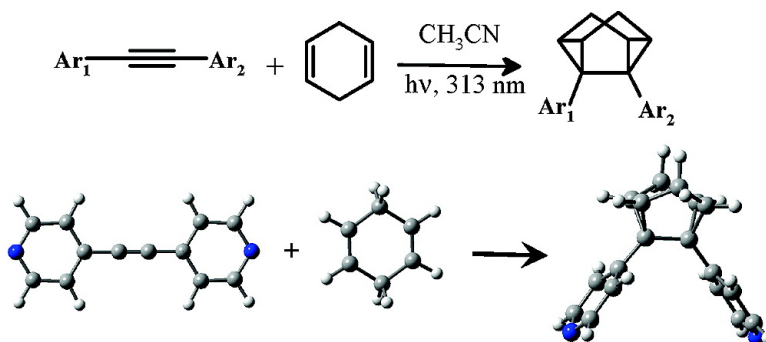


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## Triplet Acetylenes as Synthetic Equivalents of 1,2-Bicarbenes: Phantom $n,\pi^*$ State Controls Reactivity in Triplet Photocycloaddition

Tarek A. Zeidan,<sup>†</sup> Serguei V. Kovalenko,<sup>†</sup> Mariappan Manoharan,<sup>†</sup> Ronald J. Clark,<sup>†</sup> Ion Ghiviriga,<sup>‡</sup> and Igor V. Alabugin<sup>†\*</sup>

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**Abstract:** Diaryl acetylenes, in which one of the aryl groups is either a pyridine or a pyrazine, undergo efficient triplet state photocycloaddition to 1,4-cyclohexadiene with formation of 1,5-diaryl substituted tetracyclo[3.3.0.0<sup>2,8</sup>.0<sup>4,6</sup>]octanes (homoquadricyclanes). In the case of pyrazinyl acetylenes, the primary homoquadricyclane products undergo a secondary photochemical rearrangement leading to diaryl substituted tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-enes. Mechanistic and photophysical studies suggest that photocycloaddition proceeds through an electrophilic triplet excited state whereas the subsequent rearrangement to the tricyclooctenes proceeds through a singlet excited state. Chemical and quantum yields for the cycloaddition, in general, correlate with the electron acceptor character of aryl substituents but are attenuated by photophysical factors, such as the competition between the conversion of acetylene singlet excited state into the reactive triplet excited states (intersystem crossing: ISC) and/or to the radical-anion (photoelectron transfer from the diene to the excited acetylene: PET). Dramatically enhanced ISC between  $\pi-\pi^*$  S<sub>1</sub> state and “phantom”  $n,\pi^*$  triplet excited state is likely to be important in directing reactivity to the triplet pathway. The role of PET can be minimized by the judicious choice of reaction conditions (solvent, concentration, etc.). From a practical perspective, such reactions are interesting because “capping” of the triple bond with the polycyclic framework orients the terminal aryl (4-pyridyl, 4-tetrafluoropyridyl, phenyl, etc.) groups in an almost perfect 60° angle and renders such molecules promising supramolecular building blocks, especially in the design of metal coordination polymers.

### Introduction

The triple bond is among the most important functional groups in organic chemistry. As a result, further understanding of the chemical and photochemical reactions of the acetylenic moiety is a desirable goal. Recently, photochemistry of acetylenes received a lot of attention from the point of view of their biological activity.<sup>1,2</sup> However, despite continuing effort,<sup>3</sup> the photochemistry of alkynes is still considerably less studied than the photochemistry of alkenes.

