra were recorded with a FTIR spectrometer. UV–vis spectra were taken by a JASCO V-630 spectrophotometer. Mass-spectrometric data were measured by a Mass Spectrometric Thermo Fisher Scientific LTQ Orbitrap XL, performed by the Natural Science Center for Basic Research and Development (NBARD), Hiroshima University.

Preparation of diazenes AZc–g

\( 3,6\)-Diaryl-1,2,4,5-tetrazine 1. 3,6-Diphenyl-1,2,4,5-tetrazine was purchased and directly used. The preparation of 3,6-(3,5-dimethoxyphenyl)-1,2,4,5-tetrazine (Ar = 3,5-dimethoxyphenyl) is as follows: In a 50 mL round-bottom flask, benzonitrile (3.7 g, 22.7 mmol) was dissolved in 10 mL of absolute ethanol. Hydrazine (3.6 mL, 90 mmol) and sulfur (0.43 g, 13.5 mmol) were quickly added, and the solution was stirred at room temperature for 1 h and then heated under reflux for 3 h. The remaining orange cake was solidified further in an ice bath. The solid was vacuum filtered, and washed with cold ethanol (3 × 10 mL) giving the crude dihydrotetrazine. The crude orange solid was then placed in a 50 mL beaker and dissolved in 20% acetic acid (15 mL) and 10 mL ether at room temperature with stirring. An aqueous solution of 10% NaNO\(_2\) (20 mL) was added to the solution in an ice bath. The immediate purple cloudiness signifies the completion of the reaction, as well as the evolution of brown nitric oxide gas. Vacuum filtration and washing with hot methanol (3 × 10 mL) gave the tetrazine as a red solid (3.07 g, 81%). mp: 248–250 °C; IR (neat, cm\(^{-1}\)): 3022, 2981, 2947, 1611, 1462, 1393, 1221, 1067, 944, 843, 683; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 3.88 (s, 6H), 6.60 (t, \( J = 2.23 \) Hz, 1H), 7.17 (d, \( J = 2.23 \) Hz, 2H); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \( \delta \) 55.68 (q, OCH\(_3\)), 105.84 (d, CH), 105.90 (d, CH), 133.44 (s, C1), 161.54 (s, COCH\(_3\)), ESIMS (m/z): [M + Na]\(^+\) calcd for C\(_{15}\)H\(_{20}\)N\(_4\)O\(_4\), 379.13768; found, 379.13776.

5,5-Dimethyl-2,2-bis(3,5-dimethoxybenzyl)-1,3,4-oxadiazoline (2f). A solution of (3,5-dimethoxybenzoxo-carbonyl)hydrazone of acetone \((1.30 \text{ g }, 4.87 \text{ mmol})\) in CH\(_2\)Cl\(_2\) (5 mL) was added dropwise to a stirred solution of Pb(OAc)\(_4\) (2.59 g, 5.84 mmol) under nitrogen. The reaction mixture was stirred in an ice bath for 2 h, and then at room temperature for 24 h. After the stirring, the solid was filtered over Celite and the organic layer was washed with 10% aq NaHCO\(_3\). The mixture was filtered again until no precipitate was deposited. The organic phase was concentrated under reduced pressure. The corresponding 3,5-dimethoxybenzyl alcohol (2.46 g, 14.6 mmol) and TFA (0.04 mL, 0.49 mmol) were then added to the organic mixture. The solution was heated to 40 °C and stirred for 24 h before KOH pellets were added, and stirring was continued for another 3 h. After extracting with CH\(_2\)Cl\(_2\), washing with brine, and drying by MgSO\(_4\), the organic layer was concentrated under reduced pressure. The product was purified by column chromatography (eluent: EtOAc/hexane = 30/70, \( R = 0.17 \)) to give the product as a yellow liquid (0.48 g, 23%). IR (neat, cm\(^{-1}\)): 3022, 2981, 2947, 1611, 1462, 1393, 1221, 1067, 944, 843, 687; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \( \delta \) 1.49 (s, 6H), 3.67 (s, 12H), 4.66 (q, \( J = 11.8 \) Hz, 36.78 Hz, 4H), 6.29 (t, \( J = 2.21 \) Hz, 2H), 6.41 (d, \( J = 2.21 \) Hz, 4H); \(^{13}\)C NMR (125 MHz, CDCl\(_3\)) \( \delta \) 124.12 (q, CH\(_3\)), 55.29 (q, OCH\(_3\)), 66.72 (t, CH\(_2\)), 99.94 (d, CH, Ar ring), 105.50 (d, CH, Ar ring), 119.63 (s, C(CH\(_3\))\(_2\)), 136.71 (s, C), 138.97 (s, C(OCH\(_2\)Ar)), 160.83 (s, COCH\(_3\)); ESIMS (m/z): [M + Na]\(^+\) calcd for C\(_{22}\)H\(_{26}\)O\(_7\)N\(_2\)Na, 455.17887; found, 455.17899.

