

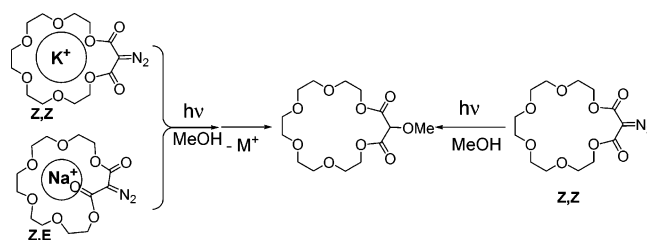
Structure and Photochemistry of 18-Diazo-1,4,7,10,13,16-hexaoxacyclononadeca-17,19-dione and Its Sodium and Potassium Complexes. Control of the Ground-State Conformation of 2-Diazo-1,3-dicarbonyl Fragment via Host–Guest Complexation

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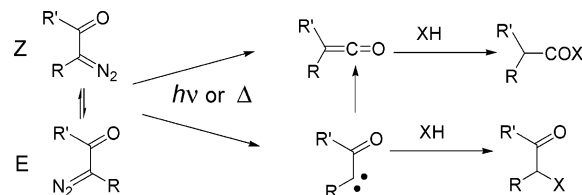


The macrocyclic 18-diazo-1,4,7,10,13,16-hexaoxacyclononadeca-17,19-dione (3-diazo-2,4-dioxo-19-crown-6, **1**) readily forms complexes with potassium (**2**, stability constant in methanol is $K_{K^+} = 229 \pm 25 \text{ M}^{-1}$) and sodium ions (**3**, $K_{Na^+} = 84.2 \pm 7.9 \text{ M}^{-1}$ in methanol). According to B3LYP/6-31G+(d,p) calculations and temperature-dependent ^1H NMR spectroscopy, the predominant conformation of **1** has a *Z,Z* arrangement of the diazo and carbonyl groups. The X-ray crystal structure analysis showed that the potassium complex (**2**) has the same *Z,Z* arrangement, while the sodium analogue (**3**) exists in conformation with *Z,E* geometry of the diazodicarbonyl moiety. Direct 254 nm photolysis of diazo compounds **1–3** in methanol results in the formation of 3-methoxy-2,4-dioxo-19-crown-6 (**5**), the product of the insertion of corresponding α,α' -dicarbonylcarbene into the O–H bond of the solvent. The triplet-sensitized photolysis of diazomalones **1–3** produces 2,4-dioxo-19-crown-6 (**6**), which is apparently formed via the triplet state of the intervening carbene.

Introduction

The UV irradiation or thermolysis of α -diazocarbonyl compounds usually results in the loss of nitrogen accompanied or followed by a migration of the other substituent at the carbonyl group to give a ketene (Scheme 1).^{1,2} The latter is often trapped with various nucleophiles producing carboxylic acid derivatives.^{1,3} This reaction, known as the Wolff rearrangement, has a broad range of industrial,⁴ synthetic,⁵ and biochemical⁶ applications. Wolff rearrangement, however, is often accompa-

SCHEME 1



nied or even completely suppressed by the reactions of α -carbonylcarbenes, which undergo an O–H or C–H insertion, add to π -bonds, or form ylides.⁷

The factors that direct decomposition of α -diazocarbonyl compounds into a ketene or carbene pathway are still

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(1) (a) Kirmse, W. *Eur. J. Org. Chem.* **2002**, 2193. (b) Meier, H.; Zeller, K.-P. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 32. (c) Zeller, K.-P.; Meier, H.; Muller, E. *Tetrahedron* **1972**, *28*, 5831.

(2) (a) Regitz, M.; Maas, G. *Diazo compounds: properties and synthesis*; Academic Press: Orlando, FL, 1986. (b) *The Chemistry of Diazonium and Diazo Groups*; Patai, S., Ed.; J. Wiley: New York, 1978.

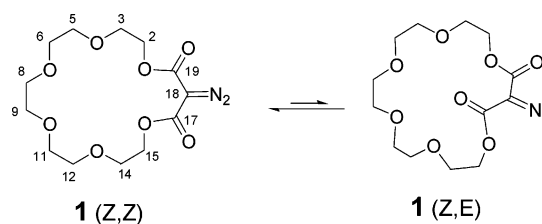
(3) Tidwell, T. T. *Ketenes*; J. Wiley: New York, 1976; pp 84–100.

(4) Moreau, W. M. *Semiconductor Lithography*; Plenum Press: New York, 1988. Reiser, A. *Photoreactive Polymers: The Science and Technology of Resists*; Wiley: New York, 1989. Reichmanis, E.; Thompson, L. F. *Chem. Rev.* **1989**, *89*, 1273.

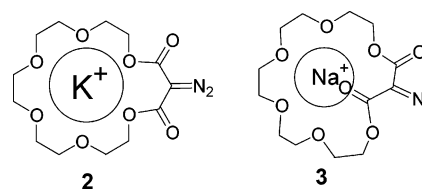
not fully understood. Soon after the first NMR observation of *s-Z*–*s-E* conformational isomerism^{8,9} of diazoketones (Scheme 1), Kaplan and co-workers postulated that *s-Z* conformers of α -diazocarbonyl compounds undergo a concerted Wolff rearrangement, whereas the *s-E* form loses nitrogen to produce α -carbonylcarbenes.¹⁰ The latter can undergo isomerization into ketenes or be trapped by external reagents. In accordance with this hypothesis, the cyclic α -diazoketones, which are locked in the *s-Z* conformation, usually undergo a clean Wolff rearrangement, while decomposition of acyclic analogues is often accompanied by the formation of carbenic products.¹ On the other hand, some established *s-E* diazo ketones produce ketenes with ease.¹¹ In our recent study, we found that acyclic ethyl diazomalonnate, which produces only O–H insertion products on photolysis in methanol, exists in the same *Z,Z* conformation¹² as cyclic isopropylidene diazomalonnate, which undergoes a quantitative Wolff rearrangement upon irradiation with 254 nm light.¹³

