Pergamon

SCIENCE DIRECT®

Tetrahedron Letters 44 (2003) 8103–8107

TETRAHEDRON
LETTERS

Regioselectivity of *E*/*Z* photoisomerization of fluorinated cisoid (1*E*,3*E*)-1,4-diphenylbutadienes via direct irradiation☆

Jin Liu,* Eric L. Suits and Kelly J. Boarman

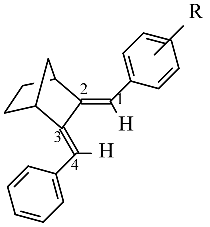
Department of Chemistry, Murray State University, Murray, KY, 42071, USA

Received 24 August 2003; revised 4 September 2003; accepted 4 September 2003

Abstract—Direct irradiation of the 1*E*,3*E* isomers of six cisoid fluorinated butadienes in an organic solvent at room temperature showed a predominant formation of the 1*Z*,3*E* isomers.

The mechanisms of photo-induced *cis*/*trans* isomerization of arylethenes such as stilbenes have been extensively investigated during the past four decades.[1] The photochemical and photophysical properties of arylethenes have been well understood.[2] As compared to the number of studies of arylethenes, only a few studies of photoisomerization of 1,4-diphenyl-1,3-butadienes have been reported,[3] due to the complexity caused by the existence of three *E*/*Z* isomers. In 1988, Yee and his co-workers[4] reported their findings on direct and sensitized photoisomerization of 1,4-diphenyl-1,3-butadienes. In 1995, Kauffman and his co-worker[5] investigated solvent effects on direct photoisomerization of 1,4-diphenyl-1,3-butadienes. Photoisomerization of (*E*,*E*)-1,4-diphenyl-1,3-butadiene gives only one (*E*,*Z*)-isomer, because of the equivalence of two aryl groups in its structure. However, photoisomerization will produce two different isomers (1*Z*,3*E*) and (1*E*,3*Z*) when two aryl groups are not identical in the structures of phenyl-substituted 1,4-diphenyl-1,3-butadienes. Photoisomerization will be a useful synthetic method, if the (*E*,*E*)-isomer of a substituted 1,4-diphenyl-1,3-butadiene could be selectively converted to one of its *E*,*Z* isomers. Nevertheless, our current understanding of regioselectivity of *E*/*Z* photoisomerization of unsymmetrically substituted 1,4-diphenyl-1,3-butadienes is very limited.[6]

Previous studies[7,8] have found that major products of photoisomerization of 1,3-butadienes in the excited singlet state are single bond s-*cis*/s-*trans* and double bond *cis*/*trans* isomerizations. In order to better focus on studies of double bond *cis*/*trans* isomerization, we chose a cisoid 1,4-diphenyl-1,3-butadiene system,[9,10] in which a conjugated diene was locked. To differentiate between the two phenyl rings that were attached to the conjugated diene, at lease one of the rings was substituted with an electron-withdrawing or electron-donating group.[11] Herein, we report our results observed in the *E*/*Z* photoisomerization of unsymmetrically substituted cisoid (1*E*,3*E*)-1,4-diphenylbutadienes by direct irradiation.



R = -2,3,4,5,6-pentafluoro (**1**),
-2,3,5,6-tetrafluoro (**2**),
-3,5-difluoro (**3**),
-4-fluoro (**4**).

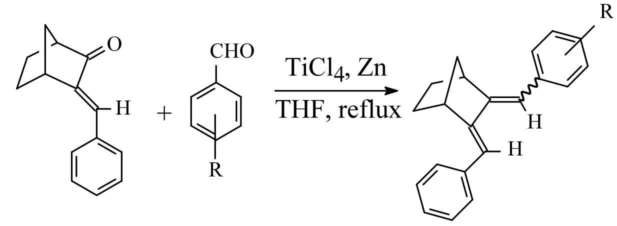
First, four fluorinated cisoid butadienes (**1**–**4**) were synthesized. Symmetrical cisoid 1,4-diphenyl-1,3-butadienes were prepared by Liu et al. in 1997 using the Wittig reaction of a conjugated enone in Scheme 1 with benzylidenetriphenylphosphorane.[9] Due to the relative low yield of the Wittig reaction, preparation of the unsymmetrical 1,4-diphenyl-1,3-butadienes was achieved by means of the McMurry reaction.[10] The enone prepared from the Aldol condensation of racemic norcamphor with benzaldehyde was coupled with pentafluorobenzaldehyde to produce compound **1** (in ca. 30% yield) and two dimers, which were formed from dimerization of pentafluorobenzaldehyde and the