1,3-Bis(3,5-dimethoxyphenyl)propane-1,3-dione (4). 3,5-dimethoxyacetophenone (2.1 g, 11.7 mmol), 3,5-dimethoxybenzoic acid (2.75 g, 14.04 mmol), and NaH (0.94 g, 23.4 mmol) was dissolved in THF (20 mL) under N\(_2\) atmosphere in a 50 mL flask. The mixture was heated under reflux (75 °C) for 14 h under a N\(_2\) atmosphere, then cooled down to room temperature. The mixture was slowly added to cold HCl. The organic layer was extracted with ether, washed with brine, and dried with anhydrous MgSO\(_4\). The solvent was removed by vacuum evaporator. The dry solid was then recrystallized in methanol to give the compound as a yellow crystal (2.77 g, 69%). mp: 132 °C; IR (neat, cm\(^{-1}\)): 3140, 2943, 1562, 1466, 1351, 1298, 1158, 1053, 842, 668; \(^1\)H NMR (500 MHz,
CDCl$_3$) δ 3.78 (s, 12H), 6.56 (t, $J = 2.28$ Hz, 2H), 6.65 (d, $J = 2.28$ Hz, 4H); $^{13}$C NMR (125 MHz, CDCl$_3$) δ 55.56 (q, OCH$_3$), 93.56 (t, CH$_3$), 104.62 (d, CH), 105.05 (d, CH), 137.52 (s, C), 160.92 (s, COCH$_3$), 185.47 (s, OC=O); ESIMS (m/z): [M + Na]$^+$ calculated for C$_{10}$H$_{12}$O$_2$Na, 367.11521; found, 367.11456.

1,3-Bis(3,5-dimethoxyphenyl)-2,2-dimethoxypropane-1,3-dione (5), 1,3-Dione (4) (2.76 g, 8 mmol) and diphenyl diselenide (1.25 g, 4 mmol) were dissolved in methanol (50 mL), and ammonium persulfate (3.65 g, 16 mmol) was added to the mixture. The solution was heated under reflux for 4 h with stirring under nitrogen. Then the mixture was cooled to room temperature, and slowly added to ice water. The organic compound was extracted by chloroform and purified by silica-gel column chromatography (eluent: EtOAc/hexane = 30:70, $R_f = 0.30$) to give the product as a yellow liquid (2.9 g, 90%).

$^{1}$H NMR (500 MHz, CDCl$_3$) δ 3.41 (s, 6H), 3.77 (s, 12H), 6.59 (t, $J = 2.44$ Hz, 2H), 7.29 (d, $J = 2.44$ Hz, 4H); $^{13}$C NMR (125 MHz, CDCl$_3$) δ 50.97 (q, C(OCH$_3$)$_2$), 55.53 (q, OCH$_3$), 103.89 (s, C), 107.22 (d, CH), 107.34 (d, CH), 135.50 (s, C), 160.66 (s, COCH$_3$), 192.47 (s, C=O); IR ( neat, cm$^{-1}$): 3070, 3066, 2970, 2931, 2845, 1691, 1605, 1466, 1429, 1321, 1162, 1070, 1036, 863, 671; ESIMS (m/z): [M + H]$^+$ calculated for C$_{33}$H$_{32}$O$_4$Na, 533.23331; found, 533.23267; $R_f = 0.13$ (EtOAc/hexane = 20:80).