Our group recently reported the photochemical transformation of benzannelated enediyne possessing electron-accepting sub-

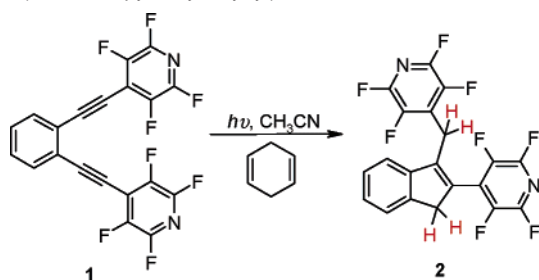
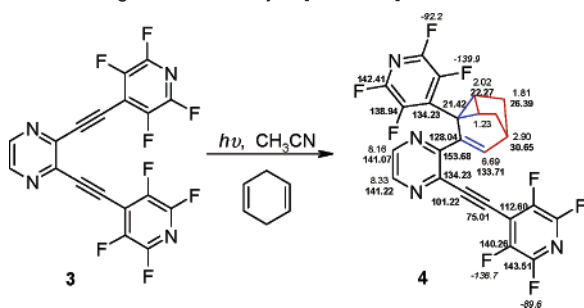
stituents on the acetylenic termini (e.g., tetrafluoropyridyl = TFP) into respective indene products (Scheme 1).<sup>4,5</sup> In contrast to the photochemical Bergman cyclization,<sup>6–9</sup> the C1C5 cy-

<sup>†</sup> Florida State University.

<sup>‡</sup> University of Florida.

- (1) DNA cleavage photosensitized by simple enediyne compounds: Kagan, J.; Wang, X.; Chen, X.; Lau, K. Y.; Batac, I. V.; Tuveson, R. W.; Hudson, J. B. *J. Photochem. Photobiol., B* **1993**, *21*, 1352.
- (2) Marchant, Y. Y.; Towers, G. H. N. *Biochem. Syst. Ecol.* **1986**, *14*, 565. McLachlan, D.; Arnason, T.; Lam, J. *Biochem. Syst. Ecol.* **1986**, *14*, 17. Mizel, F.; FitzGerald, S.; Beeby, A.; Faust, R. *Chem.—Eur. J.* **2003**, *9*, 1233.
- (3) For selected recent references on the cycloaddition reactions of alkynes, see: Margaretha, P.; Agosta, W. C.; Reichow, S. *J. Org. Chem.* **1994**, *59*, 5393. Wang, C.; Sheridan, J. B.; Chung, H. J.; Cote, M. L.; Lalancette, R. A.; Rheingold, A. L. *J. Am. Chem. Soc.* **1994**, *116*, 8966. Wenk, H. H.; Huebert, R.; Sander, W.; Zhang, X.; Fan, A.; Foote, C. S. *J. Org. Chem.* **1996**, *61*, 5456. Wenk, H. H.; Hubert, R.; Sander, W. *J. Org. Chem.* **2001**, *66*, 7994. Alibes, R.; De March, P.; Figueredo, M.; Font, J.; Fu, X.; Racamonde, M.; Alvarez-Larena, A.; Piniella, J. F. *J. Org. Chem.* **2003**, *68*, 1283.

