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Reaction of Dimethoxycarbene−DMAD Zwitterion with 1,2-Diones and Anhydrides: A Novel Synthesis of Highly Substituted Dihydrofurans and Spirodihydrofurans

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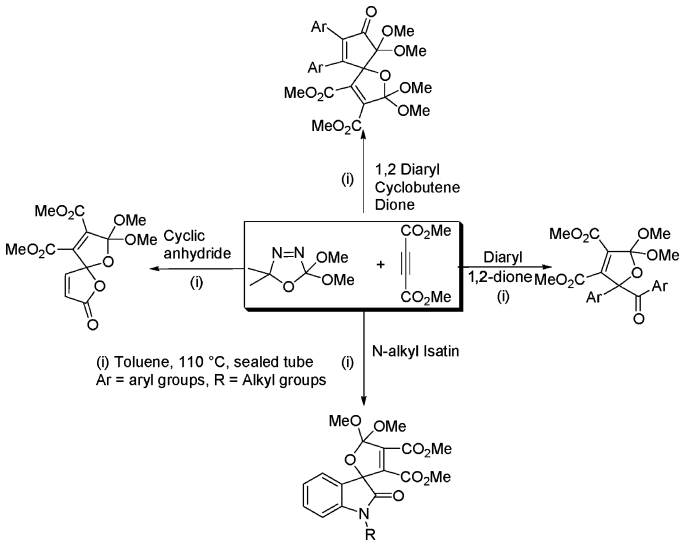

The zwitterion formed by the reaction of dimethoxycarbene and DMAD adds efficiently to one of the carbonyl groups of 1,2-dicarbonyl compounds and anhydrides to generate dihydrofurans and spirodihydrofurans in good yields. In many cases, the carbene inserts into the C−C bond of the dione to yield masked vicinal tricarbonyl systems.

Introduction

In his pioneering work three decades ago, Hoffmann[1] had shown the synthetic utility of dialkoxycarbenes, especially dimethoxycarbene. This work, however, did not attract much attention presumably due to the operational difficulty in generating the carbenes.[2] The introduction of a simple and efficient protocol for the generation of dialkoxycarbenes by Warkentin in 1994 has rekindled interest in this area.[3] In recent years, a number of research groups, most notably that of Warkentin, have extensively studied the chemistry and mechanistic aspects of dialkoxy- and related bis-heteroatom carbenes.[4,5] Dialkoxycarbenes are now known to participate in [4 + 1] cycloadditions leading to pyrazoles[6] and hydroindolones.[7] Also noteworthy is the preparation of the sceletium alkaloid mesembrine via the [4 + 1] cycloaddition of bis(alkylthio)carbene and

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(1) (a) Hoffmann, R. W.; Steinbach, K.; Dittrich, B. *Chem. Ber*. **1973**, *106*, 2174−2184. (b) Hoffmann, R. W.; Steinbach, K.; Lilienblum, W. *Chem. Ber*. **1976**, *109*, 1759−1768.

(2) Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl*. **1971**, *10*, 529.

(3) Kassam, K.; Pole, D. L.; El-Saidi, M.; Warkentin, J. *J. Am. Chem. Soc*. **1994**, *116*, 1161.

(4) (a) Kassam, K.; Warkentin, J. *J. Org. Chem*. **1994**, *59*, 5071. (b) Venneri, P. C.; Warkentin, J. *J. Am. Chem.* Soc. **1998**, *120*, 11182. (c) Lu, X.; Warkentin, J. *Tetrahedron Lett.* **1999**, *40*, 1483. (d) Dunn, J. A.; Pezacki, J. P.; McGlinchey, M. J.; Warkentin, J. *J. Org. Chem*. **1999**, *64*, 4344. (e) Pezacki, J. P.; Loncke, P. G.; Ross, P. J.; Warkentin, J.; Gadosy, T. A. *Org. Lett*. **2000**, *2*, 2733. (f) Plazuk, D.; Warkentin, J.; Werstiuk, N. H. *Tetrahedron* **2005**, *61*, 5788.

(5) For reviews, see: Warkentin, J. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2161−2169 and references cited therein.

(6) Gerninghaus, C.; Kümmell, A.; Seitz, G. *Chem. Ber*. **1993**, *126*, 733.

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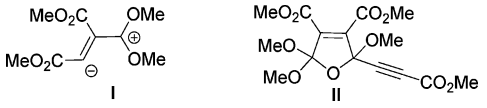


FIGURE 1. Zwitterion I and the 1:2 Adduct II of Dimethoxycarbene and DMAD.

functionalized vinyl isocyanates.[8] Very recently, dialkoxycarbenes have also been utilized in intra- and intermolecular [4 + 1] cycloadditions with electron-deficient dienes.[9] Contemporaneous with these efforts, work in our laboratory has shown that zwitterions formed from nucleophilic species such as isocyanides, N-heterocyclic carbenes, and nitrogen heterocycles such as isoquinolines can react with electrophiles leading to novel heterocycles.[10] The formation of zwitterion **I** by the reaction of dimethoxycarbene and dimethyl acetylenedicarboxylate (DMAD) as well as its reaction with a second molecule of DMAD to afford **II** is known from the work of Hoffmann (Figure 1).[11]

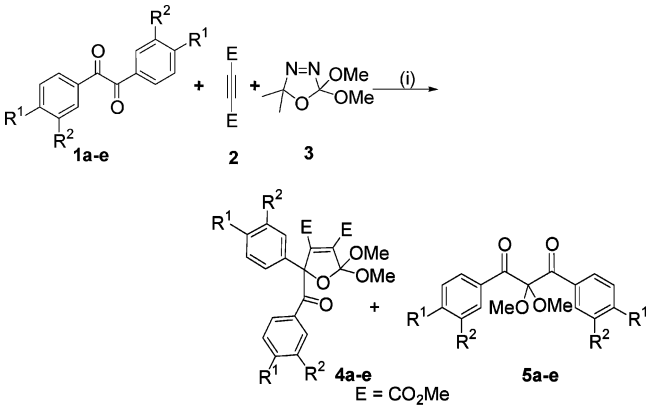
We have recently shown that zwitterion **I** can be engaged in reactions with aldehydes and activated styrenes leading to dihydrofurans and cyclopentenone derivatives, respectively.[12] Zwitterion **I** was also reported to efficiently annulate divinyl ketones to afford γ-lactones.[13] Sustained interest in this general area of research and the recent observation that the DMAD−pyridine zwitterion underwent novel reactions with benzils and cyclobutene-1,2-diones leading to aroyl fumarates and highly substituted benzene derivatives, respectively,[14] an investigation of the reaction of the dimethoxycarbene−DMAD zwitterions **I** with 1,2-diones was undertaken, and the results are presented in this paper.

Results and Discussion

In our initial experiment, benzil **1a**, DMAD **2**, and oxadiazoline **3** in dry toluene were degassed, sealed, and heated in a resealable tube. Concentration of the reaction mixture followed by column chromatography yielded the dihydrofuran **4a** in 83% yield. Ring substituted benzils (**1b**−**d**) also afforded the dihydrofuran under the same reaction conditions. It was, however, observed that in the case of highly electron deficient benzils (**1d**,**e**) the carbene undergoes insertion into the C−C bond to yield the products (**5d**,**e**) in major amounts (Table 1).