---

[☆] Supplementary data associated with this article can be found at doi:10.1016/j.tetlet.2003.09.043

[*] Corresponding author. Fax: 270-762-6474; e-mail: jin.liu@murraystate.edu

0040-4039/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2003.09.043



A conjugated enone

1, 2, 3, 4

Scheme 1.

enone, respectively.[12] Compound **1** contained two stereoisomers in a ratio of 95:5. The two isomers as white solids were separated by silica gel column chromatography. The same synthetic approach was used for the preparation of the cisoid butadienes **2**–**4**.

To properly assign the *E*/*Z* configuration of the isomers, the major isomers of compounds **1** and **2** were recrystallized from ethyl acetate to give crystals that were suitable for X-ray crystallographic studies. The *E* configuration of the double bonds in the two structures was confirmed by crystal structures (Figs. 1 and 2).[13] Therefore, it was deduced that the minor isomers of **1** and **2** from the synthesis were the 1*Z*,3*E* isomers. Also, the two X-ray crystal structures indicate that the average bond length of the carbon–carbon double bonds of the cisoid 1,3-butadienes is ca. 1.34 Å. The average bond length of the central carbon–carbon single bonds, which attaches to the two carbon double bonds, is ca. 1.49 Å.

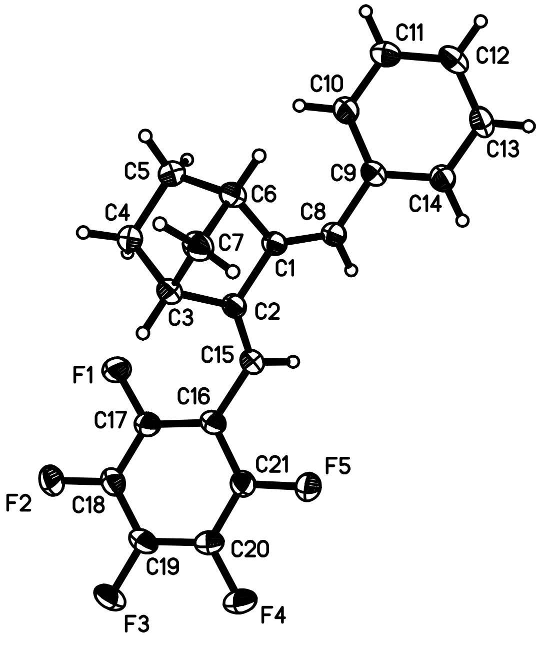


Figure 1. The X-ray structure of the (1*E*,3*E*)-isomer of **1** at 173 K.

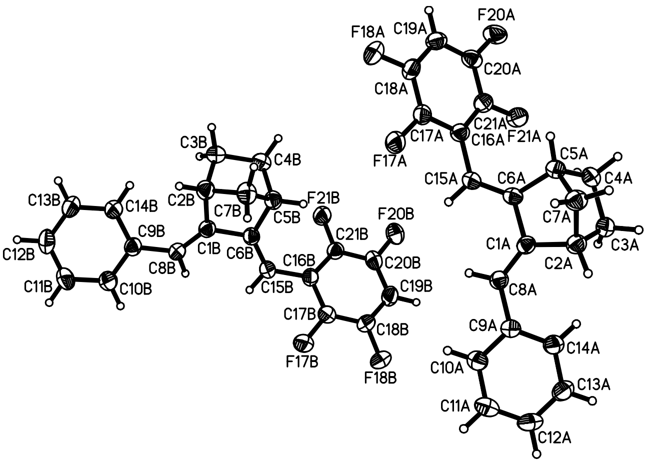
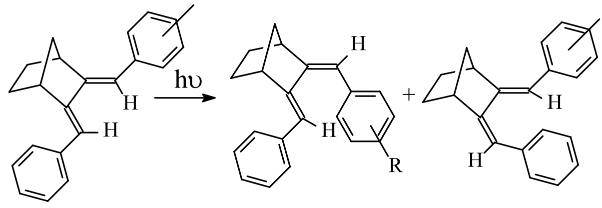


Figure 2. The X-ray structure of the (1*E*,3*E*)-isomer of **2** at 173 K; a pair of the enantiomers was found in the asymmetric unit.