4,4-Dibenzyloxy-3,5-bis(3,5-dimethoxyphenyl)pyrazole (3e). Yellow powder (from MeOH), mp: 153–155 °C; IR ( neat, cm$^{-1}$): 3025, 2952, 2847, 1605, 1551, 1456, 1426, 1371, 1160, 1117, 849, 670; $^{1}$H NMR (500 MHz, CD$_2$Cl$_2$) δ 3.33 (s, 12H), 4.31 (s, 2H), 6.78 (t, $J = 2.28$ Hz, 2H), 6.93–7.01 (m, 10H), 8.02 (t, $J = 2.28$ Hz, 4H); $^{13}$C NMR (125 MHz, CD$_2$Cl$_2$) δ 55.06 (q, OCH$_3$), 67.02 (t, CH$_2$), 105.54 (d, CH, aryl), 106.52 (d, CH, aryl), 116.22 (s, C), 128.59 (d, CH, phenyl), 128.45 (d, CH, phenyl), 128.19 (d, CH, phenyl), 130.47 (s, C, aryl), 136.24 (s, C, phenyl), 161.81 (s, COCH$_3$), 167.53 (s, C); ESIMS (m/z): [M + Na]$^+$ calculated for C$_{33}$H$_{32}$N$_4$O$_5$, 533.23331; found, 533.23267; $R_f = 0.13$ (EtOAc/hexane = 20:80).

4,4-Bis(3,5-dimethoxybenzyl)-3,5-bis(3,5-dimethoxyphenyl)pyrazole (3f). IR ( neat, cm$^{-1}$): 3010, 2942, 1605, 1552, 1441, 1371, 1140, 1120, 849; $^{1}$H NMR (500 MHz, CD$_2$Cl$_2$) δ 3.24 (s, 12H), 3.34 (s, 12H), 4.36 (s, 6H), 6.38 (d, $J = 2.36$ Hz, 4H), 6.43 (t, $J = 2.36$ Hz, 2H), 6.70 (t, $J = 2.28$ Hz, 2H), 8.04 (d, $J = 2.28$ Hz, 4H); $^{13}$C NMR (125 MHz, CD$_2$Cl$_2$) δ 54.74 (q, OCH$_3$), 55.03 (q, OCH$_3$), 67.19 (t, CH$_3$), 101.16 (d, CH), 105.71 (d, CH), 106.08 (d, CH), 116.36 (s, C), 130.46 (s, C), 138.47 (s, C), 161.33 (s, COCH$_3$), 167.77 (s, C), 167.58 (s, C); ESIMS (m/z): [M + Na]$^+$ calculated for C$_{34}$H$_{33}$O$_7$Na, 695.25752; found, 695.25775; $R_f = 0.17$ (EtOAc/hexane = 30:70).