In the IR spectrum of **4a** the vibrational stretching of the ester and benzoyl carbonyl groups were discernible at 1743 and 1686 cm^{-1}, respectively. In the ^{1}H NMR spectrum, the methoxy protons resonated as sharp singlets at δ 3.68 and 3.06 while the protons of the carbomethoxy groups resonated at δ 3.83 and 3.73. Lower chemical shift values have been assigned to the methoxy protons than the carbomethoxy protons on the basis of the X-ray structures. Interestingly, the ORTEP diagram (included in the Supporting Information) shows that the methoxy protons are in the shielding region of the benzene ring compared to the carbomethoxy protons, and hence, the lower values assigned are reasonable. The ^{13}C NMR spectrum displayed the characteristic signal for the ester and benzoyl carbonyl carbons at δ 167.9, 167.3, and 192.3, respectively. Final confirmation of the structure of **4a** was obtained from single-crystal X-ray analysis.

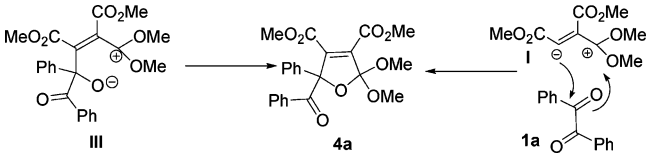
TABLE 1. Addition of Dimethoxycarbene−DMAD Zwitterion to Diaryl 1,2-dione



(i) Toluene, sealed tube, 110 °C, 24 h

entry	**1**	**4**,**5**	R^1	R^2	% **4**	% **5**
1	**1a**	**4a**, **5a**	H	H	83	0
2	**1b**	**4b**, **5b**	F	H	65	0
3	**1c**	**4c**, **5c**	CH3	H	45	0
4	**1d**	**4d**, **5d**	CF_3	H	31	66
5	**1e**	**4e**, **5e**	H	NO_2	0	96

SCHEME 1



Mechanistically, it is conceivable that the zwitterionic intermediate **I**[15] initially formed by the 1:1 interaction of dimethoxycarbene **3** and DMAD **2** adds to one of the carbonyl groups of the dione leading to a zwitterionic species **III** and cyclization of the latter yields the dihydrofuran product **4a**. Alternatively, a cycloaddition of the zwitterion with the C═O can also lead to the dihydrofuran (Scheme 1).

A rationalization of the predominant formation of the carbene insertion products **5d** and **5e**, respectively, may be outlined as follows. The BDE of the C−C bond connecting the carbonyls in the case of **1d** and **1e** is likely to be 60−65 kcal/mol, which is lower than that of **1a**−**c** (the known BDE of **1a** is 70 kcal/

(7) (a) Rigby, J. H.; Cavezza, A.; Ahmed, G. *J. Am. Chem. Soc*. **1996**, *118*, 12848. (b) Rigby, J. H.; Cavezza, A.; Heeg, M. J. *Tetrahedron Lett*. **1999**, *40*, 2473. (c) Rigby, J. H.; Danca, M. D. *Tetrahedron Lett*. **1999**, *40*, 6891.

(8) Rigby, J. H.; Dong, W. *Org. Lett*. **2000**, *2*, 1673.

(9) Spino, C.; Rezaei, H.; Dupont-Gaudet, K.; Bèlanger, F. *J. Am. Chem. Soc*. **2004**, *126*, 9926.

(10) (a) Nair, V.; Menon, R. S.; Beneesh, P. B.; Sreekumar, V.; Bindu, S. *Org. Lett*. **2004**, *6*, 767. (b) Nair, V.; Sreekumar, V.; Bindu, S.; Suresh, E. *Org. Lett*. **2005**, *7*, 2297. (c) Nair, V.; Remadevi, B.; Luxmi, V. *Tetrahedron Lett*. **2005**, *46*, 5333. (d) Nair, V.; Rajesh, C.; Vinod, A. U.; Bindu, S.; Sreekanth, A. R.; Mathen, J. S.; Balagopal, L. *Acc. Chem. Res*. **2003**, *36*, 899.

(11) Hoffmann, R. W.; Lilienblum, W.; Dittrich, B. *Chem. Ber*. **1974**, *107*, 3395−3407.

(12) (a) Nair, V.; Bindu, S.; Balagopal, L. *Tetrahedron Lett*. **2001**, *42*, 2043. (b) Nair, V.; Beneesh, P. B.; Sreekumar, V.; Bindu, S.; Menon, R. S.; Deepthi, A. *Tetrahedron Lett*. **2005**, *46*, 201.

(13) Nair, V.; Bindu, S.; Sreekumar, V.; Chiaroni, A. *Org. Lett*. **2002**, *4*, 2821.

(14) (a) Nair, V.; Abhilash, N.; Menon, R, S.; Suresh, E. *Org. Lett*. **2005**, *7*, 1189. (b) Nair, V.; Abhilash, N.; Beneesh, P. B.; Suresh, E. *Org. Lett*. **2005**, *7*, 4625.

(15) It may be mentioned that, although, zwitterionic species can be considered to be in equilibrium with the parent nucleophile and activated acetylene, in the case of the zwitterion derived from a transient species such as dimethoxycarbene and DMAD, it is reasonable to assume that the equilibrium will be shifted largely to the right.

SCHEME 2

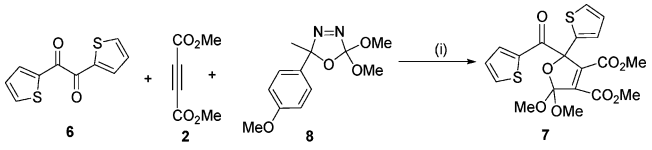
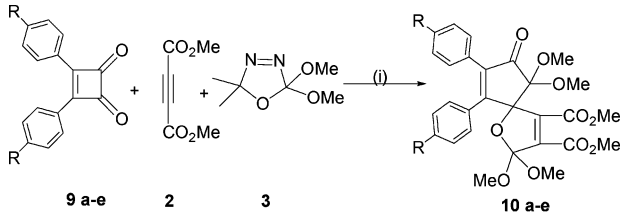


TABLE 2. Reaction of Dimethoxycarbene and DMAD with 3,4-Diarylcyclobut-3-ene-1,2-diones



entry	substrate **9**	R	product **10**	% **10**
1	**9a**	CH_3	**10a**	53
2	**9b**	H	**10b**	80
3	**9c**	Cl	**10c**	50
4	**9d**	Br	**10d**	88
5	**9e**	OMe	**10e**	42

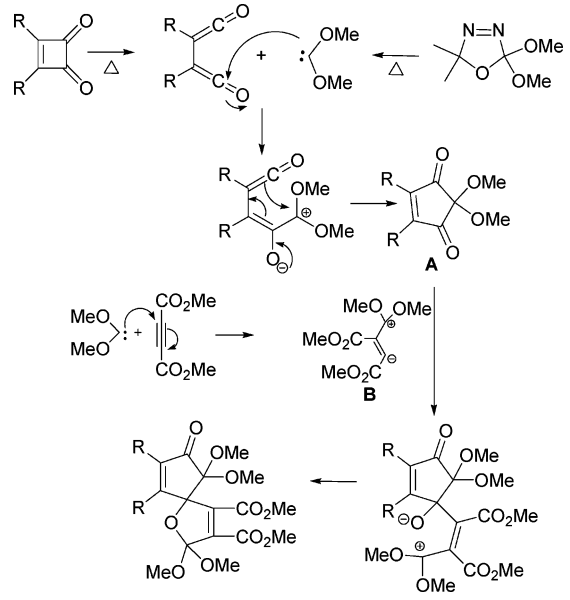
mol), thus facilitating carbene insertion to form products **5d** and **5e**. This implies that **1d** and **1e** are better traps than dimethyl acetylenedicarboxylate (DMAD) for the carbene.

Treatment of thenil **6** with DMAD **2** and oxadiazoline **3** under identical reaction conditions led to the formation of the dihydrofuran **7** in 15% yield. When oxadiazoline **8**, known to generate the carbene at 50 °C,[16] was used in place of **3** the product **7** was formed in 71% yield (Scheme 2).