^{1}H NMR spectra of the (1*E*,3*E*) and (1*Z*,3*E*) isomers of compound **1** indicates the vinyl-H resonances of the (1*E*,3*E*)-isomer are shifted downfield relative to those of the (1*Z*,3*E*)-isomer. A similar pattern was found from the ^{1}H NMR study of the two isomers of **2**. Also, UV-vis absorptions of the two 1*E*,3*E* isomers of compounds **1** and **2** are appreciably red-shifted from those of the 1*Z*,3*E* isomers. Because suitable single crystals of compounds **3** and **4** were not obtained, the correct configuration of the 1*E*,3*E* isomers of **3** and **4** was assigned by comparing the downfield shifts of the vinyl Hs and the red-shifted UV absorptions of the 1*E*,3*E* isomers to those of the corresponding 1*Z*,3*E* isomers (see the Supplementary Data).

Direct irradiation of the cisoid butadienes (**1**–**4**) in chloroform-*d* was carried out using a 200 W Hanovia medium pressure mercury lamp with the Corning glass filter O-52 (>340 nm light) (Scheme 2). In Figure 3, the progress of direct photoisomerization of the (1*E*,3*E*)-isomer (**1**) is illustrated. During the reaction, ^{1}H NMR spectra were recorded every 15 min until no further change was observed. The photoisomerization of the (1*E*,3*E*)-isomer to the (1*Z*,3*E*)-isomer was indicated by the decreasing intensity of two norbornyl bridgehead-H signals of (1*E*,3*E*) at δ 3.48 and 2.88, and the increasing intensity of two bridgehead-H signals of (1*Z*,3*E*) at δ 3.41 and 3.03. The very low intensity of two proton resonances at δ 2.93 and 2.78 indicated the barely formed (1*E*,3*Z*)-isomer at the end of the photo-reac-



(1*E*,3*E*)-isomer (1*Z*,3*E*)-isomer (1*E*,3*Z*)-isomer

1, 2, 3, 4

Scheme 2.

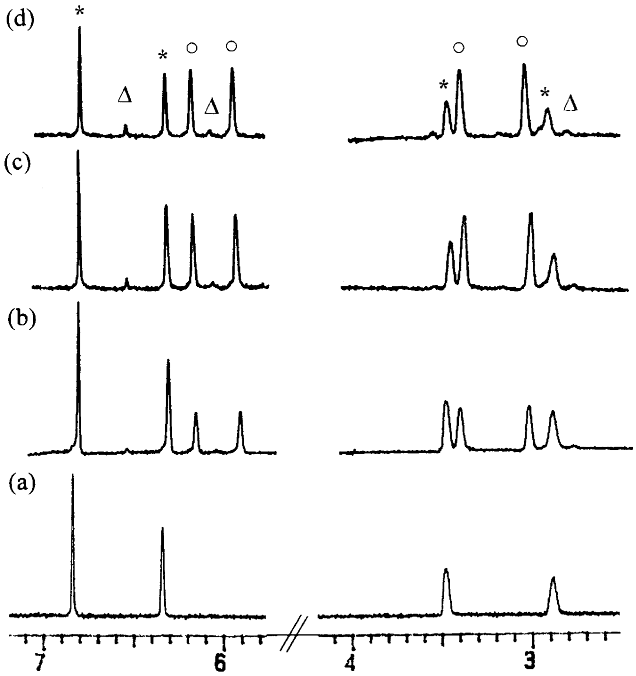


Figure 3. ^{1}H NMR spectra (a)–(d) were recorded at irradiation time 0, 15, 30, 45 min. Symbols (*), (○) and (Δ) are used for the signals from the (1*E*,3*E*)-isomer, the (1*Z*,3*E*)-isomer and the (1*E*,3*Z*)-isomer, respectively.