4,4-Dibenzoyloxy-3,5-diphenylpyrazole (3g). To a solution of 1,3-bis(3,5-dimethoxyphenyl)-2,2-dimethoxypropane-1,3-dione (2.8 g, 6.92 mmol) in chloroform (10 mL) was added dropwise NH$_2$NH$_2$H$_2$O (0.40 mL, 8.30 mmol). The mixture was heated under reflux and kept under stirring for 6 h. The reaction was quenched with HCl. A solution of 10% NaHCO$_3$ was added to the mixture. After extraction with chloroform, the organic phase was washed with brine, dried with Na$_2$SO$_4$, and then purified by column chromatography to give 3g in 89.6% yield. mp: 179–180 °C; $^{1}$H NMR (500 MHz, CDCl$_3$) δ 3.04 (s, 6H), 3.83 (s, 12H), 6.62 (t, $J = 2.28$ Hz, 2H), 7.40 (d, $J = 2.28$ Hz, 4H); $^{13}$C NMR (125 MHz, CDCl$_3$) δ 51.93 (q, CH$_3$), 55.52 (q, OCH$_3$), 105.21 (d, CH$_3$), 105.27 (d, CH), 116.91 (s, C), 129.23 (s, C), 161.00 (s, COCH$_3$), 166.84 (s, C); IR ( neat, cm$^{-1}$): 3012, 2951, 1597, 1548, 1427, 1375, 1158, 1125, 1062, 980, 844; ESIMS (m/z): calculated for C$_{35}$H$_{34}$N$_4$O$_6$, 401.17071; found, 401.17041; $R_f = 0.10$ (EtOAc/hexane = 20:80).
**endo-2,3-Diazo-10,10-diaryloxy-1,4-diyndicyclo[5.2.1.0^{3,6}]dec-2-ene (AZc-g)**

**General procedure.** To a solution of cyclopentadiene (1 mL) and pyrazole (2 mmol) in CH₂Cl₂ (2 mL) was added dropwise trifluoroacetic acid (1 mmol) in an ice bath under nitrogen. The reaction was traced by TLC analysis. After stirring for about 15 min, the reaction was quenched with 10% aq NaHCO₃ until the pH of the solution reached 8. After washing with water and brine, the organic phase was dried with MgSO₄, then filtered and concentrated. The [4 + 2] cycloadduct was dissolved in benzene (2 mL), and 5 mg of P₂O₅ was added as a catalyst. The mixture was stirred under a hydrogen atmosphere for 24 h at room temperature. After stirring, the catalyst was removed by filtration over Celite, and the solvent was evaporated under reduced pressure. The product was purified by column chromatography to give the product as colorless liquid (ca. 60%). The endo configuration was determined by NOE measurements.

**endo-2,3-Diazo-10,10-dibenzylxyloxy-1,4-diphenyltricyclo[5.2.1.0^{3,5}]dec-2-ene (AZe).** IR (neat, cm⁻¹): 3077, 2968, 2886, 1739, 1607, 1498, 1456, 1387, 1139, 1085, 1029, 702; UV (MTHF) λmax 365 (ε 1067); 1H NMR (500 MHz, CDCl₃) δ 1.20–1.75 (m, 6H), 3.69 (t, J = 5.13 Hz, 2H), 4.15 (s, 2H), 4.29 (s, 2H), 6.90–8.19 (m, 20H, overlapping with C₆H₄); 13C NMR (125 MHz, C₆D₆) δ 25.96 (t, CH₂, cyclopentane), 28.16 (t, CH₂, cyclopentane), 49.27 (d, CH, cyclopentane), 66.16 (t, COCH₂), 66.34 (t, OCH₂), 94.83 (s, C), 119.57 (s, C), 126.66 (d, CH), 126.87 (d, CH), 127.33 (d, CH), 128.61 (d, CH), 128.71 (d, CH), 129.01 (d, CH), 137.22 (s, C), 138.13 (s, C), 138.19 (s, C); HRMS–EI ([M + Na]+) calced for C₄₂H₂₆O₅N₂Na, 643.27786; found, 643.27802.