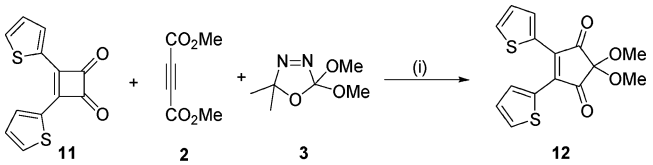
Subsequently, the reaction of the zwitterion **I** with 3,4-diarylcyclobut-3-ene-1,2-diones **9** was investigated. It is known that dimethoxycarbene reacts with the diketene formed from cyclobutenedione to form the 2,2-dimethoxycyclopent-4-ene-1,3-dione.[17] In a prototype experiment, 3,4-bis(4-methylphenyl)-cyclobut-3-ene-1,2-dione **9a** was treated with DMAD **2** and oxadiazoline **3** in a sealed tube in dry toluene. The reaction afforded the spirodihydrofuran derivative **10a** in 53% yield. The reaction was found to be general with other substituted cyclobutenediones (Table 2), which were prepared by a reported protocol starting from commercially available squaric acid.[18]

The IR spectrum of **10a** showed characteristic vibrations at 1730 and 1671 cm^{-1} corresponding to the ester and ketone carbonyls, respectively. In the ^1H NMR spectrum, the carbomethoxy protons displayed their signals at δ 3.87 and 3.73 while the methoxy protons adjacent to the ketone carbonyl were discernible at δ 3.51 and 2.68. The protons of the remaining two methoxy groups resonated at δ 3.57 and 3.55 (the assignment is based on the ORTEP diagram presented in the Supporting Information). The ^{13}C NMR spectrum revealed the spirocarbon at δ 100.2, the ester carbons at δ 162.7 and 162.3, and the ketone carbonyl at δ 195.9. Final confirmation of the structure of **10a** was obtained by single-crystal X-ray analysis.

SCHEME 3



SCHEME 4



Mechanistically, the reaction may be envisaged as involving two stages. The initial [4 + 1] cycloaddition between the carbene and the diketene formed by the thermolysis of the cyclobutenedione can deliver the cyclopentenedione **A**. The latter then undergoes a formal [3 + 2] cycloaddition with the zwitterion **B** to yield the spiroadduct (Scheme 3).

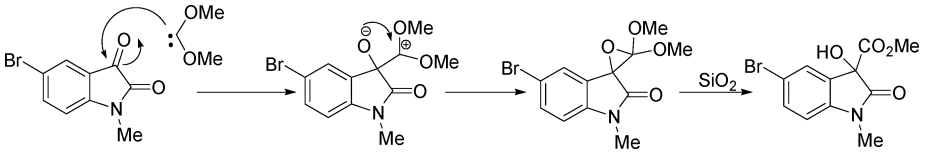
However, the reaction of 3,4-dithien-2-ylcyclobut-3-ene-1,2-dione **11** with DMAD **2** and oxadiazoline **3** under the same conditions afforded only the 2,2-dimethoxy-4,5-dithien-2-ylcyclopent-4-ene-1,3-dione **12** in 48% yield (Scheme 4).

In the case of reaction of **11** with the zwitterion, **12** is the only product obtained, and subjecting it to further reaction with dimethoxycarbene−DMAD zwitterion did not furnish any addition product. It is also noteworthy that **12** is not formed in high yields. The formation of small amounts of the 1:2 adduct between the carbene and DMAD is also observed in this case. The exact reason why **12** does not undergo further reaction cannot be rationalized at this stage.

Encouraged by the interesting results obtained with benzils and cyclobutene diones, we extended our investigations to N-substituted isatins, a class of compounds with interesting pharmacological activities.[19] *N*-Methylisatin **13a**, DMAD, and oxadiazoline **3** were heated in a sealed tube in dry toluene. The reaction afforded the product **14a** in 54% yield. The reaction was found to be general with other N-substituted isatins, and the results are presented in Table 3. An additional product **15e** was obtained in the case of 5- bromo-*N*-methylisatin, showing that **13e** also acts as a trap for the carbene.

(16) Zhou, H.; Mloston, G.; Warkentin, J. *Org. Lett*. **2005**, *7*, 487.
(17) Colomvakos, J. D.; Egle, I.; Ma, J.; Pole, D. L.; Tidwell, T. T.; Warkentin, J. *J. Org. Chem*. **1996**, *61*, 9522.
(18) De Selms, R. C.; Fox, C. J.; Riordan, R. C. *Tetrahedron Lett*. **1970**, *11*, 781.
(19) Lackey, K.; Besterman, J. M.; Fletcher, W.; Leitner, P.; Morton, B.; Sternbach, D. D. *J. Med. Chem*. **1995**, *38*, 906.

SCHEME 5



SCHEME 6

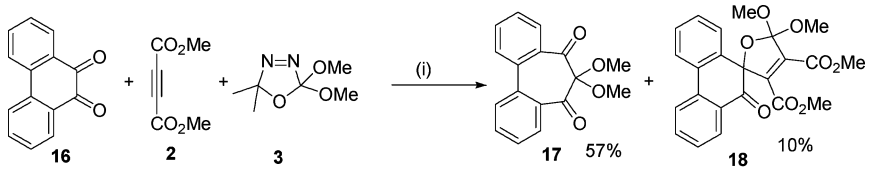
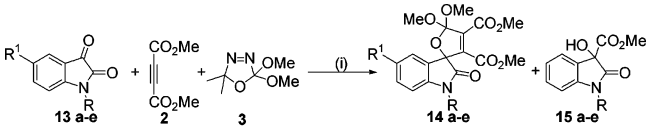


TABLE 3. Addition of Isatins 13 to Dimethoxycarbene−DMAD Zwitterion



entry	13	14, 15	R^1	R^2	% 14	% 15
1	**13a**	**14a**, **15a**	Me	H	54	0
2	**13b**	**14b**, **15b**	Et	H	50	0
3	**13c**	**14c**, **15c**	Pr	H	50	0
4	**13d**	**14d**, **15d**	CH_2Ph	H	48	0
5	**13e**	**14e**, **15e**	Me	Br	32	48

The structure of the adduct **14a** was ascertained by spectroscopic methods. In the ^{1}H NMR spectrum, signals due to the carbomethoxy and methoxy protons were discernible as sharp singlets at δ 3.91, 3.65, 3.62, and 3.43. The amide and ester carbonyl groups gave ^{13}C resonance signals at δ 171.0, 162.2, and 160.0 respectively, supporting the IR absorptions at 1678 and 1745 cm^{-1}. The spirocarbon was found to resonate at δ 86.4 in the ^{13}C NMR.

A mechanistic postulate analogous to the one suggested for the reaction of benzils could be invoked to explain the formation of the cycloadduct **14**. Formation of the hydroxy ester **15** can be explained by assuming that dimethoxycarbene first adds to the C-3 carbonyl group of isatin to form the epoxide which during column chromatography on SiO_2 rearranges to the hydroxy ester **15** (Scheme 5). Warkentin and co-workers observed a similar reaction of dimethoxycarbene with fluorenone where the oxirane formed undergoes hydrolysis on silica to yield the hydroxy ester.[20]

The reaction involving phenanthrene quinone **16**, DMAD **2**, and oxadiazoline **3** afforded the ring-enlarged compound **17** as the major product, and only a small amount of the spiro-adduct **18** was obtained (Scheme 6).