The discussion of the conformational effects on the Wolff rearrangement is complicated by the fact that α -diazocarbonyl compounds with the planar *Z*- or *Z,Z*-arrangement of diazo and carbonyl groups are readily available, while substrates, which exist predominantly or exclusively in alternative planar conformations, are not. Here, we report the experimental study of the

SCHEME 2



SCHEME 3



photolytic reactivity of 18-diazo-1,4,7,10,13,16-hexaoxacyclononadeca-17,19-dione (3-diazo-2,4-dioxo-19-crown-6, **1**, Scheme 2) and its potassium (**2**) and sodium (**3**) complexes (Scheme 3). Compound **1** was designed to test the feasibility of conformational control of the 2-diazo-1,3-dicarbonyl moiety in **1** by the complexation with various size cations.

Results and Discussion

Complexation of Metal Ions by the 3-Diazo-2,4-dioxo-19-crown-6 (1). The macrocyclic polyethers are known to form stable complexes with sodium and potassium cations in methanol.¹⁴ The diazodiester **1** possesses a cavity similar to that of crown ethers, as well as the carbonyl groups capable of additional cation complexation. The stability of potassium and sodium complexes of **1** was measured using ¹H NMR spectroscopy. The ca. 0.05 M solution of 3-diazo-2,4-dioxo-19-crown-6 (**1**) in methanol-*d*₆ was titrated with 0.5 M solutions of sodium or potassium thiocyanates. Due to a rapid exchange between the complex and free species, only time-averaged spectra for the ligand and the complex were observed. The dependence of the chemical shift of methylene protons at C⁸ and C⁹ (singlet observed at $\delta = 3.600$ – 3.608 ppm in pure ligand) on the concentration sodium and potassium salts are presented in Figure 1. The stoichiometry of sodium and potassium complexes of **1** was determined to be 1:1 using a mole ratio method¹⁵ (inserts in Figure 1).

The stability constants of complexes **2** and **3** were calculated by nonlinear least-squares fitting of the data to eq 1,¹⁶ where δ_L , δ_{LM} , and δ_{obs} represent the chemical

(5) Arndt–Eistert homologation of carboxylic acids: (a) Maas, G. In *Methoden der Organischen Chemie (Houben-Weyl)*; Regitz, M., Ed.; Thieme Verlag: Stuttgart, 1989; Vol. 19b/2, 1022. (b) Ye, T.; McKervey, A. M. *Chem. Rev.* **1994**, *94*, 1091. (c) Jones, M.; Moss, R. A. *Carbenes*; Wiley: New York, 1973. (d) Doyle, M. P.; McKervey, M. A.; Ye, T. *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds*; Wiley-Intersciences: New York, 1998; pp 487–534. Ring contraction: refs 2a, 5d and (e) Fessner, W.-D.; Prinzbach, H.; Rihs, G. *Tetrahedron Lett.* **1983**, *24*, 5857. (f) Ghosh, A.; Banerjee, U. K.; Venkateswaran, R. V. *Tetrahedron* **1990**, *46*, 3077. (g) Lawton, G.; Moody, C. J.; Pearson, C. J. *J. Chem. Soc., Perkin Trans. 1* **1987**, 877. (h) Moody, C. J.; Pearson, C. J.; Lawton, G. *Tetrahedron Lett.* **1985**, *26*, 3167. (i) Redmore, D.; Gutsche, C. D. *Adv. Alicyclic. Chem.* **1971**, *3*, 125. Preparation of β -keto acid derivatives: Cossy, J.; Belotti, D.; Thellend, A.; Pete, J. P. *Synthesis* **1988**, 720. Korobitsyna, I. K.; Nikolaev, V. A. *Zh. Org. Khim.* **1976**, *12*, 1251. Wentrup, C.; Heilmayer, W.; Kollenz, G. *Synthesis* **1994**, 1219.

(6) Photoaffinity labeling: Davioud, E.; Fagat, J.; Souque, A.; Rafestin-Oblin, M.-E.; Marquet, A. *J. Med. Chem.* **1996**, *39*, 2860. Somack, R.; Nordeen, S. K.; Eberhardt, N. L. *Biochemistry* **1982**, *21*, 5651. Photonuclease: Nakatani, K.; Maekawa, S.; Tanabe, K.; Saito, I. *J. Am. Chem. Soc.* **1996**, *118*, 10635. Saito, I.; Nakatani, K. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 3007. Wender, P. A.; Touami, S. M.; Alayrac, C.; Philipp, U. C. *J. Am. Chem. Soc.* **1996**, *118*, 6522.

(7) (a) Toscano, J. P. In *Advances in Carbene Chemistry*; Brinker, U. H., Ed.; JAI Press: Greenwich, CT, 1998; Vol. 2, pp 216–245. (b) Jones, M.; Moss, R. A. *Carbenes*; Wiley: New York, 1973. (c) Zollinger, H. *Diazo chemistry: 2. Aliphatic, inorganic, and organometallic compounds*; VCH Publishers: New York, 1995; pp 305–357. (d) Kirmse, W. *Carbenes and the O–H bond in: Advances in Carbene Chemistry*; Brinker, U. H., Ed.; JAI Press, Inc.: Greenwich, CT, 1994; pp 1–57. (e) Miller, D. J.; Moody, C. J. *Tetrahedron* **1995**, *40*, 10811.