- (4) Alabugin, I. V.; Kovalenko, S. V. *J. Am. Chem. Soc.* **2002**, *124*, 9052. Alabugin, I. V.; Manoharan, M. *J. Am. Chem. Soc.* **2003**, *125*, 4495.
- (5) A topologically similar but mechanistically different C1C5 cyclization of enediyne radical-cations was also reported: Ramkumar, D.; Kalpana, M.; Varghese, B.; Sankararaman, S.; Jagadeesh, M. N.; Chandrasekhar, J. *J. Org. Chem.* **1996**, *61*, 2247. A further mechanistic study: Schmittel, M.; Kia, S. *Liebigs Ann./Recl.* **1997**, 1391. For a related triplet rearrangement of enyne allenes, see: Schmittel, M.; Rodríguez, D.; Steffen, J. P. *Angew. Chem., Int. Ed.* **2000**, *39*, 2152. For a triplet cyclization of diethynyl diphenyl methanes, see: Zimmerman, H. E.; Pincock, J. *J. Am. Chem. Soc.* **1973**, *95*, 3246.
- (6) The original work on the thermal Bergman cyclization: Jones, R. R.; Bergman, R. G. *J. Am. Chem. Soc.* **1972**, *94*, 660. Bergman, R. G. *Acc. Chem. Res.* **1973**, *6*, 25.
- (7) Photochemical Bergman cycloaromatization reaction: Turro, N. J.; Evenzahav, A.; Nicolauo, K. C. *Tetrahedron Lett.* **1994**, *15*, 8089. Evenzahav, A.; Turro, N. J. *J. Am. Chem. Soc.* **1998**, *120*, 1835.
- (8) (a) Funk, R. L.; Young, E. R. R.; Williams, R. M.; Flanagan, M. F.; Cecil, T. L. *J. Am. Chem. Soc.* **1996**, *118*, 3291. (b) Kaneko, T.; Takahashi, M.; Hiram, M. *Angew. Chem., Int. Ed.* **1999**, *38*, 1267. (c) Jones, G. B.; Wright, J. M.; Plourde, G., II; Purohit, A. D.; Wyatt, J. K.; Hynd, G.; Fouad, F. *J. Am. Chem. Soc.* **2000**, *122*, 9872. (d) Choy, N.; Blanco, B.; Wen, J.; Krishan, A.; Russell, K. C. *Org. Lett.* **2000**, *2*, 3761.
- (9) For the most recent references, see: (a) Benites, P. J.; Holmberg, R. C.; Rawat, D. S.; Kraft, B. J.; Klein, L. J.; Peters, D. G.; Thorp, H. H.; Zaleski, J. M. *J. Am. Chem. Soc.* **2003**, *125*, 6434 and references therein. (b) Schmittel, M.; Viola, G.; Dall'Acqua, F.; Morbach, G. *Chem. Comm.* **2003**, 646. (c) Theoretical description: Clark, A. E.; Davidson, E. R.; Zaleski, J. M. *J. Am. Chem. Soc.* **2001**, *123*, 2650. Clark, A. E.; Davidson, E. R.; Zaleski, J. M. *Chem. Comm.* **2003**, 2876.

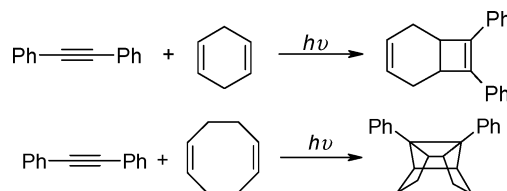
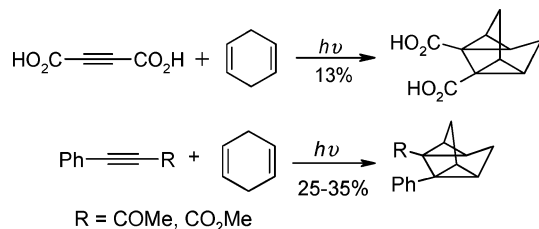
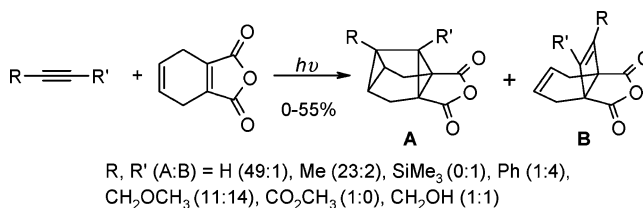
**Scheme 1.** C1C5 Photocyclization of 1,2-Bis(tetrafluoropyridinylethynyl)benzene**Scheme 2.** Photocycloaddition of Bis-TFP Pyrazine Eneidyne **3** and NMR Assignments of Tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-ene **4**

clization proceeds in polar solvents (CH<sub>3</sub>CN) in the presence of 1,4-cyclohexadiene (1,4-CHD) which plays a dual role as a hydrogen and an electron donor. In the first step, 1,4-CHD donates one electron to the singlet excited state of the eneidyne **1** diverting it to the C1C5 cyclization. In further steps, 1,4-CHD provides four hydrogens (in the form of protons or hydrogen atoms) which are incorporated into the final product.

In the course of our studies aimed at defining the scope and limitations of this process, we found that a subtle modification of the core chromophore opens a new photochemical pathway where pyrazine eneidyne **3** undergoes photocycloaddition to 1,4-CHD to give tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-ene **4** (Scheme 2). The assignments of the <sup>1</sup>H, <sup>13</sup>C, and <sup>19</sup>F NMR chemical shifts in compound **4** are given in Scheme 2. The structure was elucidated from the H1–C13 one-bond and long-range couplings revealed by the ghmqc and ghmbc spectra discussed in detail in the Supporting Information.