Although cyclic anhydrides have been known to react with dialkoxycarbenes leading to the corresponding ring-enlarged products,[21] there has not been any report on their reaction with zwitterions. We have carried out a limited investigation of the reaction of dimethoxycarbene−DMAD zwitterion with cyclic anhydrides. Exposure of maleic anhydride **19** to the DMAD−dimethoxycarbene zwitterion afforded the spirodihydrofuran **20** in 62% yield (Scheme 7).

SCHEME 7

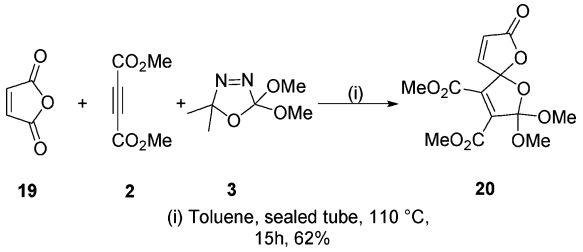
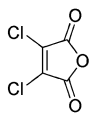
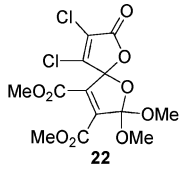
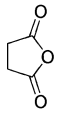
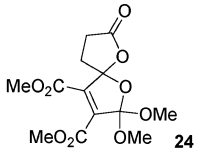
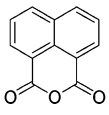
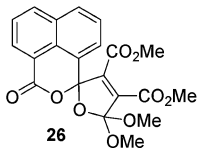


TABLE 4. Addition of Dimethoxycarbene−DMAD Zwitterion to Cyclic Anhydrides[a]

Entry	Anhydride	Product	Yield (%)
1	 **21**	 **22**	29
2	 **23**	 **24**	65
3	 **25**	 **26**	86

[a] Reaction conditions: oxadiazoline, DMAD, toluene, sealed tube, 100 °C, 15 h.

The structure of the spiroadduct **20** was ascertained by spectroscopic analysis. In the ^{1}H NMR spectrum, signals due to the carbomethoxy and methoxy protons were discernible as sharp singlets at δ 3.9, 3.76, 3.51, and 3.46. The olefinic protons afforded two separate doublets at δ 7.17 and 6.32. The lactone and ester carbonyl displayed ^{13}C resonance signals at δ 168.4, 161.4, and 160.4, respectively. The signal δ 109.4 was attributed to the spirocarbon. Similar cycloadducts were formed with dichloromaleic, succinic, and naphthoic anhydrides as well, and the results are presented in Table 4.

(20) Pole, D. L.; Warkentin, J. *J. Org. Chem.* **1997**, *62*, 4065.

(21) Pole, D. L.; Warkentin, J. *Liebigs Ann.* **1995**, 1907.

Conclusion

In conclusion, the study shows that the zwitterion formed from dimethoxycarbene and DMAD can efficiently add to cyclic and acyclic 1,2 diones and to anhydrides. The products formed are potentially amenable to further transformations. Spiroannulated oxindole derivatives form an important structural unit of biologically active natural products such as the mycotoxin triptoquivaline.[22]

Experimental Section

All of the ^{1}H NMR (300 MHz, $CDCl_3$) and ^{13}C NMR (75 MHz, $CDCl_3$) reported herein and the X-ray crystal data and structure of compounds **4a** and **10a** are presented in the Supporting Information.

Dimethyl 2-Benzoyl-5,5-dimethoxy-2-phenyl-2,5-dihydrofuran-3,4-dicarboxylate (4a). Benzil **1a** (100 mg, 0.48 mmol), dimethyl acetylenedicarboxylate **2** (102 mg, 0.72 mmol), and oxadiazoline **3** (154 mg, 0.96 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, and the residue was subjected to column chromatography (silica gel, 100−200 mesh; 80:20 *n*-hexane/ethyl acetate) to give dihydrofuran **4a** (168 mg, 83%) as a white crystalline solid (recrystallized from DCM−hexane). Mp = 123.0−125.0 °C. R_f: 0.08 (3:7 ethyl acetate/hexanes). IR (KBr) ν_{max}: 3077, 2954, 2845, 1743, 1686, 1594, 1573, 1449, 1434, 1331, 1295, 1187. ^{1}H NMR: δ 7.89 (d, 2H, J = 7.5), 7.49−7.42 (m, 3H), 7.36−7.33 (m, 5H), 3.83 (s, 3H), 3.73 (s, 3H), 3.68 (s, 3H), 3.06 (s, 3H). ^{13}C NMR: δ 192.4, 167.9, 167.4, 155.9, 135.6, 133.9, 133.8, 130.2, 129.3, 129.2, 128.9, 128.7, 128.4, 128.3, 111.2, 53.1, 53.0, 52.9, 52.9. HRMS (EI): *m*/*z* calcd for $C_{23}H_{22}O_8$ 426.1315, found 426.1319. Anal. Calcd for $C_{23}H_{22}O_8$: C, 64.78; H, 5.20. Found: C, 64.72; H, 5.19.

Dimethyl 2-(4-Fluorobenzoyl-2(4-fluorophenyl)-5,5-dimethoxy-2,5-dihydrofuran-3,4-dicarboxylate (4b). 4,4′-Difluorobenzil **1b** (100 mg, 0.41 mmol), dimethyl acetylenedicarboxylate **2** (87 mg, 0.61 mmol), and oxadiazoline **3** (131 mg, 0.82 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, and the residue was subjected to column chromatography (silica gel, 100−200 mesh; 80:20 *n*-hexane/ethyl acetate) to give dihydrofuran **4b** (123 mg, 65%) as a colorless viscous liquid. R_f: 0.06 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2954, 2928, 2851, 1743, 1686, 1619, 1491, 1434, 1357, 1341,1207, 1146, 1108. ^{1}H NMR: δ 7.95−7.91 (m, 2H), 7.43−7.38 (m, 2H), 7.05−7.00 (m, 4H), 3.84 (s, 3H), 3.74 (s, 3H), 3.66 (s, 3H), 3.07 (s, 3H). ^{13}C NMR: δ 193.5, 167.3, 155.4, 134.4, 134.3, 134.1, 134.0, 133.9, 129.3, 128.9, 124.5, 116.6, 116.1, 115.9, 111.0, 53.5, 53.4, 52.8, 52.6. HRMS (EI): *m*/*z* calcd for $C_{23}H_{20}F_2O_8$ 462.1126, found 462.1125.

Dimethyl 2,2-Dimethoxy-5-(4-methylbenzoyl)-5-*p*-tolyl-2,5-dihydrofuran-3,4-dicarboxylate (4c). 4,4′-Dimethylbenzil **1c** (100 mg, 0.42 mmol), dimethyl acetylenedicarboxylate **2** (90 mg, 0.63 mmol), and oxadiazoline **3** (134 mg, 0.84 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, and the residue was subjected to column chromatography (silica gel, 100−200 mesh; 80:20 *n*-hexane/ethyl acetate) to give dihydrofuran **4c** (86 mg, 45%) as a colorless viscous liquid. R_f: 0.10 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2959, 2922, 2856, 1743, 1686, 1604, 1444, 1264, 1192, 1125, 1042, 970. ^{1}H NMR: δ 7.80 (d, 2H, J = 8.07), 7.31−7.25 (m, 3H), 7.14−7.11 (m, 4H), 3.82 (s, 3H), 3.73 (s, 3H), 3.66 (s, 3H), 3.05 (s, 3H), 2.35 (s, 3H), 2.33 (s, 3H). ^{13}C NMR: δ 194.9, 162.1, 161.9, 144.2, 143.5, 138.5, 134.7, 133.4, 131.2, 130.3, 129.9, 128.3, 126.8, 124.1, 111.1, 53.1, 52.3, 51.7, 50.6, 40.2, 25.1, 21.3. HRMS (EI): *m*/*z* calcd for $C_{25}H_{26}O_8$ 454.1628, found 454.1625.