(8) α -Diazocarbonyl compounds: Kaplan, F.; Meloy, G. K. *Tetrahedron Lett.* **1964**, 2427. Kaplan, F.; Meloy, G. K. *J. Am. Chem. Soc.* **1966**, *88*, 950. Kessler, H.; Rosenthal, D. *Tetrahedron Lett.* **1973**, 393. Curci, R.; DiFuria, F.; Lucchini, V. *Spectrosc. Lett.* **1974**, *7*, 211. Lichter, R.L.; Srinivasan, P. R.; Smith, A. B., III; Dieter, R. K.; Denny, C. T. *Chem. Commun.* **1977**, 366. Dickert, F. L.; Soliman, F. M.; Bestmann, H. J. *Tetrahedron Lett.* **1982**, *23*, 2639.

(9) Diazo-1,3-diketones: Nikolaev, V. A.; Rodina, L. L.; Korobitsyna, I. K. *Zh. Org. Khim.* **1974**, *10*, 1555. Lauer, W.; Krause, V.; Wengenroth, H.; Meier, H. *Chem. Ber.* **1988**, *121*, 465. Nikolaev, V. A.; Popik, V. V. *Zh. Org. Khim.* **1989**, *25*, 1014.

(10) Kaplan, F.; Mitchell, M.L. *Tetrahedron Lett.* **1979**, *9*, 759.

(11) Zeller, K.-P. *Chem. Ber.* **1979**, *112*, 678. Fenwick, J.; Frater, G.; Ogi, K.; Strausz, O. P. *J. Am. Chem. Soc.* **1973**, *95*, 124. Torres, M.; Ribo, J.; Clement, A.; Strausz, O. P. *Can. J. Chem.* **1983**, *61*, 996.

(12) Bogdanova, A.; Popik, V. V. *J. Am. Chem. Soc.* **2004**, *126*, 11293.

(13) Bogdanova, A.; Popik, V. V. *J. Am. Chem. Soc.* **2003**, *125*, 14153.

(14) Christensen, J. J.; Eatough, D. J.; Izatt, R. M. *Chem. Rev.* **1974**, *74*, 351; Bradshaw, J. S. In *Synthetic Multidentate Macrocyclic Compounds*; Izatt, R. M., Christensen, J. J., Eds.; Academic Press: New York, 1978; pp 53–109. Izatt, R. M.; Nelson, D. P.; Rytting, J. H.; Haymore, B. L.; Christensen, J. J. *J. Am. Chem. Soc.* **1971**, *93*, 1619. Dalley, N. K. In *Synthetic Multidentate Macrocyclic Compounds*; Izatt, R. M., Christensen, J. J., Eds.; Academic Press: New York, 1978; pp 207–243.

(15) Tsukube, H.; Furuta, H.; Odani, A.; Takeda, Y.; Kudo, Y.; Inoue, Y.; Liu, Y.; Sakamoto, H.; Kimura, K. In *Comprehensive Supramolecular Chemistry*; Davies, J. E. D., Ripmeester, J. A., Eds.; Pergamon Press: Oxford, 1996; Vol. 8, pp 425–482.

(16) Cox, B.; Schneider, H. In *Coordination and Transport Properties of Macrocyclic Compounds in Solution*; Elsevier Publishing Co., Inc.: New York, 1992; pp 58–62.

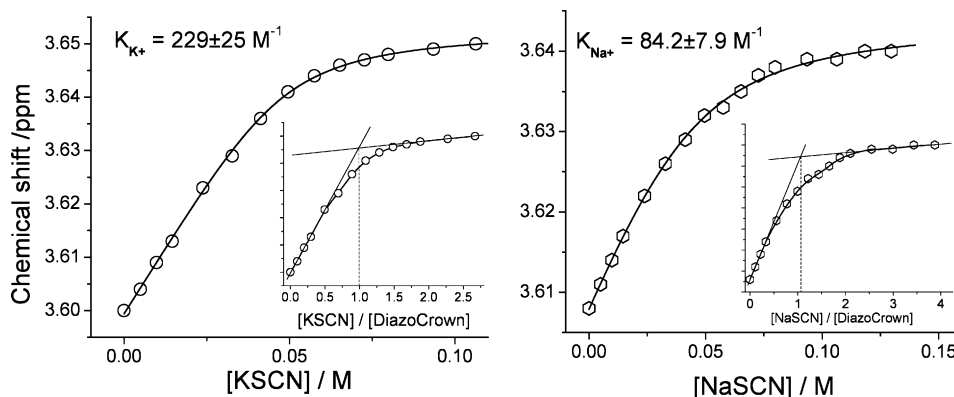


FIGURE 1. Chemical shift of C⁸ and C⁹ methylene protons of **1** plotted as a function of KSCN (left panel) and NaSCN (right panel) concentrations in deuteriomethanol. Curves represent the calculated fit to eq 1. The insets show the plot of C⁸ and C⁹ chemical shift as a function of cation to diazo compound **1** molar ratio. Inflection point corresponds to stoichiometry of the complex.

shift of methylene protons at C⁸ and C⁹ in pure ligand **1**, in metal complex (**2** or **3**); and the chemical shift observed at given concentration of potassium or sodium salts correspondingly; [L] and [L]⁰ represent an equilibrium and stoichiometric concentration of ligand **1**; [M]⁰ represents the stoichiometric concentration of the corresponding cation; *K* is stability constant of the complex. The equilibrium concentration of the ligand was calculated using eq 2.

$$\delta_{\text{obs}} = \frac{[\text{L}]^0 - [\text{L}]}{[\text{L}]^0} \delta_{\text{L}} + \frac{[\text{L}]}{[\text{L}]^0} \delta_{\text{LM}} \quad (1)$$

$$[\text{L}] = \frac{1}{2} \left([\text{M}]^0 + [\text{L}]^0 + \frac{1}{K} \right) - \sqrt{\frac{1}{4} \left([\text{M}]^0 + [\text{L}]^0 + \frac{1}{K} \right)^2 - [\text{M}]^0 - [\text{L}]^0} \quad (2)$$