The new photoreaction with 1,4-CHD transforms the eneidyne into a diaryl substituted tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-ene. Topologically, this unusual transformation involves formal double cycloaddition of the acetylene moiety to both double bonds of 1,4-CHD followed by a mechanistically interesting skeletal rearrangement (Scheme 2).

Both the dramatic change in photochemical reactivity of the eneidyne moiety and structure of the product are intriguing because literature photocycloadditions of acetylenes to dienes lead to products that differ from tricyclooctene **4**.<sup>10</sup> For example, the parent diaryl acetylene, tolane, reacts with 1,4-CHD when irradiated with high energy 254 nm light but gives the cyclobutene [2+2] adduct (Scheme 3).<sup>11</sup> When the two double bonds of the diene are separated by a more flexible linker (e.g., in 1,5-cyclooctadiene), the initially formed [2+2] adduct reacts with the second double bond of the diene forming a polycyclic product.<sup>12</sup>

**Scheme 3.** Photochemical Reactions of Toluene with Cyclic Dienes**Scheme 4.** Literature Examples of Photochemical Formation of Homoquadricyclanes in Reactions of Acetylenes with 1,4-CHD**Scheme 5.** Competing Reaction Pathways in Reaction of Acetylenes with Dicarboxylic Acid Anhydride<sup>14b</sup>

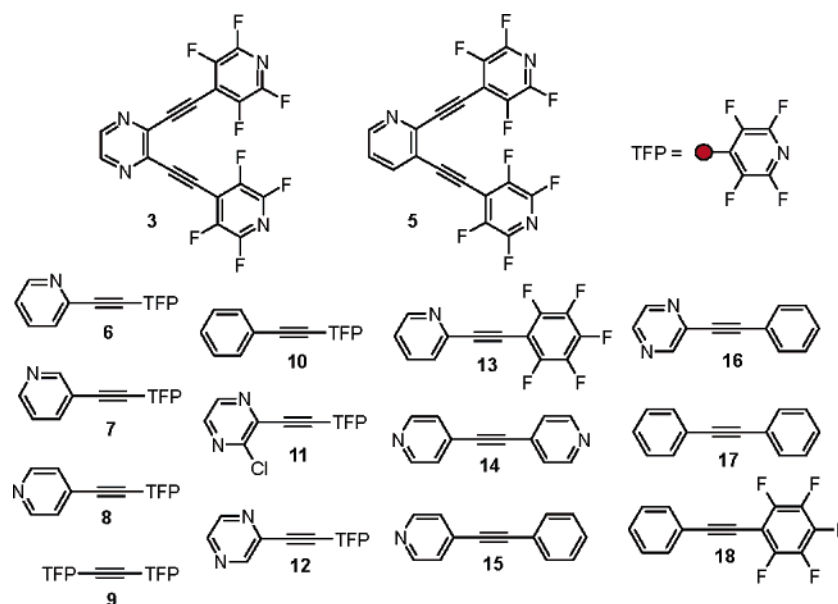
The other reported photocycloaddition pathway involves several acetylenes containing a carbonyl or carboxyl group leading to formation of homoquadricyclane products (Scheme 4).<sup>13</sup> Only a handful of acetylenes undergoes this reaction in rather low isolated yields. The structure of the tetracyclic products was derived exclusively from spectroscopic analysis without crystallographic evidence to confirm these assignments.

Literature data suggest that the competition between the [2+2] and homoquadricyclane pathways is sensitive to the structure of the reagents. For example, although photocycloaddition of several acetylenes to a carboxyl substituted cyclohexadiene also leads to homoquadricyclanes,<sup>14,15</sup> the reaction of diphenyl acetylene proceeds mainly through the [2+2] pathway (Scheme 5). Even though the factors controlling the competition between the two pathways remain unknown, the regiochemistry of [2+2] cycloadditions suggests that they are likely to proceed through an excited state of the diene where the excitation is concentrated at the double bond conjugated with the carbonyl groups.