Dimethyl 2,2-Dimethoxy-5-(4-trifluoromethylbenzoyl)-5-(4-trifluoromethyl)phenyl-2,5-dihydrofuran-3,4-dicarboxylate (4d) and 2,2-Dimethoxy-1,3-bis(4-(trifluoromethyl)phenyl)propane-1,3-dione (5d). 4,4′-Trifluoromethylbenzil **1d** (100 mg, 0.28 mmol), dimethyl acetylenedicarboxylate **2** (62 mg, 0.43 mmol), and oxadiazoline **3** (92 mg, 0.58 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, the residue was subjected to column chromatography (silica gel, 100−200 mesh), and the products were obtained in increasing order of polarity. Elution with 2:98 ethyl acetate/hexane solvent mixtures afforded the product **5d** (80 mg, 66%) as a colorless viscous liquid. R_f: 0.40 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2964, 2918, 2851, 1831, 1676, 1614, 1578, 1413, 1326, 1249, 1161, 1130, 1068, 1011. ^{1}H NMR: δ 7.64−7.62 (m, 8H), 3.55 (s, 6H). ^{13}C NMR: δ 189.4, 131.2, 130.6, 128.8, 127.1, 126.5, 126.5, 126.4, 126.4, 126.3, 54.9, 30.5, 30.0. HRMS (EI): *m*/*z* calcd for $C_{19}H_{14}F_6O_4$ 420.0796, found 420.0791. Elution with 30:70 ethyl acetate/hexane solvent mixture afforded **4d** (50 mg, 31%) as a colorless viscous liquid. R_f: 0.05 (3:7 ethyl acetate/hexanes). IR (thin film) υ_{max}: 2964, 2845, 1743, 1696, 1619, 1444, 1408, 1326, 1264, 1176, 1135, 1068. ^{1}H NMR: δ 8.02−7.97 (m, 2H), 7.68−7.56 (m, 6H), 3.85 (s, 3H), 3.76 (s, 3H), 3.69 (s, 3H), 3.08 (s, 3H). ^{13}C NMR: δ 193.2, 162.2, 161.9, 140.8, 131.0, 130.5, 129.9, 128.8, 127.2, 125.5, 125.4, 124.7, 124.6, 124.6, 111.0, 55.5, 52.7, 52.5, 51.8, 51.4, 50.8, 50.8, 29.7. HRMS (FAB): ($M + H^+$) calcd for $C_{25}H_{20}F_6O_8$ 563.1062, found 563.1064.

2,2-Dimethoxy-1,3-bis(3-nitrophenyl)propane-1,3-dione (5e). 3,3′-Dinitrobenzil **1e** (100 mg, 0.33 mmol), dimethyl acetylenedicarboxylate **2** (70 mg, 0.49 mmol), and oxadiazoline **3** (106 mg, 0.66 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, and the residue was subjected to column chromatography (silica gel, 100−200 mesh 20:80 ethyl acetate/hexane) to afford the product **5e** (118 mg, 96%) as a yellow oil. R_f: 0.13 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2959, 1686, 1532, 1346, 1228, 1120. ^{1}H NMR: δ 8.39 (s, 2H), 8.20 (d, 2H, J = 8.06), 7.81−7.78 (m, 2H), 7.56 (uneven triplet, 2H, J_1 = 8.06, J_2 = 8.54), 3.61 (s, 6H). ^{13}C NMR: δ 189.5, 148.9, 136.3, 135.6, 133.9, 131.7, 130.7, 130.1, 129.4, 128.7, 125.7, 124.4, 123.9, 121.3, 52.2. HRMS (EI): *m*/*z* calcd for $C_{17}H_{14}N_2O_8$ 374.0750, found 374.0738.

Dimethyl 2,2-Dimethoxy-5-(thiophen-2-yl)-5-(thiophene-2-carbonyl)-2,5-dihydrofuran-3,4-dicarboxylate (7). Thenil **6** (100 mg, 0.45 mmol), dimethyl acetylenedicarboxylate **2** (96 mg, 0.68 mmol), and oxadiazoline **8** (227 mg, 0.90 mmol) were heated in dry toluene (2 mL) in a sealed tube. The tube was degassed and heated to 110 °C for 24 h. The solvent was removed on a rotary evaporator, and the residue was subjected to column chromatography (silica gel, 100−200 mesh 20:80 ethyl acetate/hexane) to afford the product **7** (140 mg, 71%) as a yellow oil. R_f: 0.16 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2958, 2850, 1743, 1717, 1665, 1614, 1434, 1408, 1305, 1259, 1130. ^{1}H NMR: δ 7.85 (d, 2H, J = 3.18), 7.66 (d, 1H, J = 4.47), 7.34 (d, 1H, J = 4.41),7.08−7.04 (m, 2H), 6.93 (uneven triplet, 1H, J_1 = 4.68, J_2 = 3.87), 3.84 (s, 3H), 3.79 (s, 3H), 3.67 (s, 3H), 3.18 (s, 3H). ^{13}C NMR: δ 186.7, 161.6, 161.5, 142.2, 140.5, 139.2, 136.1, 135.1, 133.3, 131.2, 128.1, 127.9, 127.2, 127.0, 126.6, 115.9, 111.2, 55.6, 52.6, 52.3, 51.8. HRMS (EI): *m*/*z* calcd for $C_{19}H_{18}O_8S_2$ 438.0443, found 438.0449.

6,7-Bis(4-methylphenyl)-2,2,9,9-tetramethoxy-8-oxo-1-oxaspiro-[4.4]nona-3,6-diene-3,4-dicarboxylic Acid Dimethyl Ester (10a). 3,4-Ditolylcyclobutene 1,2-dione **9a** (100 mg, 0.38 mmol), DMAD **2** (81 mg, 0.51 mmol), and oxadiazoline **3** (122 mg, 0.76 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the

(22) (a) Büchi, G.; DeShong, P. R.; Katsumura, S.; Sugimura, Y. *J. Am. Chem. Soc.* **1979**, *101*, 5084. (b) Ohnuma, T.; Kimura, Y.; Ban, Y. *Tetrahedron Lett.* **1981**, *22*, 4969. (c) Nakagawa, M.; Taniguchi, M.; Sodeoka, M.; Ito, M.; Yamaguchi, K.; Hino, T. *J. Am. Chem. Soc.* **1983**, *105*, 3709.

residue was purified by column chromatography (silica gel, 100−200 mesh; 80:20 hexane/EtOAc) to give the spirodihydrofuran **10a** (111 mg, 53%) as a colorless crystalline solid. R_f: 0.23 (3:7 ethyl acetate/hexanes). Mp = 131.0−133.0 °C. IR (KBr) ν_{max}: 3000, 2954, 2850, 1738, 1671, 1609, 1506, 1434, 1352, 1331, 1274, 1207, 1182, 1130. ^{1}H NMR: δ 7.18−7.04 (m, 8H), 3.87 (s, 3H), 3.73 (s, 3H), 3.57 (s, 3H), 3.55 (s, 3H), 3.51 (s, 3H), 2.68 (s, 3H), 2.31 (s, 3H), 2.28 (s, 3H). ^{13}C NMR: δ 195.9, 162.7, 162.4, 141.3, 138.8, 138.6, 138.2, 129.7, 129.5, 129.1, 128.8, 128.8, 127.2, 122.9, 100.2, 93.7, 52.9, 52.5, 51.5, 51.5, 50.2, 21.4, 21.4. Anal. Calcd for $C_{30}H_{32}O_{10}$: C, 65.21; H, 5.84. Found: C, 65.25; H, 5.96.