Least-squares fitting of the data to eqs 1 and 2 give the following stability constants: $K = 229 \pm 25 \text{ M}^{-1}$ for the potassium complex **2** in methanol, and $K = 84.2 \pm 7.9 \text{ M}^{-1}$ for the sodium complex **3** in methanol. The higher selectivity of the macrocyclic diazo compound **1** for the potassium ion than for sodium is apparently the result of a better match between the cavity size of the macrocycle **1** (2.74–2.85 Å, vide infra) and the ionic diameter of the cation (2.66 Å and 1.9 Å).¹⁷ It is noteworthy that the stability of complexes **2** and **3** is considerably lower than that of the potassium and sodium complexes of 18-crown-6 ($K_{\text{K}^+} = 1.12 \times 10^6 \text{ M}^{-1}$ and $K_{\text{Na}^+} = 2.29 \times 10^4 \text{ M}^{-1}$).¹⁸ The larger ring size¹⁹ and the effect of the two carbonyl groups¹⁸ might be responsible for this difference. In fact, the values of stability constants for complexes **2** and **3** are very similar to the binding constants of the corresponding complexes of the parent compound, 2,4-dioxo-19-crown-6, determined by the calorimetric titration ($K_{\text{K}^+} = 355 \text{ M}^{-1}$ and $K_{\text{Na}^+} = 63.1 \text{ M}^{-1}$).¹⁸

Conformational Analysis. The diazodicarbonyl fragment of 3-diazo-2,4-dioxo-19-crown-6 (**1**) can adopt two

relatively stable conformations with *Z,Z* or *Z,E* arrangement of diazo and carbonyl groups (Scheme 2). According to the B3LYP/6-31+G(d,p) calculations, the *Z,Z* conformer is ca. 9.1 kcal mol⁻¹ more stable than the *Z,E*. There is no energy minimum corresponding to the *E,E* conformer apparently due to very high ring strain.

The cavity size of the macrocyclic polyether part of **1** depends on the conformation of the 2-diazo-1,3-dicarbonyl fragment. The B3LYP/6-31+G(d,p) optimized geometry of *Z,Z* conformer has cavity of 2.74–2.85 Å in diameter, while the cavity in the alternative *Z,E* conformer is only 2.16 Å.²⁰ According to B3LYP/6-31+G(d,p) calculations, the potassium ion would fit in the center of the cavity of the *Z,Z* conformer and coordinate with all six ether oxygen atoms. The cavity size of the *Z,E* form, on the other hand, is too small for K⁺, and the cation in a corresponding complex is predicted to be located above the ring. The DFT analysis of the complex of **1** with the much smaller sodium ion (**3**) shows that it can exist in both *Z,Z* and *Z,E* conformations. The energies of alternative conformers are very close, with *Z,E* conformations 1.3 kcal mol⁻¹ lower in energy than the respective *Z,Z* form. This effect, apparently, is due to the additional coordination of the cation with the negatively charged *E*-carbonyl group. It is important to note that diazodicarbonyl fragment of both conformers of 3-diazo-2,4-dioxo-19-crown-6 (**1**) and its complexes (**2** and **3**) is virtually planar in DFT-optimized geometries.²⁰

The ¹³C NMR spectrum of **1** in CD₃OD at room temperature contains only one signal for both carbonyl carbons (Figure 2). We did not observe splitting or substantial broadening of the signal even at -90 °C. On the other hand, the signal of the carbonyl carbons in the ¹³C spectrum of the parent ethyl diazomalonnate splits in two at temperatures below -60 °C, and similar temperature dependence was observed for the methylene group signals.¹² These observations allow us to conclude that one symmetrical conformer of macrocycle **1** dominates in methanol solutions. Additional support for this conclusion comes from the fact that below -75 °C we were able to observe broadening of methylene groups signals and even splitting of the signal, corresponding to carbon atoms C⁸ and C⁹ (atom numbering is shown in Scheme 2). These

(17) Huheey, J. E.; Keiter, E. A.; Keiter R. L. In *Inorganic Chemistry: Principles of Structure and Reactivity*, 4th ed.; HarperCollins: New York, 1993.

(18) Izatt, R. M.; Lamb, J. D.; Maas, G. E.; Asay, R. E.; Bradshaw, J. S.; Christensen, J. J. *J. Am. Chem. Soc.* **1977**, *99*, 2365.

(19) Liu, Y.; Zhang, L.; Li, Y.; Chen, Y.; S., H.; J., M.; Inoue, Y.; Ouchi, M. *Thermochim. Acta* **1995**, *253*, 93.

(20) Supporting Information; see the paragraph at the end of this paper regarding availability.

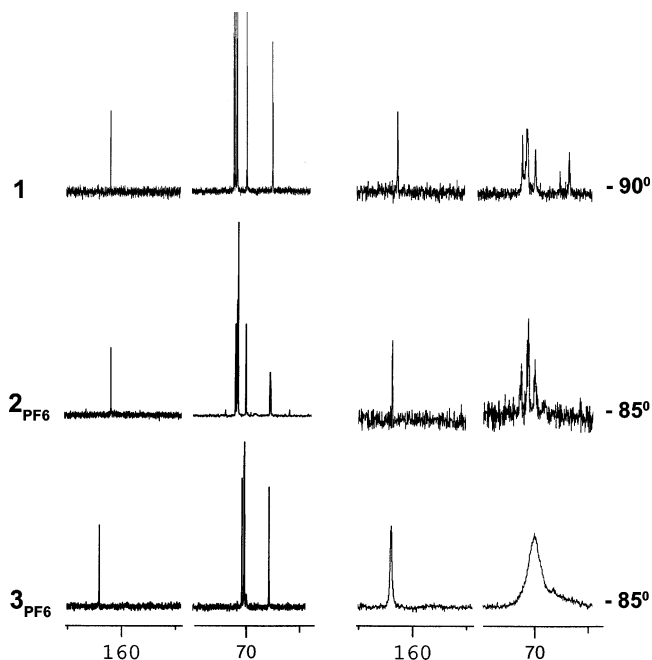


FIGURE 2. ^{13}C spectra of pure 3-diazo-2,4-dioxo-19-crown-6 (**1**) and in the presence of 0.5 M KPF_6 (**2** $_{\text{PF}_6}$) or 1 M NaPF_6 (**3** $_{\text{PF}_6}$) in deuteriomethanol. Spectra recorded at 25 °C are shown in the left column, while low-temperature spectra are shown in the right column.