tion. After the irradiation, the remaining (1*E*,3*E*)-isomer in the mixture was isolated by silica gel column chromatography, and the photo-conversion yield (73.5%) of the *E*,*E* isomer (**1**) to the *E*,*Z* isomers was determined. The two *E*,*Z* isomers, partially separated by column chromatography, were further purified by preparative HPLC. The (1*Z*,3*E*)/(1*E*,3*Z*) ratio of **1** was determined to be 26:1. In Figure 4, the UV-vis absorption spectra of the three isomers (**1**) are shown. The results from the direct irradiation of **1** indicated the preferred *E*/*Z* photoisomerization at the carbon–carbon double bond on the pentafluorophenyl side. Other organic solvents such as benzene-d_6 and hexafluorobenzene were found to have little effect on the regioselectivity of the photoisomerization. Different concentrations of **1** in chloroform-*d* (0.002~0.015 M) had no influence on the observed regioselectivity.

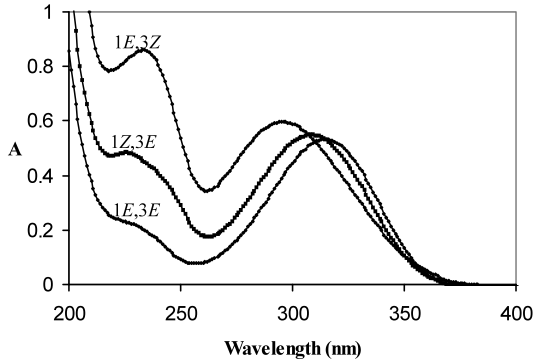
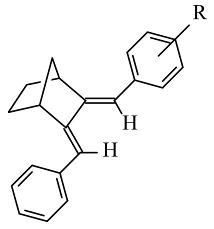


Figure 4. Absorption spectra of three *E*/*Z* isomers (**1**) in hexanes.

The *E*/*Z* photoisomerization of **2**–**4** was studied under the same photoirradiation conditions, and the results also showed the preferred isomerization at the carbon–carbon double bonds connected with the fluorinated phenyl rings. However, the ratios of (1*Z*,3*E*)/(1*E*,3*Z*) of **2**, **3**, **4** were 23:1, 13:1 and 1.5:1, respectively (Table 1). The gradually decreasing selectivity appears to be related to the number of F-substituents on the phenyl rings.

Some substituent effects on photochemistry of stilbene[14–16] and 1,4-diphenyl-1,3-butadiene[17] were reported in the literature. The photochemical behavior of **1**–**4** by direct irradiation is clearly sensitive to the F-substituents on the phenyl rings. Although the average bond length of the carbon–carbon double bonds connecting with the fluorinated rings is the same as that of the double bonds with the phenyl rings, the two types of double bonds are not the same in the excited singlet state.[18] The strong electron-withdrawing effect of fluorine substituents weakens the carbon–carbon double bonds facilitating the isomerization process. The results from **1**–**3** demonstrate the strong isomerization preference for the carbon–carbon double bonds closer to the F-substituents. The mono-fluorinated case (**4**) shows a low selectivity (1.5:1), as the number of fluorine substituents decreases.



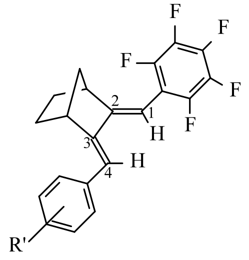
R = -4-CH_3 (**5**);
-2-CH_3 (**6**);
-4-OCH_3 (**7**);
-2,4,6-trimethoxy (**8**).

To further confirm the electron-withdrawing fluorine effect on the regioselectivity, we prepared unsymmetrical non-fluorinated compounds (**5**–**8**). The (1*E*,3*E*)-isomers and the (1*Z*,3*E*)-isomers of **5**–**8** were prepared using the same synthetic approach, and the structures were fully characterized. Interestingly, the two *E*,*Z* isomers of **5**–**6** in an almost equal amount were obtained from the photoisomerization of the (1*E*,3*E*)-isomers of **5**–**6** by direct irradiation (Table 1). The results were in agreement with our earlier observation from **4**. Surprisingly, the *E*/*Z* photoisomerization of **7**–**8** under the same irradiation conditions was not observed, and the starting materials were recovered. The unexpected observation might indicate that the strong electron-donating methoxy groups strengthened the carbon–carbon double bonds of **7**–**8** in the excited singlet states.