2,2,9,9-Tetramethoxy-8-oxo-6,7-diphenyl-1-oxaspiro[4.4]nona-3,6-diene-3,4-dicarboxylic Acid Dimethyl Ester (10b). 3,4-Diphenylcyclobutene-1,2-dione **9b** (100 mg, 0.43 mmol), DMAD **2** (91 mg, 0.64 mmol), and oxadiazoline **3** (138 mg, 0.86 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; 80:20 hexane/EtOAc) to give the spirodihydrofuran **10b** (185 mg, 82%) as a colorless oil. R_f: 0.21 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2954, 2845, 1727, 1671, 1480, 1439, 1362, 1326, 1274, 1130, 1068, 975. ^{1}H NMR: δ 7.27−7.08 (m, 10H), 3.78 (s, 3H), 3.75 (s, 3H), 3.57 (s, 6H), 3.51 (s, 3H), 2.58 (s, 3H). ^{13}C NMR: δ 195.6, 163.1, 162.2, 141.5, 138.5, 132.4, 129.9, 129.5, 129.0, 128.9, 128.7, 128.6, 128.4, 128.3, 127.9, 122.9, 100.1, 52.9, 52.7, 52.5, 51.7, 51.4, 50.1. HRMS (EI): *m*/*z* calcd for $C_{28}H_{28}O_{10}$ 524.1683, found 524.1685.

6,7-Bis(4-chlorophenyl)-2,2,9,9-tetramethoxy-8-oxo-1-oxaspiro-[4.4]nona-3,6-diene-3,4-dicarboxylic Acid Dimethyl Ester (10c). 3,4-Dichlorophenylcyclobutene-1,2-dione **9c** (100 mg, 0.33 mmol), DMAD **2** (70 mg, 0.49 mmol), and oxadiazoline **3** (106 mg, 0.66 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; 80:20 hexane/EtOAc) to give the spirodihydrofuran **10c** as a yellow oil. R_f: 0.20 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max} 3000, 2958, 2850, 1732, 1671, 1635, 1593, 1439, 1351, 1336, 1284, 1171, 1124. ^{1}H NMR: δ 7.23−7.17 (m, 8H), 3.87 (s, 3H), 3.75 (s, 3H), 3.57 (s, 6H), 3.51 (s, 3H), 2.65 (s, 3H). ^{13}C NMR: δ 195.0, 162.9, 162.1, 132.7, 131.7, 131.5, 131.4, 131.0, 130.1, 129.9, 129.5, 129.2, 128.9, 128.7, 128.5, 128.4, 128.3, 123.3, 100.2, 53.3, 53.0, 52.8, 52.9, 51.9, 51.8. HRMS (FAB): (M + 2 + H$^+$) calcd for $C_{28}H_{26}Cl_2O_{10}$ 595.0903, found 595.0900.

6,7-Bis(4-bromophenyl)-2,2,9,9-tetramethoxy-8-oxo-1-oxaspiro-[4.4]nona-3,6-diene-3,4-dicarboxylic Acid Dimethyl Ester (10d). 3,4-Dibromophenylcyclobutene-1,2-dione **9d** (100 mg, 0.26 mmol), DMAD **2** (55 mg, 0.39 mmol), and oxadiazoline (83 mg, 0.52 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; 80:20 hexane/EtOAc) to give the spirodihydrofuran **10d** as a yellow oil. R_f: 0.16 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2959, 2923, 2850, 1743, 1681, 1650, 1599, 1444, 1279, 1135, 1063. ^{1}H NMR: δ 7.23−7.17 (m, 8H), 3.87 (s, 3H), 3.76 (s, 3H), 3.57 (s, 6H), 3.51 (s, 3H), 2.66 (s, 3H). ^{13}C NMR: δ 195.0, 162.9, 162.2, 132.7, 131.6, 131.5, 131.5, 131.1, 130.2, 129.9, 129.8, 129.4, 129.2, 128.9, 128.8, 128.5, 128.5, 128.3, 123.2, 100.2, 53.2, 53.1, 52.9, 52.8, 51.9, 51.8. HRMS (FAB): (M + 2 + H$^+$) calcd for $C_{28}H_{26}Br_2O_{10}$ 682.9893, found 682.9899.

6,7-Bis(4-bromophenyl)-2,2,9,9-tetramethoxy-8-oxo-1-oxaspiro-[4.4]nona-3,6-diene-3,4-dicarboxylic Acid Dimethyl Ester (10e). 3,4-Dimethoxyphenylcyclobutene-1,2-dione **9e** (100 mg, 0.34 mmol), DMAD **2** (72 mg, 0.72 mmol), and oxadiazoline **3** (109 mg, 0.68 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; 80:20 hexane/EtOAc) to give the spirodihydrofuran **10e** as a yellow oil. R_f: 0.11 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2954, 2928, 2850, 1743, 1681, 1604, 1501, 1434, 1326, 1248, 1181, 1032. ^{1}H NMR: δ 7.26−7.23 (m, 2H), 7.15−7.13 (m, 2H), 6.90 (d, 2H, J = 8.3), 6.75 (d, 2H, J = 8.5), 3.93−3.87 (m, 6H), 3.83−3.79 (m, 4H), 3.77−3.72 (m, 6H), 3.66−3.60 (m, 5H), 3.00 (s, 3H). ^{13}C NMR: δ 195.1, 166.7, 165.3, 160.4, 160.1, 152.9, 145.3, 130.9, 130.8, 130.7, 129.5, 123.6, 120.8, 115.2, 114.4, 113.9, 113.8, 113.7, 110.3, 100.2, 55.2, 55.0, 53.2, 53.0, 52.8, 51.9, 51.7. HRMS (FAB): (M + H$^+$) calcd for $C_{30}H_{32}O_{12}$ 585.1894, found 585.1890.

2,2-Dimethoxy-4,5-dithien-2-ylcyclopent-4-ene-1,3-dione (12). 3,4-Dithienylcyclobutene 1,2-dione **11** (100 mg, 0.26 mmol), DMAD **2** (56 mg, 0.39 mmol), and oxadiazoline **3** (83 mg, 0.52 mmol) in dry toluene (2 mL) were degassed and heated in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; 90:10 hexane/EtOAc) to give the product **12** as a yellow oil. R_f: 0.38 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2923, 2856, 1702, 1645, 1583, 1506, 1454, 1402, 1372, 1089. ^{1}H NMR: δ 7.85 (d, 2H, J = 3.78), 7.68 (d, 2H, J = 4.98), 7.14 (t, 2H, J = 4.23), 3.64 (s, 6H). ^{13}C NMR: δ 193.4, 140.9, 132.9, 132.6, 129.2, 127.6, 109.6, 51.8, 29.8. HRMS (EI): *m*/*z* calcd for $C_{15}H_{12}O_4S_2$ 320.0177, found 320.0171.

Spiro[1′-methylindole-1(2*H*)-4-dimethoxy-2,3-bis(methoxycarbonyl)furan]-2-one (14a). A mixture of **13a** (50 mg, 0.31 mmol), DMAD **2** (132.06 mg, 0.93 mmol), and oxadiazoline **3** (198 mg, 1.24 mmol) was refluxed in dry toluene (2 mL) in sealed tube for 24 h.The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; neutralized by adding triethylamine) using 70:30 hexane/EtOAc to give the product **14a** as a yellow oil. R_f: 0.35 (3:7 ethyl acetate/hexanes). IR (KBr) ν_{max}: 2945, 2850, 1745, 1678,1602, 1457, 1270,1162, 1055 cm^{-1}. ^{1}H NMR: δ 7.37−6.83 (m, 4H), 3.91 (s, 3H), 3.65 (s,3H), 3.62 (s, 3H), 3.43 (s, 3H), 3.25 (s, 3H). ^{13}C NMR: δ 171.1, 162.2, 160.0, 143.6, 140.5, 130.8, 126.5, 125.0, 124.9, 123.1, 108.6, 86.0, 53.2, 52.8, 52.8, 52.5, 52.4, 51.9, 50.6, 50.6, 50.6, 26.5. HRMS (EI): *m*/*z* calcd for $C_{18}H_{19}NO_8$ 377.1111, found 377.1115.