methylene groups belong to a more flexible macrocyclic part of the molecule.

The ^{13}C NMR spectra of potassium complex of 3-diazo-2,4-dioxo-19-crown-6 (**2** $_{\text{PF}_6}$) recorded at +25 and -85 °C also show no changes in the carbonyl carbon signal (Figure 2). The temperature-dependent ^{13}C NMR data coupled with the results of the DFT calculation (vide supra) allow us to assign *Z,Z* geometry to the predominant conformer of the macrocycle **1** and potassium complex **2** $_{\text{PF}_6}$ (Scheme 3).

In contrast to **1** and **2** $_{\text{PF}_6}$, the ^{13}C spectrum of **1** in the presence of 1 M of NaPF_6 (**3** $_{\text{PF}_6}$, Figure 2) shows very different behavior. The carbonyl carbon signal, which is a sharp singlet at 25 °C, becomes ca. 280 Hz wide at -85 °C, while all methylene groups collapse to a very broad signal (Figure 2). Since at this Na^+ concentration 99% of **1** exist in complexed form, the dynamics effects in NMR spectrum can be explained by a rapid conformational equilibrium between two identical *Z,E* forms or *Z,E* and *Z,Z* conformers. Taking into account the results of DFT calculation as well as closer size match, we prefer the former assignment (Scheme 3). Additional support for the assignment of the *Z,E* structure to the predominant conformer of **3** $_{\text{PF}_6}$ in methanol solution comes from the fact that the carbonyl signal of the *s-E* carbonyl group in diazodicarbonyl compounds is usually observed at lower fields than the *s-Z* signal.^{9,21} In fact, the carbonyl resonance in ^{13}C spectra of **1** and **2** $_{\text{PF}_6}$ is found at 162.5 and 162.9 ppm, while for **3** $_{\text{PF}_6}$ this signal is observed at 164.3 ppm (Figure 2).

X-ray Crystal Structures of Potassium (2) and Sodium (3) Complexes. A summary of the crystal-

lographic data for the potassium and sodium perchlorate, as well as potassium hexafluorophosphate, complexes of 3-diazo-2,4-dioxo-19-crown-6 (**1**) is given in Table S1,²⁰ with accompanying digrams shown in Figure 3. Crystals of the potassium hexafluorophosphate complex **2** $_{\text{PF}_6}$ were grown by slow diffusion of hexane vapors into acetonitrile solution of 3-diazo-2,4-dioxo-19-crown-6 (**1**) and potassium hexafluorophosphate, while potassium perchlorate complex **2** $_{\text{ClO}_4}$ formed crystals upon diffusion of hexane vapors into methanol solution of a complex. Crystals of the sodium perchlorate complex **3** $_{\text{ClO}_4}$ precipitated from the chloroform–methanol solution (20:1) of diazodiester **1** and sodium perchlorate.

The geometries of the macrocyclic part of complexes **2** $_{\text{PF}_6}$ and **2** $_{\text{ClO}_4}$ are almost identical, indicating that counterion and crystallization solvents have limited influence on the structure of the complexed ligand. Compound **2** $_{\text{PF}_6}$ cocrystallizes with one molecule of acetonitrile. The ORTEP plot of a potassium hexafluorophosphate complex (**2** $_{\text{PF}_6}$, Figure 3) shows that the potassium atom is located in the middle of the cavity of macrocycle **1** and is coordinated to all ether oxygens. In agreement with the results of DFT calculations, the diazodicarbonyl moiety has *Z,Z* conformation and is virtually planar. The dihedral angles between the diazo group and carbonyl groups at C^{17} and C^{19} are -1.8° and $+3.5^\circ$, respectively. It is interesting to note that the plane of the diazo dicarbonyl fragment is almost orthogonal to the plane of the crown ether part of the molecule. This conformation apparently helps to reduce the size of the cavity for a tighter binding of potassium ion.

The structure of the sodium complex (**3** $_{\text{ClO}_4}$, Figure 3) is very different from that of the potassium one. The diazodicarbonyl fragment of the molecule adopts almost ideally a planar *Z,E* conformation. The dihedral angles between the diazo and carbonyl groups are 4.3° (*Z*) and 176.6° (*E*). The diazodiester **1** cocrystallizes with two molecules of sodium perchlorate. In addition to the ether oxygen atoms, one of the carbonyl oxygens, which is pointed inward the macrocycle, is also involved in coordination with sodium ions. Overall, the geometry of the molecule obtained from X-ray analysis of a crystal is very similar to the geometry predicted by the DFT calculation for monosodium complex **3** in a gas phase. This observation suggests that the ligand structural perturbations by the second sodium ion found in a crystal cell of **3** $_{\text{ClO}_4}$ are limited.