None of the literature photocycloaddition reactions produced the tricyclooctene skeleton of **4**. Intrigued by the dramatic change in photochemical reactivity of the eneidyne moiety and by the intricate polycyclic structure of the product **4**, we

(10) Horspool, W. M. *Photochemistry* **2003**, *34*, 69.(11) Kaupp, G.; Stark, M. *Chem. Ber.* **1978**, *111*, 8.(12) Kubota, T.; Sakurai, H. *J. Org. Chem.* **1973**, *38*, 1762.(13) Hubner, C. F.; Donoghue, E.; Dorfman, L.; Stuber, F. A.; Danieli, N.; Wenkert, E. *Tetrahedron* **1966**, *7*, 1185. Takahashi, M.; Kitahara, Y.; Murata, I.; Nitta, T.; Woods, M. C. *Tetrahedron Lett.* **1968**, *30*, 3387. Fujita, K.; Matsui, K.; Shono, T. *Nippon Kagaku Kaishi* **1975**, *6*, 1024. Shim, S. C.; Kim, S. S. *Tetrahedron Lett.* **1985**, *26*, 765.(14) (a) Askani, R. *Chem. Ber.* **1965**, *98*, 3618. (b) Askani, R.; Hoffmann, J. *Chem. Ber.* **1991**, *124*, 2307 and references therein.(15) The same is usually true for cycloadditions of acetylenes with quinones. For [2+2] addition to the carbonyl group, see: Zimmerman, H. E.; Craft, L. *Tetrahedron Lett.* **1964**, 2131. (b) Bryce-Smith, D.; Fray, G. I.; Gilbert, A. *Tetrahedron Lett.* **1964**, 2137. (c) Bosch, E.; Hubig, S. M.; Kochi, J. K. *J. Am. Chem. Soc.* **1998**, *120*, 386. For a [2+2] addition to the C=C bond, see: (d) Pappas, S. P.; Pappas, B. C.; Portnoy, N. A. *J. Org. Chem.* **1969**, *34*, 520.

Scheme 6. Choice of Model Substrates



undertook a more detailed study aimed at the elucidation of the mechanism of this reaction. Our original goals were to determine the spin multiplicity of the excited states involved in this transformation, to define its scope and limitations, and to understand photochemical and photophysical factors controlling chemical and quantum efficiency of this process. Several possibilities were considered a priori: (a) a truly one-photon process where concerted formation of the four new bonds is driven by absorption of a single photon, (b) a stepwise process where all but the initial step are thermally activated, or (c) a sequential multiphoton process with intermediates successfully competing for light with the starting material. Since only one of the triple bonds of the enediyne moiety is involved in the transformation, we tested the reactivity of a family of diaryl monoacetylenes different in acceptor ability and photophysical properties of aryl substituents.

This choice allowed us to concentrate on fundamental processes which should be of general importance in the photochemistry of acetylenes. In addition, in the course of these studies, we found a convenient entry to a new family of well-defined molecular scaffolds for molecular recognition with an almost perfect  $60^\circ$  angle between the two functional groups defining a hydrophobic cavity.

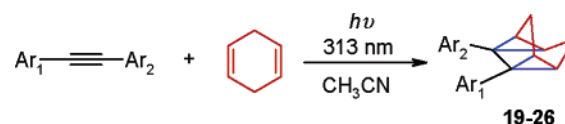
## Results and Discussion

**Model Substrates.** The diaryl *mono*acetylenes designed and prepared for these mechanistic studies are summarized in Scheme 6. They are roughly organized in three overlapping groups: (a) the diarylacetylenes **6–13**, **18** with strong acceptor substituents, (b) acetylenes **6–8**, **11–16** bearing simple pyridine and pyrazine moieties, and (c) acetylenes **17,18** with either a phenyl and/or pentafluorophenyl moiety but without a nitrogen-containing heterocycle. These three sets were chosen to probe the role of triple bond polarization as well as the role of the nature of the excited state. We also included diphenylacetylene (tolane) as a useful reference point.

Depending on the nature of the aryl substituents, the acetylenes were prepared via two different synthetic routes. Pyridine, pyrazine, and pentafluorobenzene substituents were combined with an acetylene moiety via a standard Sonogashira

protocol,<sup>16</sup> whereas the TFP moiety was introduced by a one-pot sequence which involves fluoride-assisted in situ desilylation of TMS acetylene followed by selective “para” nucleophilic substitution in pentafluoropyridine.<sup>17</sup> Yields of the products are given in the Experimental Section (see Supporting Information).