Spiro[1′-ethylindole-1(2*H*)-4-dimethoxy-2,3-bis(methoxycarbonyl)furan]-2-one (14b). A mixture of **13b** (50 mg, 0.28 mmol), DMAD **2** (119 mg, 0.84 mmol), and oxadiazoline **3** (179. mg, 1.24 mmol) was refluxed in dry toluene (2 mL) in sealed tube for 24 h. The solvent was removed on a rotary evaporator and the residue was purified by column chromatography (silica gel, 100−200 mesh; neutralized by adding triethylamine) using 70:30 hexane/EtOAc to give the product **14b** (55 mg, 50%) as a yellow oil. R_f: 0.32 (3:7 ethyl acetate/hexanes). IR (neat) ν_{max}: 2948, 2847, 1730, 1681, 1613, 1485, 1465, 1249, 1150, 1051 cm^{-1}. ^{1}H NMR: δ 7.33−6.84 (m, 4H), 3.91 (s, 3H), 3.49 (s, 3H), 3.14 (q, 2H), 1.31 (t, 3H). ^{13}C NMR: δ 171.2, 162.4, 160.1, 143.7, 140.6, 136.3, 130.9, 126.6, 125.1, 125.0, 123.3, 108.8, 85.4, 53.4, 53.1, 52.7, 50.8, 35.2, 12.5. HRMS (EI): *m*/*z* calcd for $C_{19}H_{21}NO_8$ 391.1267 found 391.1269.

Spiro[1′-propylindole-1(2*H*)-4-dimethoxy-2,3-bis(methoxycarbonyl)furan]-2-one (14c). A mixture of **13c** (50 mg, 0.26 mmol), DMAD **2** (111 mg, 0.78 mmol), and oxadiazoline **3** (166. mg, 1.04 mmol) was refluxed in dry toluene (2 mL) in sealed tube for 24h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh; neutralized by adding triethylamine) using 70:30 hexane/EtOAc to give the product **14c** (53 mg, 50%) as yellow oil. R_f: 0.35 (3:7 ethyl acetate/hexanes). IR (neat) ν_{max}: 2955, 2890, 2850, 1730, 1681, 1613, 1472, 1450, 1310, 1250, 1190, 1050 cm^{-1}. ^{1}H NMR: δ 7.3−6.78 (m, 4H), 3.85 (s, 3H), 3.71 (t, 2H), 3.70 (s, 3H), 3.55 (s, 3H), 3.43 (s, 3H), 1.66 (sextet, 2H), 0.99 (s, 3H). ^{13}C NMR: δ 171.9, 162.9, 160.7, 135.7, 130.3,128.9, 126.9, 123.8, 120.1, 109.6, 86.4, 55.9, 54.6, 51.9, 51.7, 35.1, 15.6, 12.3. HRMS (EI): *m*/*z* calcd for $C_{20}H_{23}NO_8$ 405.1424, found 405.1420.

Spiro[1′-benzylindole-1(2*H*)-4-dimethoxy-2,3-bis(methoxycarbonyl)furan]-2-one (14d). A mixture of **13d** (50 mg, 0.21 mmol), DMAD **2** (89 mg, 0.63 mmol), and oxadiazoline **3** (134. mg, 0.84 mmol) was refluxed in dry toluene (2 mL) in a sealed tube for 24

h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh, neutralized by adding triethylamine) using 70:30 hexane/EtOAc to give the product **14d** (46 mg, 48%) as yellow oil. R_f: 0.37 (3:7 ethyl acetate/hexanes). IR (neat) ν_{max}: 2955, 2847, 1742, 1679, 1620, 1495, 1445, 1256, 1182, 1128, 980 cm^{-1}. ^{1}H NMR: δ 7.33−7.16 (m, 7H), 5.12 (d, 1H, J = 9 Hz), 4.66 (d, 1H, J = 15 Hz), 3.84 (s, 3H), 3.60 (s, 3H), 3.44 (s, 3H), 3.43 (s, 3H). ^{13}C NMR: δ 171.7, 162.2, 160.1, 143.7, 140.8, 136.2, 135.5, 130.8, 128.8, 127.3, 127.6, 126.4, 125.0, 124.7, 123.3, 109.6, 86.4, 53.2, 52.8, 52.5, 51.8, 50.7. HRMS (EI): *m*/*z* calcd for $C_{24}H_{23}NO_8$ 453.1424, found 453.1428.

Spiro[1′-methyl-5-bromoindole-1(2*H*)-4-dimethoxy-2,3-bis-(methoxycarbonyl)furan]-2-one (14e) and 5-Bromo-1-methyl-3-carbomethoxy-3-hydroxyindol-2-one (15e). A mixture of **13e** (50 mg, 0.21 mmol), DMAD **2** (89 mg, 0.63 mmol), and oxadiazoline **3** (134. mg, 0.84 mmol) was refluxed in dry toluene (2 mL) in sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel, 100−200 mesh neutralized by adding triethylamine) using ethyl acetate/hexane solvent mixture to afford the products in increasing polarities. Elution with 85:15 hexane/EtOAc gave the product **15e** (27 mg, 48%) as colorless oil. R_f: 0.42 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 3451, 2954, 2650, 1734, 1618, 1470, 1347, 1260, 1152, 1113, 1105, 980 cm^{-1}. ^{1}H NMR: δ 7.85−7.82 (m, 1H), 7.41−7.38 (m, 1H), 6.49 (d, 1H, J = 9 Hz), 3.68 (s, 3H). ^{13}C NMR: δ 171.83, 159.22, 133.88, 131.46, 128.26, 121.64, 116.41, 107.68, 85.72, 52.68, 26.25. HRMS (EI): *m*/*z* calcd for $C_{12}H_{13}NO_3$ 270.9844, found 270.9840. Further elution with 70:30 hexane/ethyl acetate yielded the product **14e** (31 mg, 32%) as a yellow oil. R_f: 0.80 (3:7 ethyl acetate/hexanes). IR (neat) ν_{max}: 2949, 2846, 1744, 1678, 1609, 1485, 1444, 1227, 1279, 980 cm^{-1}. ^{1}H NMR: δ 7.25−7.22 (m, 2H), 6.48−6.40 (m, 1H), 3.81 (s, 3H), 3.69 (s, 3H), 3.62 (s, 3H), 3.40 (s, 3H), 3.25 (s, 3H). ^{13}C NMR: δ 171.1, 162.1, 160.0, 142.6, 141.5, 130.7, 126.6, 125.0, 124.9, 52.7, 52.5, 51.8, 50.7, 50.6, 26.5. HRMS (EI): *m*/*z* calcd for $C_{18}H_{18}BrNO_8$ 455.0216, found 455.0218.