Photochemistry of 3-Diazo-2,4-dioxo-19-crown-6 (1) and Its Potassium hexafluorophosphate (2_{PF6}), Sodium Thiocyanate (3_{SCN}), and Sodium Hexafluorophosphate (3_{PF6}) Complexes. The UV spectra of diazo compounds **1**, **2** $_{\text{PF}_6}$, **3** $_{\text{SCN}}$, and **3** $_{\text{PF}_6}$ are almost identical and possess a characteristic strong absorbance band at 251 nm ($\log \epsilon = 4.32$, Figure 4). The 254 nm irradiation of methanolic solution of diazodiester **1** results in a rapid bleaching of the absorbance of the starting material and the formation of photoproducts with low absorbance in the UV region (Figure 4). Similar changes were observed upon photolysis of complexes **2** $_{\text{PF}_6}$, **3** $_{\text{SCN}}$, and **3** $_{\text{PF}_6}$ in methanol.

The irradiation of 3-diazo-2,4-dioxo-19-crown-6 (**1**) in methanol at 254 nm efficiently ($\Phi_{254} = 0.22$) and quantitatively converts the starting material into 2,4-dioxo-3-methoxy-19-crown-6 (**5**, Scheme 4). No Wolff rearrange-

(21) Nikolaev, V. A.; Popik, V. V.; Korobitsyna, I. K. *Zh. Org. Khim.* 1991, 27, 505.

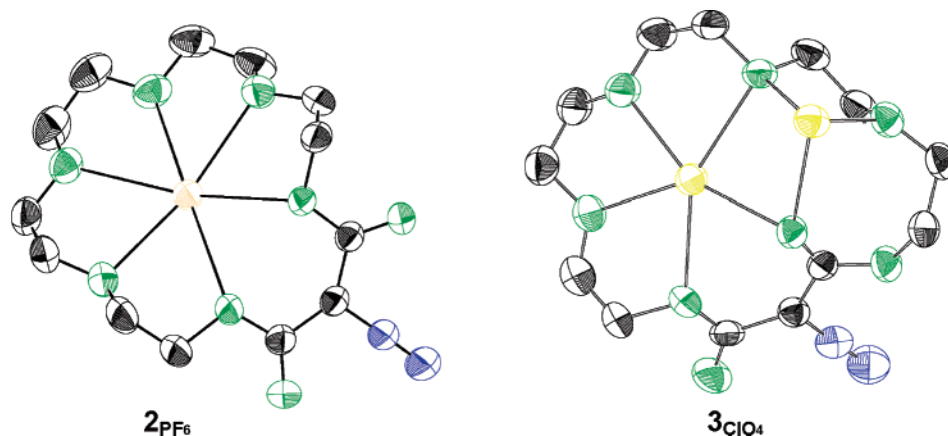


FIGURE 3. ORTEP representations of the X-ray crystal structures of potassium (**2PF₆**) and sodium (**3ClO₄**) complexes of 3-diazo-2,4-dioxo-19-crown-6 (**1**). Anions are removed for clarity. Thermal ellipsoids are illustrated at 50% probability.

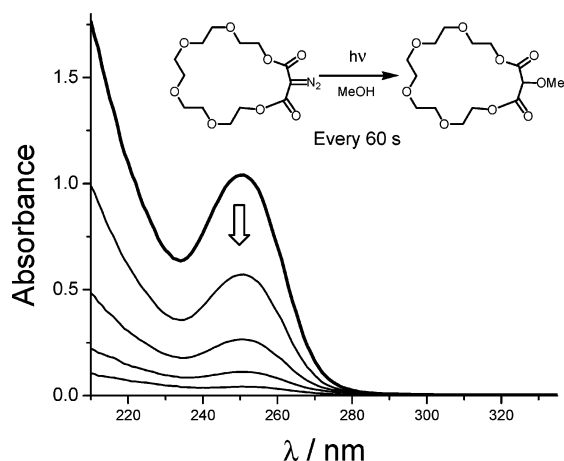
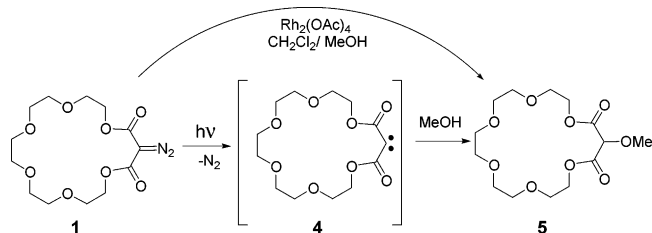


FIGURE 4. UV spectra of 254 nm photolysis of 5×10^{-5} M solution of 3-diazo-2,4-dioxo-19-crown-6 (**1**) in methanol.

SCHEME 4



ment products were detected in the reaction mixture. The structure of product **5** was confirmed by the independent synthesis using rhodium-catalyzed decomposition of **1** in methylene chloride in the presence of methanol.

Formation of the O-H insertion product **5** suggests that the photolysis of **1** proceeds with a loss of nitrogen and the formation of the singlet α,α' -dicarbonylcarbene **4**. The carbene **4** then undergoes an O-H insertion reaction with the solvent (Scheme 4). The photoreactivity of **1** is similar to that of its acyclic analogue, diethyl diazomalonate, which also produces a high yield of the O-H insertion product on photolysis.^{12,22} It is interesting to note that we were unable to detect 2,4-dioxo-19-crown-6 (**6**), which is expected to be formed from the triplet state of carbene **4**. This observation indicates that

the intersystem crossing of the excited state of **1** is rather inefficient.

The direct photolysis of a methanolic solution of potassium complex **2PF₆** also yields 2,4-dioxo-3-methoxy-19-crown-6 (**5**) as a major photoproduct (more than 95%) with good quantum yield ($\Phi_{254} = 0.35$). Small amounts of parent malonate **6** (<3%), the product of the double hydrogen abstraction from the solvent by triplet α,α' -dicarbonylcarbene **4**, were detected by GC/MS analysis (Scheme 5).