**Photochemistry of Pyridinyl Arylacetylenes.** Having the requisite acetylenes in hand, we proceeded to study their photochemistry using 313 nm irradiation<sup>18</sup> in the presence of 1,4-CHD in acetonitrile. Although tolane is unreactive under these conditions,<sup>11</sup> pyridinyl aryl acetylenes yielded 1,5-diaryl substituted tetracyclo[3.3.0.0<sup>2,8</sup>.0<sup>4,6</sup>]octanes (homoquadricyclanes) in good yields (Scheme 7, Table 1). Pyridinyl enediyne **5**

Scheme 7. Photochemical Reactions of Aryl Pyridinyl Acetylenes with 1,4-CHD<sup>a</sup>

<sup>a</sup> The newly formed bonds are shown in blue.

provided a mixture of homoquadricyclane monoadducts to both of the triple bonds in a 2:1 ratio.<sup>19</sup>

Structures of the products were confirmed by <sup>1</sup>H, <sup>13</sup>C, <sup>19</sup>F NMR, mass-spectrometry, and, in the cases of tetracyclooctanes **19** and **22**, X-ray crystallographic analysis (Figure 1).<sup>20</sup> The presence of the homoquadricyclane products in the <sup>1</sup>H NMR

- (16) (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467. (b) Sonogashira, K. In *Metal-Catalyzed Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: New York, 1998. (c) Stang, P. J. In *Modern Acetylene Chemistry*; Diederich, F., Ed.; VCH: Weinheim, Germany, 1995. (d) Tykwinski, R. R. *Angew. Chem., Int. Ed.* **2003**, *42*, 1566.
- (17) Artamkina, G. A.; Kovalenko, S. V.; Beletskaya, I. P.; Reutov, O. A. *Russ. J. Org. Chem.* **1990**, *26*, 225. For fluoride-induced reaction of organosilicon compounds with electron-deficient aromatic substrates, see also: (a) RajanBabu, T. V.; Reddy, G. S.; Fukunaga, T. *J. Am. Chem. Soc.* **1985**, *107*, 5473. (b) Kovalenko, S. V.; Artamkina, G. A.; Beletskaya, I. P.; Reutov, O. A. *J. Organomet. Chem.* **1988**, *1*, 125.
- (18) Solution of 0.001 M K<sub>2</sub>CrO<sub>4</sub> was used as a filter; maximum transmission at 313 nm wavelength.
- (19) 35% Overall yield; 2:1 ratio of inseparable regioisomers determined from <sup>1</sup>H NMR integration of peaks.
- (20) The details of X-ray analysis are included in the Supporting Information. Detailed X-ray analysis including the interesting  $\pi$ - $\pi$  interactions and H-bonding patterns will be reported separately.





Figure 1. ORTEP presentations of homoquadricyclanes **22**, **19**, **27**, and tricyclo[3.2.1.0.4.6]oct-2-ene **29**.