**endo-2,3-Diazo-10,10-bis(3,5-dimethoxybenzylxyloxy)-1,4-diphenyltricyclo[5.2.1.0^{3,5}]dec-2-ene (AZd).** IR (neat, cm⁻¹): 3022, 2966, 2844, 1751, 1603, 1473, 1326, 1162, 1072, 930, 844, 702; UV (MTHF) λmax 366 (ε 1751); 1H NMR (500 MHz, CDCl₃) δ 1.25–1.66 (m, 6H), 3.68 (s, 6H), 3.70 (t, J = 5.33 Hz, 2H), 3.75 (s, 6H), 3.89 (s, 2H), 4.12 (s, 2H), 6.07 (d, J = 2.36 Hz, 2H), 6.24 (t, J = 2.36 Hz, 1H), 6.30 (d, J = 2.36 Hz, 2H), 6.36 (t, J = 2.36 Hz, 1H), 7.40–8.03 (m, 10H); 13C NMR (125 MHz, CDCl₃) δ 26.21 (t, CH₂, cyclopentane), 28.34 (t, CH₂, cyclopentane), 49.42 (d, CH, cyclopentane), 55.69 (s, OCH₂), 55.74 (q, OCH₂), 66.17 (t, COCH₂), 95.15 (s, C), 99.80 (d, CH), 100.00 (d, CH), 104.26 (d, CH), 105.04 (d, CH), 119.54 (s, C), 128.55 (d, CH), 128.92 (d, CH), 128.96 (d, CH), 136.67 (s, C), 140.41 (s, C), 140.67 (s, C), 161.00 (s, C), 161.28 (s, C); ESIMS (m/z): [M + H]+ calced for C₄₈H₃₉O₇N₂Na, 763.32012; found, 763.32043.

**endo-2,3-Diazo-1,4-bis(3,5-dimethoxybenzylxyloxy)-10,10-dimethylyxyloxytricyclo[5.2.1.0^{3,5}]dec-2-ene (AZg).** IR (neat, cm⁻¹): 2973, 2846, 1602, 1464, 1359, 1158, 1088, 1022, 942, 848; UV (MTHF) λmax 364 (ε 1699); 1H NMR (500 MHz, CDCl₃) δ 0.9–1.75 (m, 6H), 2.69 (s, 3H), 2.80 (s, 3H), 3.36 (t, J = 5.49 Hz, 2H), 3.42 (s, 12H), 6.64 (t, J = 2.28 Hz, 2H), 7.48 (d, J = 2.28 Hz, 4H); 13C NMR (125 MHz, CDCl₃) δ 26.08 (t, CH₂, cyclopentane), 28.16 (t, CH₂, cyclopentane), 49.29 (d, CH, cyclopentane), 51.46 (s, OCH₂), 51.75 (q, OCH₂), 51.92 (2×q, OCH₂), 94.65 (s, C), 100.30 (d, CH), 107.33 (d, CH), 119.76 (s, C), 139.86 (s, C), 161.52 (s, C); ESIMS (m/z): [M + Na]+ calced for C₂₆H₃₂O₇N₂Na, 491.21526; found, 491.21466.

**General procedure for photolysis.** A sample (30.0 mg) of the diazenes AZ was dissolved in 1.0 mL of CD₆D₆. The photolysis was performed with a 500 W Xenon-lamp through a Pyrex filter (λ > 300 nm) at room temperature (ca. 20 °C). The photolyte was directly analyzed by NMR spectroscopy (1H: 500 MHz, 13C: 125 MHz).
13C: 125 MHz), which indicated the quantitative formation of the housanes CP. The housanes CPe–g were isolated by using silica-gel column chromatography. The spectroscopic data are as follows:

3,3-Dibenzylxoy-2,4-diphenyltricyclo[3.3.0.02,4]octane (CPe). 1H NMR (500 MHz, CD8O) δ 1.41–1.93 (m, 6H), 3.19 (d, J = 6.34 Hz, 2H), 4.31 (s, 2H), 4.92 (s, 2H), 6.96–7.45 (m, 20H, overlapping with C6D6): 13C NMR (125 MHz, C6D6) δ 25.28 (t, CH2, cyclopentane), 28.38 (t, CH2, cyclopentane), 41.73 (d, CH, cyclopentane), 48.05 (s, C), 67.16 (t, COCH3), 69.66 (t, OCH3), 98.43 (s, C), 126.57 (d, CH), 127.26 (d, CH), 127.40 (d, CH), 128.12 (d, CH), 128.35 (d, CH), 128.46 (d, CH), 130.54 (d, CH), 135.25 (s, C, phenyl), 135.90 (s, C, benzylxoy); HRMS – EI (m/z): caleed for C34H32O2, 472.2402; found, 472.2424.