6,6-Dimethoxydibenzo[*a*,*c*]cycloheptene-5,7-dione (17) and Spiro[phenanthrene-1(2*H*)-4-dimethoxy-2,3-bis(methoxycarbonyl)furan]-2-one (18). A mixture of **16** (100 mg, 0.48 mmol), DMAD **2** (102 mg, 0.72 mmol), and oxadiazoline **3** (154. mg, 0.96 mmol) were refluxed in dry toluene (2 mL) in a sealed tube for 24 h. The solvent was removed on a rotary evaporator, and the residue was purified by column chromatography (silica gel 100−200 mesh, neutralized by adding triethylamine) using 70:30 hexane/ethyl acetate solvent mixture to afford the products in increasing order of polarities. Elution with hexane gave the product **17** (77 mg, 57%) as an amorphous solid. R_f: 0.41 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2921, 2850, 1667, 1607, 1482, 1380, 1250, 1130, 1100, 1031, 750, 980 cm^{-1}. ^{1}H NMR: δ 8.57 (d, J = 8.26 Hz, 2H), 7.92−7.89 (m, 2H), 7.57−7.4 (m, 4H), 3.5 (s, 6H). ^{13}C NMR: δ 197.6, 136.4, 132.9, 127.2, 126.7, 124.2, 123.3, 54.7, 52.1. HRMS (EI): *m*/*z* calcd for $C_{17}H_{14}O_4$ 282.0892, found 282.0899. Further elution with 90:10 hexane/ethyl acetate afforded the product **18** as a colorless liquid (21 mg, 10%). R_f: 0.33 (3:7 ethyl acetate/hexanes). IR (thin film) ν_{max}: 2955, 2850, 1742, 1694, 1600, 1380, 1120, 1010, 985 cm^{-1}. ^{1}H NMR: 7.99−7.88 (m, 3H), 7.64−7.53 (m, 2H), 7.40−7.27 (m, 3H), 3.83 (s, 3H), 3.49 (s, 3H), 3.4 (s, 3H), 3.35 (s, 3H). ^{13}C NMR: 191.2, 162.9, 160.3, 147.6, 134.0, 132.9, 129.5, 128.5, 127.1, 124.1, 113.5, 110.8, 108.1, 53.8, 52.9, 52.5, 51.9, 50.2. HRMS (EI): *m*/*z* calcd for $C_{23}H_{20}O_8$ 424.1158, found 424.1179.

(5*S*)-Dimethyl-2, 2-dimethoxy-7-oxo-1, 6-dioxaspiro[4.4]nona-3, 8-diene-3,4-dicaboxylate (20). A mixture of maleic anhydride **19** (100 mg, 1 mmol), DMAD **2** (217 mg, 1.5 mmol), and oxadiazoline **3** (326 mg, 2 mmol) was refluxed in dry toluene in a sealed tube for 24 h. The solvent was removed under vacuum and the residue subjected to chromatography on a silica gel column using 80:20 hexanes−ethyl acetate solvent mixture to afford **20** as a yellow viscous liquid (211 mg, 68%). IR (neat) ν_{max}: 3117, 2969, 2854, 1802, 1731, 1725, 1687, 1452, 1161, 906, 467 cm^{-1}. ^{1}H NMR: δ 7.17 (d, J = 5.5, 1H), 6.32 (d, J = 5.52, 1H), 3.9 (s, 3H), 3.76 (s, 3H), 3.51 (s, 3H) 3.46 (s, 3H). ^{13}C NMR: δ 168.4, 161.1, 160.4, 143.5, 142.4, 132.5, 124.5,122.8, 109.4, 53.7, 52.9, 51.0, 50.4. HRMS (EI): *m*/*z* calcd for $C_{13}H_{14}O_9$ 314.0638, found 314.0639.

(5*R*)-Dimethyl 8,9-dichloro-2,2-dimethoxy-7-oxo-1,6-dioxaspiro-[4.4]nona-3,8- diene-3,4-dicarboxylate (22). A mixture of dichloromaleic anhydride **21** (100 mg, 0.59 mmol), DMAD **2** (126 mg, 0.89 mmol), and oxadiazoline **3** (190 mg, 1.19 mmol) was refluxed in dry toluene in a sealed tube for 24 h. The solvent was removed under vacuum and the residue subjected to chromatography on a silica gel column using 80:20 hexanes−ethyl acetate solvent mixture to afford **22** as a yellow viscous liquid (66 mg, 29%). IR (neat) ν_{max}: 3006, 2965, 2862, 1806, 1765, 1744, 1738, 1681, 1651, 1444, 1294, 1243, 1144, 968, 886, 793, 751 cm^{-1}. ^{1}H NMR: δ 3.92 (s, 3H) 3.84(s, 3H), 3.55(s, 3H), 3.50 (s,3H). ^{13}C NMR: δ 165.3, 161.5, 160.8, 147.0, 145.0, 130.0, 124.3, 123.8, 107.6, 53.2, 53.1, 52.6, 51.7. HRMS (EI): *m*/*z* calcd for $C_{13}H_{12}Cl_2O_9$ 381.9858, found 381.9850.

(5*S*)-Dimethyl 2,2-Dimethoxy-7-oxo-1,6-dioxaspiro[4.4]non-3-ene-3,4-dicarboxylate (24). A mixture of succinic anhydride **23** (100 mg, 0.99 mmol), DMAD **2** (212 mg, 1.4 mmol), and oxadiazoline **3** (319 mg, 1.9 mmol) was refluxed in dry toluene in a sealed tube for 24 h. The solvent was removed under vacuum, and the residue subjected to chromatography on a silica gel column using 80:20 hexanes−ethyl acetate solvent mixture to afford **24** as a yellow viscous liquid (200 mg, 65%). IR (neat) ν_{max}: 2975, 2854, 1742, 1739, 1452, 1249, 1202, 1148, 980, 906, 798, 683, 427. ^{1}H NMR: δ 3.89 (s, 3H), 3.83 (s, 3H), 3.43 (s, 3H), 3.42 (s, 3H), 2.96−2.71 (m, 3H), 2.48−2.34(m, 1H). ^{13}C NMR: δ 173.7, 161.5, 159.9, 141.3, 134.0, 122.5, 111.0, 52.8, 52.7, 52.0, 50.9. HRMS (EI): *m*/*z* calcd for $C_{13}H_{18}O_9$ 316.0794, found 316.0798.

(1′*S*)-Dimethyl 5,5-Dimethoxy-3′-oxospiro[furan-2(5*H*),1′-[1*H*,3*H*]naphtho[1,8-*cd*]pyran]-3,4-dicarboxylate (26). A mixture of 1,8-naphthoic anhydride **25** (100 mg, 0.5 mmol), DMAD **2** (107 mg, 0.75 mmol), and oxadiazoline **3** (161 mg, 1 mmol) was refluxed in dry toluene in a sealed tube for 24 h. The solvent was removed under vacuum and the residue subjected to chromatography on a silica gel column using 80:20 hexanes−ethyl acetate solvent mixture to afford **26** as a white solid (181 mg, 86%). Mp: 164−165 °C. IR (KBr) ν_{max}: 2955, 2871, 1742, 1738, 1682, 1589, 1439, 1300, 1263, 1196, 1134, 1056, 1031, 958, 901, 793, 720 cm^{-1}. ^{1}H NMR: δ 8.48 (d, J = 6.93, 1H), 8.16 (d, J = 8.22, 1H), 7.99 (d, J = 7.58, 1H), 7.70−7.60 (m, 3H), 3.93 (s, 3H), 3.66 (s, 3H), 3.51 (s, 6H). ^{13}C NMR: δ 161.6, 161.2, 159.5, 140.1, 135.7, 133.7, 131.5, 129.9, 129.1, 127.4, 127.1, 126.6, 126.2, 125.2, 123.2, 118.8, 108.1, 52.8, 52.7, 52.3, 50.7. HRMS (EI): *m*/*z* calcd for $C_{21}H_{18}O_9$ 414.0951, found 414.0950.

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Supporting Information Available: ^{1}H and ^{13}C NMR spectra of all new compounds and crystallographic data of compounds **4a** and **10a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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