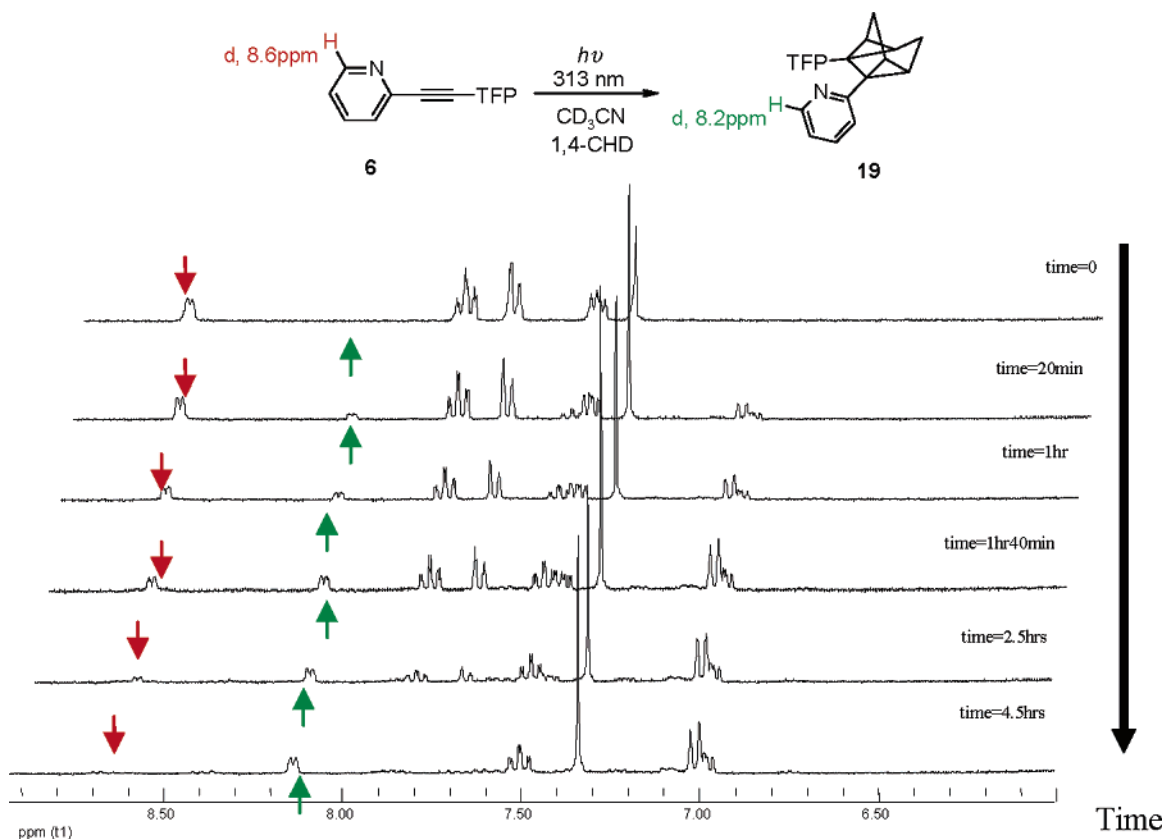


Figure 2. Changes in the <sup>1</sup>H NMR spectra of the aromatic region during irradiation of acetylene **6** in the presence of 5-fold equivalent of 1,4-CHD.

Table 1. Conditions and Yields for the Photochemical Cycloaddition of Acetylenes to 1,4-Cyclohexadiene<sup>a,b</sup>

compounds	product	Ar <sub>1</sub>	Ar <sub>2</sub>	irradiation time, h <sup>c</sup>	isolated yield, %
<b>6</b>	<b>19</b>	2-Py	TFP	1	61
<b>7</b>	<b>20</b>	3-Py	TFP	1.5	55
<b>8</b>	<b>21</b>	4-Py	TFP	0.5	80 <sup>d</sup>
<b>9</b>	<b>26</b>	TFP	TFP	0.75	48
<b>10</b>	<b>22</b>	Ph	TFP	4	35
<b>13</b>	<b>24</b>	2-Py	PFB	20	20
<b>14</b>	<b>25</b>	4-Py	4-Py	10	65
<b>15</b>	<b>23</b>	4-Py	Ph	5	25
<b>17</b>		Ph	Ph	>48	no rxn <sup>e</sup>
<b>18</b>		Ph	PFB	>48	no rxn <sup>e</sup>

<sup>a</sup> Irradiation was performed at 313 nm in acetonitrile at 25 °C; initial [acetylenes] =  $1.0 \times 10^{-3}$  M with 100-fold excess [1,4-CHD] = 0.1 M. <sup>b</sup> Ph = phenyl, Py = pyridinyl, Pyra = pyrazinyl, TFP = tetrafluoropyridinyl, PFB = pentafluorobenzene. <sup>c</sup> Irradiation time until complete consumption of the acetylene according to TLC analysis. <sup>d</sup> >95% yield determined by GC. <sup>e</sup> Acetylenes were completely recovered under these conditions.