The different photochemical properties of **7** and **8** prompted us to prepare two unsymmetrically substituted cisoid butadienes with substituents on both of the phenyl rings (**9**–**10**). Figure 5 shows UV-vis absorption spectra of the 1*E*,3*E* isomers of **7**–**10** in hexanes, illustrating the similar absorption bands of **7**–**10**. Under the same irradiation conditions, the *E*/*Z* photoisomerization of **9** and **10** was not only found, but the regioselec-

Table 1. The percentages of three E/Z isomers at the end of photoisomerization of the (1E,3E)-isomers of **1**–**10**

Compound	(1E,3E) (%)	(1Z,3E) (%)	(1E,3Z) (%)	(1Z,3E)/(1E,3Z) ratio
1	26.6	70.8	2.7	26:1
2	33.3	63.9	2.8	23:1
3	41.7	54.2	4.1	13:1
4	50.0	30.0	20.0	1.5:1
5	88.2	5.9	5.9	1:1
6	32.6	34.8	32.6	1.1:1
7	>99	0	0	–
8	>99	0	0	–
9	47.4	42.1	10.5	4:1
10	45.0	51.0	4.0	13:1



R' = -2,4,6-trimethoxy (**9**);
-4-methoxy (**10**).

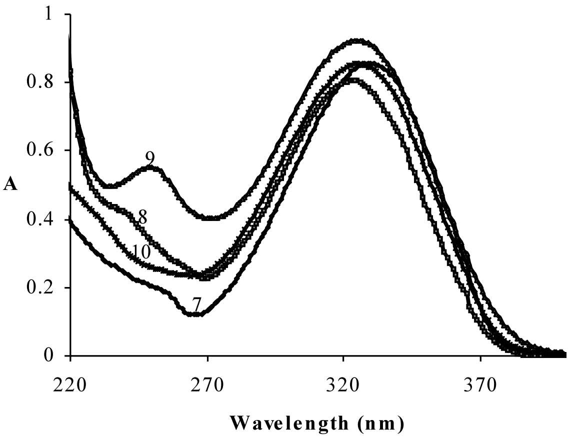


Figure 5. Absorption spectra of compounds **7**–**10** in hexanes.

tivity of the photoisomerization was also regained (Table 1). The photo-conversion yields of 1E,3E isomers of **9**–**10** were about the same (53% and 55%). However, the (1Z,3E)/(1E,3Z) ratio of **10** was higher than that of **9**. In the case of **10**, the better selectivity was due to the fact that the electron-withdrawing effect of F-substituents was much stronger than the electron-donating effect of the single methoxy group. Thus, we believe that the methoxy groups strengthened the carbon–carbon double bonds of **7**–**8** in the excited singlet states.

In summary, we demonstrate that electron-withdrawing F-substituents and electron-donating methoxy groups have significant effects on the regioselectivity of the E/Z photoisomerization of unsymmetrically substituted (1E,3E)-1,4-diphenylbutadienes by direct excitation. Other substituent effects as well as medium effects[19] on direct photoisomerization of these cisoid 1,4-diphenyl-1,3-butadienes, and the role of substituents on photoisomerization mechanisms of butadienes[20] are under investigation.

Supplementary material

Representative procedures and spectroscopic data for new compounds are included in Supplementary Data, which is available on the web.

Acknowledgements

This work was supported by grants from Kentucky NSF EPSCoR and Howard Hughes Medical Institution. We thank Drs. William W. Brennessel and Victor G. Young, Jr at Department of Chemistry, University of Minnesota, for the X-ray crystallographic studies of **1** and **2**.