As in the case of a pure ligand, no Wolff rearrangement products were formed upon irradiation of the potassium complex **2PF₆** in methanol.

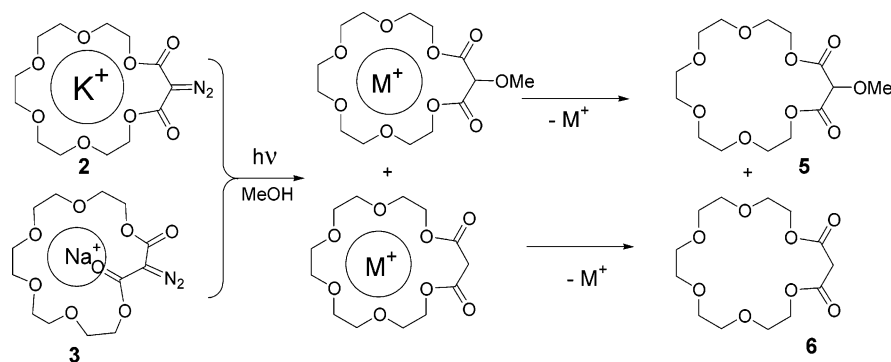
The 254 nm photolysis of a methanol solution of the sodium complexes **3SCN** and **3PF₆** ($\Phi_{254} = 0.27$) produces similar results. Chromatographic analysis of the reaction mixtures showed the O-H insertion product **5** to be the major component in a 88% yield, while only traces of 2,4-dioxo-19-crown-6 (**6**) were detected (<3%, Scheme 5).

The fact that photolysis of the diazodiester **1**, as well as its potassium (**2PF₆**) and sodium (**3SCN** and **3PF₆**) complexes, each leads to the formation of the O-H insertion product **5** indicates participation of a singlet α,α' -dicarbonylcarbene **4** in all four cases. The lack of the Wolff reaction products shows that the rate of the rearrangement of carbene **4** into corresponding ketene is much slower than trapping of the former by the hydroxylic solvent and that the concerted Wolff rearrangement does not take place for the diazoesters **1–3**.

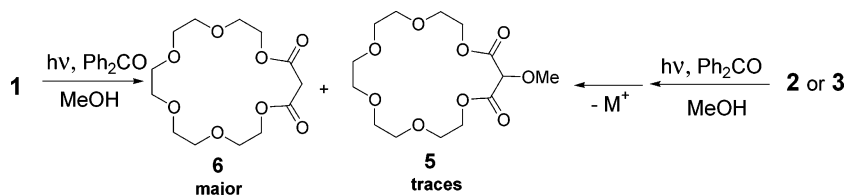
Singlet-Triplet Interconversion of α,α' -Dicarbonylcarbene **4.** In sharp contrast to a direct irradiation, triplet-sensitized photolysis of 3-diazo-2,4-dioxo-19-crown-6 (**1**), as well as of its potassium (**2PF₆**) and sodium (**3SCN**) complexes produces mostly diester **6** (>80%) and only minor amounts (<10%) of O-H insertion product **5** (Scheme 6). These results are in line with the accepted mechanism of the photochemical reduction of α -diazo-carbonyl compounds through a triplet carbonylcarbene intermediate.¹

(22) (a) Wang, J.-L.; Toscano, J. P.; Platz, M. S.; Nikolaev, V.; Popik, V. *J. Am. Chem. Soc.* **1995**, *117*, 5477. (b) Jones, M., Jr.; Ando, W.; Hendrick, M. E.; Kulczucki, A.; Howley, P. M.; Hummel, K. F.; Malament, D. S. *J. Am. Chem. Soc.* **1972**, *94*, 7469. (*Chem. Soc. Chim. Fr.* **1973**, 2065.

SCHEME 5



SCHEME 6



Since the direct photolyses of diazodiester **1** and complexes **2** and **3** produce no, or minor amounts, of 2,4-dioxo-19-crown-6 (**6**), we can conclude that a singlet-triplet equilibration of α,α' -dicarbonylcarbene **4** and its sodium or potassium complexes is slower than the intermolecular reactions of the respective states. Structurally similar singlet α,α' -dicarbonylcarbenes react with methanol at $1.5 \times 10^9 \text{ s}^{-1} \text{ M}^{-1}$.^{22a} This value allows us to estimate the lower limit for the activation energy of singlet to triplet ($4^S \rightarrow 4^T$) intersystem crossing (ISC) at 4–5 kcal/mol. The rate of the hydrogen abstraction by triplet carbenes from methanol is usually in the order of $1\text{--}5 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$,²³ which puts the barrier for the reverse ISC ($4^T \rightarrow 4^S$) in the range of at least 6–7 kcal/mol. It is interesting to note that the efficiency of the ISC of the excited state of potassium (**2**) and sodium (**3**) complexes is somewhat higher than in the parent diazodiester **1**, which is evident from the formation of small amounts of diester **6** in the direct photolyses of **2** and **3**. This increased efficiency of ISC is apparently caused by the presence of sodium and potassium ions representing another manifestation of the so-called “heavy atom” effect.