3,3-Bis(3,5-dimethoxybenzylxoy)-2,4-diphenyltricyclo[3.3.0.02,4]octane (CPd). 1H NMR (500 MHz, CDCl3) δ 1.40–1.92 (m, 6H), 3.12 (d, J = 6.29 Hz, 2H), 3.22 (s, 6H), 3.37 (s, 6H), 4.35 (s, 2H), 4.99 (s, 2H), 6.31 (d, J = 2.36 Hz, 2H), 6.41 (t, J = 2.36 Hz, 1H), 6.56 (d, J = 2.36 Hz, 1H), 6.81 (d, J = 2.36 Hz, 2H), 7.02–7.46 (m, 10H, overlapping with C6D6); 13C NMR (125 MHz, C6D6) δ 25.28 (t, CH2, cyclopentane), 28.34 (t, CH2, cyclopentane), 41.68 (d, CH, cyclopentane), 48.18 (s, C), 54.68 (q, OCH3), 54.89 (q, OCH3), 67.07 (t, COCH3), 69.78 (t, COCH3), 98.43 (s, C), 100.04 (d, CH), 100.91 (d, CH), 105.94 (d, CH), 126.48 (2×d, CH, phenyl), 128.04 (2×d, CH, phenyl), 130.51 (2×d, CH, phenyl), 135.22 (2×s, C, phenyl), 140.90 (s, C), 141.30 (s, C), 161.19 (s, COCH3), 161.64 (s, COCH3), 161.64 (s, COCH3); ESIMS (m/z): [M + Na]+ caleed for C52H44O10Na, 735.3139; found, 735.3145.

3,3-Dimethoxy-2,4-bis(3′,5′-dimethoxyphenyl)tricyclo[3.3.0.02,4]octane (CPg). 1H NMR (500 MHz, CD8O) δ 1.43–2.03 (m, 6H), 2.94 (s, 3H), 2.96 (d, J = 6.47 Hz, 2H), 3.37 (s, 12H), 3.48 (s, 3H), 6.51 (t, J = 2.28 Hz, 2H), 3.79 (d, J = 2.28 Hz, 4H); 13C NMR (125 MHz, C6D6) δ 25.49 (t, CH2, cyclopentane), 28.45 (t, CH2, cyclopentane), 41.83 (d, CH, cyclopentane), 48.13 (s, C), 52.37 (q, OCH3), 54.01 (q, OCH3), 54.85 (2×q, OCH3), 98.61 (s, C), 99.05 (d, CH), 108.88 (d, CH), 137.59 (s, COCH3), 161.07 (s, C), ESIMS (m/z): [M + Na]+ caleed for C62H46O8Na, 643.20911; found, 643.20844.

Supporting Information

Supporting Information File 1
NMR spectra of compounds 1–5, AZc–g, and CPe–g.
[http://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-9-106-S1.pdf]

Acknowledgements
NMR and MS measurements were performed at N-BARD, Hiroshima University. This work was supported by a Grant-in-Aid for Science Research on Innovative Areas “Stimuli-responsive Chemical Species” (No. 21409008), “pi-Space” (No. 2108516), and No. 19350021 from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and by the Tokuyama Science Foundation.

References
1. Abe, M.; Ye, J.; Mishima, M. Chem. Soc. Rev. 2012, 41, 3808–3820. doi:10.1039/c2cs00005a
2. Abe, M. Chem. Rev. 2013, in press.
3. De Feyter, S.; Diao, E. W.-G.; Zewail, A. H. Angew. Chem., Int. Ed. 2000, 39, 260–263. doi:10.1002/(SICI)1521-3773(20000103)39:1<260::AID-ANIE260>3.0.CO;2-R