References

1. Saltiel, J.; Charlton, J. L. In *Rearrangments in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. 3, pp. 25–89.
2. Waldeck, D. H. *Chem. Rev.* **1991**, *91*, 415–436.
3. Allen, M. T.; Whitten, D. G. *Chem. Rev.* **1989**, *89*, 1691–1702.
4. Yee, W. A.; Hug, S. J.; Kliger, D. S. *J. Am. Chem. Soc.* **1988**, *110*, 2164–2169.
5. Anderton, R. M.; Kauffman, J. F. *J. Phys. Chem.* **1995**, *99*, 14628–14631.
6. Liu, R. S. H.; Hammond, G. S. *Proc. Natl. Acad. Sci. USA* **2000**, *97*, 11153–11158.

7. Olivucci, M.; Ragazos, I. N.; Bernardi, F.; Robb, M. A. *J. Am. Chem. Soc.* **1993**, *115*, 3710–3721.
8. Squillacote, M.; Semple, T.; Chen, J.; Liang, F. *Photochem. Photobiol.* **2002**, *76*, 634–639.
9. Liu, J.; Liu, R. S. H.; Simmons, C. J. *Tetrahedron Lett.* **1997**, *38*, 3999–4002.
10. Liu, J.; Murray, E. M.; Young, V. G., Jr. *Chem. Commun.* **2003**, 1904–1905.
11. Muszkat, K. A.; Castel, N.; Jakob, A.; Fischer, E.; Luettke, W.; Rauch, K. *J. Photochem. Photobiol. A: Chem.* **1991**, *56*, 219–226.
12. It was reported that pentafluorobenzaldehyde decomposed with the titanium reagent (Ref. 11). Compound **1** was stable under the reaction conditions.
13. Crystal data. The (1*E*,3*E*)-isomer of **1**, $C_{21}H_{15}F_5$, M= 362.34, monoclinic, space group: $P2_1/c$; a=11.867(1) Å, b=10.0392(9) Å, c=14.179(1) Å, α=90°, β=103.472(2)°, γ=90°, V=1642.7(3) Å^3, Z=4, D_{calc}=1.465 Mg/m^3, μ= 0.124 mm^{-1} R1=0.0348 for 3235 data [I>2s(I)] and =0.0417 for all 3773 data. The (1*E*,3*E*)-isomer of **2**, $C_{21}H_{16}F_4$, M=344.35, monoclinic, space group: $P2_1$; a= 9.7284(13) Å, b=10.1166(13) Å, c=16.724(2) Å, α=90°, β=100.994°, γ=90°, V=1615.8(4) Å^3, Z=4, D_{calc}= 1.416 Mg/m^3, μ=0.113 mm^{-1}, R1=0.0324 for 3590 data [I>2s(I)] and =0.0366 for all 3919 data. Data integration was carried out with SAINT V6.1 (Bruker Analytical X-Ray Systems, Madison, WI), corrections for absorption and decay were applied using SADABS (R. Blessing, *Acta Cryst.* **1995**, *A51*, 33–38). The structure was solved by direct methods, and refined using the SHELXTL-Plus V6.1 (Bruker Analytical X-Ray Systems, Madison, WI). Crystallographic data have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 218083 & 218084. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK.
14. Saltiel, J.; Marinari, A.; Chang, D. W.-L.; Mitchener, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 2983–2996.
15. Goerner, H.; Schulte-Frohlinde, D. *J. Am. Chem. Soc.* **1979**, *101*, 4388–4390.
16. Paper, V.; Pines, D.; Likhtenshtein, G.; Pines, E. *J. Photochem. Photobio. A* **1997**, *111*, 87–96.
17. Baretz, B. H.; Singh, A. K.; Liu, R. S. H. *Nouv. J. Chim.* **1981**, *5*, 297–303.
18. Syage, J. A.; Felker, P. M.; Zewail, A. H. *J. Chem. Phys.* **1984**, *81*, 4685–4705.
19. Kaanumalle, L. S.; Sivaguru, J.; Lakshminarasimhan, P. H.; Sunoj, R. B.; Chandrasekhar, J.; Ramamurthy, V. *J. Org. Chem.* **2002**, *67*, 8711–8720.
20. Liu, R. S. H. *Acc. Chem. Res.* **2001**, *34*, 555–562.