Structural Control of the Reactivity of Diazomalonates. The macrocyclic diazomalonates (**1–3**) discussed in the present report do not undergo Wolff rearrangement upon photodecomposition but produce carbene-derived products. The photochemical behavior of these compounds closely resembles the reactivity of their acyclic analogues, alkyl diazomalonates.^{12,22} The lack of carbene to ketene rearrangement in the photolysis of acyclic α -diazooesters is explained by the low migratory aptitude of oxygen.^{1b} On the other hand, the loss of nitrogen from cyclic isopropylidene diazomalonate (diazo Meldrum's acid) results in the quantitative Wolff rearrangement.^{13,24} The unique reactivity of this cyclic diazomalonate is usually rationalized in terms of the conformational

control of the reactivity of diazocarbonyl compounds, which was discussed in the Introduction.¹ The α -diazo- β,β -dicarbonyl fragment of isopropylidene diazomalonate is locked in a *Z,Z* configuration, where the migrating alkoxy group and leaving dinitrogen are arranged in antiperiplanar geometry, which is ideal for the concerted Wolff rearrangement. Our recent theoretical and experimental investigation of this reaction showed that the Wolff rearrangement of isopropylidene diazomalonate is, in fact, a concerted process.^{12,13}

A closer look at ethyl diazomalonate had revealed that the planar *Z,Z* conformer is predominant in solutions of this compound.¹² From the DFT calculations and the low-temperature NMR data for the 3-diazo-2,4-dioxo-19-crown-6 (**1**), or from the X-ray crystal structure for its potassium complex **2**, we know that diazo and carbonyl groups in these compounds adopt planar *Z,Z* arrangement as well (vide supra). Nevertheless, compounds **1** and **2** failed to produce Wolff rearrangement product upon photolysis. On the other hand, sodium complex **3**, which exists in a different (*Z,E*) conformation or as a mixture of *Z,E* and *Z,Z* forms, shows the same reactivity. These observations allow us to suggest that, at least for diazomalonates, the ground state conformation has rather limited influence on the outcome of photodecomposition. In our opinion, the most important factor controlling the mechanism of the Wolff rearrangement is the relative stability of the corresponding carbene, which in turn depends on the rigidity of the molecule. The acyclic or macrocyclic carbonyl carbenes can adopt a conformation in which the carbonyl group is orthogonal to the carbene plane. This geometry helps reduce the energy of the singlet carbene by conjugative stabilization of its un-

(23) Hadel, L. M.; Maloney, V. M.; Platz, M. S.; McGimpsey, W. G.; Scaiano, J. C. *J. Phys. Chem.* **1986**, *90*, 2488.

(24) (a) Livinghouse, T.; Stevens, R. V. *J. Am. Chem. Soc.* **1978**, *100*, 6479. (b) Nikolaev, V. A.; Khimich, N. N.; Korobitsyna, I. K. *Khim. Geterotsikl. Soedin.* **1985**, 321. (c) Lippert, T.; Koskelo, A.; Stoutland, P. O. *J. Am. Chem. Soc.* **1996**, *118*, 1551. (d) Winnik, M. A.; Wang, F.; Nivaggioli, T.; Hruska, Z.; Fukumura, H.; Masuhara, H. *J. Am. Chem. Soc.* **1991**, *113*, 9702. (e) Stevens, R. V.; Bisacchi, G. S.; Goldsmith, L.; Strouse, C. E. *J. Org. Chem.* **1980**, *45*, 2708. (f) Kammula, S. L.; Tracer, H. L.; Shelvin, P. B.; Jones, M., Jr. *J. Org. Chem.* **1977**, *42*, 2931.

shared pair with the π -system of the carbonyl group (or groups). Such stabilization makes the lifetime of the carbene longer and increases the probability of intermolecular reactions. The carbonyl carbene incorporated into a six-membered or a smaller cycle cannot achieve such orthogonal geometry and is, therefore, unstable directing the Wolff rearrangement into a concerted pathway. This hypothesis is supported by our recent DFT analysis of the thermal decomposition of cyclic and acyclic diazocarbonyl compounds.^{12,25}

Conclusions. The conformational structure of the macrocyclic diazomalonate, 3-diazo-2,4-dioxo-19-crown-6 (**1**), can be controlled by complexation with metal ions. The free ligand **1** exists in equilibrium of *Z,Z* and *Z,E* conformations, where the former is predominant (>90%). The complex of this diazo compound with a potassium ion (**2**, stability constant in methanol is $K_{K^+} = 229 \pm 25 \text{ M}^{-1}$) has a rigid planar *Z,Z* arrangement of α -diazo- β,β -dicarbonyl fragment, while complexation with a smaller sodium ion (**3**, $K_{Na^+} = 84.2 \pm 7.9 \text{ M}^{-1}$ in methanol) apparently results in the adoption of the *Z,E* conformation. Despite these structural differences, the direct photolysis of diazo compounds **1–3** results in the same process: the loss of nitrogen and the formation of α,α' -dicarbonylcarbene **4**. The latter is trapped by methanol to produce 3-methoxy-2,4-dioxo-19-crown-6 (**5**). The re-

activity of macrocyclic 3-diazo-2,4-dioxo-19-crown-6 (**1**) and its potassium (**2**) and sodium (**3**) complexes resembles the behavior of acyclic diazomalonates, rather than cyclic isopropylidene diazomalonate, which undergoes Wolff rearrangement on photolysis. The fact that all of the compounds mentioned above, except for **3**, have the planar *Z,Z* arrangement of diazo and carbonyl groups but produce different products suggests that ground-state conformation is not the major factor controlling the direction of the decomposition of diazomalonates.

The triplet-sensitized photolysis of diazomalonates **1–3** produces 2,4-dioxo-19-crown-6 (**6**), which is apparently formed via the triplet state of carbene **4**. The formation of very different products in direct and triplet-sensitized photolyses allows us to conclude that the singlet–triplet interconversion in the case of the carbene **4** is slower than the intermolecular reactions of respective states.

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Supporting Information Available: Detailed description of experimental and theoretical procedures; crystallographic data including complete tables of bond distances and angles, final fractional coordinates, thermal parameters, and CIF files; Gaussian 98 output files for quantum mechanical calculations. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(25) Popik, V. V. The Role of Molecular Geometry in the Wolff Rearrangement of α -Diazocarbonyl Compounds: Conformational Control or Structural Constraints? *Can. J. Chem.* **2005**, *83* (9), in press, CHEM-05-021-PI.