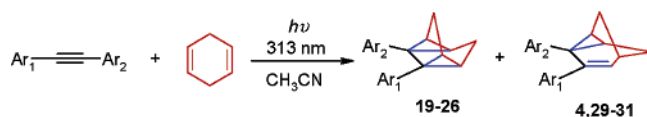
of the reaction mixture is revealed by a characteristic doublet of quintets<sup>21</sup> at ~2.4 ppm with geminal coupling of 13.0 Hz corresponding to two protons on the methylene bridges con-

necting the two cyclopropane rings. The other two protons from these bridges are shifted upfield and are displayed as a rather sharp doublet with the same geminal constant.

Since the earlier homoquadricyclane structures were suggested exclusively from NMR spectra,<sup>13,14</sup> X-ray crystallographic analysis of compounds **19** and **22** for the first time unambiguously confirmed the homoquadricyclane structure of the products. This analysis also revealed interesting structural features of the [3.3.0.2.8.0<sup>4,6</sup>]octane moiety. Most interestingly, the two aryl groups defining the hydrophobic cavity are cross-conjugated through the adjacent cyclopropane moieties and are oriented in an almost perfect 60° angle.

The isolated yields of the homoquadricyclane products are given in Table 1 (according to GC analysis, the reaction yields are even higher reaching >95% in the case of acetylene **8**). In some of the cases, the combination of high yields of the homoquadricyclane products along with the short irradiation times is quite remarkable and indicates a surprisingly efficient

(21) Apparently the vicinal and the W-constants for these protons are close in magnitude.

**Scheme 8.** Photochemical Reactions of Aryl Pyrazinyl Acetylenes with 1,4-CHD

process which contrasts sharply the observed lack of photochemical reactivity of tolane **17** and Ph-PFB acetylene **18**.

Figure 2 which shows the progress of this photochemical conversion in the case of 2-tetrafluoropyridinylethynyl pyridine further illustrates this efficiency. Since all signals in the product are uniformly moved upfield relative to the starting acetylene,<sup>22</sup> the reaction can be conveniently monitored with NMR.

Although the presence of the strong acceptor TFP moiety is beneficial and leads to the more efficient photocycloadditions, especially in nonsymmetric acetylenes, the electron deficiency and overall polarization of the triple bond per se are neither necessary nor sufficient for the reaction to occur. For example, the highly polarized phenylpentafluorophenyl acetylene **18** does not react, whereas a symmetric bis-pyridinyl acetylene **14** undergoes photoreaction with 1,4-CHD which proceeds relatively slow but in a high yield. Since the ground-state polarization of the triple bond is not a prerequisite for the cycloaddition, the lack of reactivity in the case of tolane lies elsewhere. Taken together, these trends in reactivity suggest that the presence of a nitrogen atom in a six-membered aryl ring represents a key requirement for the photocyclization.

An intriguing possible rationale for these observations is that the reactivity of diarylacetylenes correlates with the availability and electronic structure of  $n,\pi^*$  excited states in pyridinyl/pyrazinyl acetylenes and with the absence of this state in diphenylacetylenes lacking nitrogen atoms (vide infra). The presence of the nitrogen atom may allow entry to triplet intermediates of a different electronic nature and, thus, provides an alternative to carbonyl- and carboxy- substituted acetylenes. Two mechanisms for the  $n,\pi^*$  state involvement are possible. The most obvious route involves a direct change in the nature of the reactive excited state from  $\pi,\pi^*$  to  $n,\pi^*$ , the two states which are well-known to have different reactivities.<sup>23</sup> The second indirect possibility is based on differences in photophysical properties of the involved states, such as relative efficiencies of the reactive triplet state formation which may be based on the differences in the ISC rates between  $\pi,\pi^*$  singlet excited state and the  $n,\pi^*$  and  $\pi,\pi^*$  triplets.<sup>24</sup> To gain more experimental insight into these questions, we explored the photochemistry of pyrazinyl-substituted acetylenes.

**Photochemistry of Pyrazinyl Arylacetylenes.** Pyrazinyl-substituted aryl acetylenes **12** and **16** also reacted readily with 1,4-CHD under identical conditions. However, this reaction leads to the formation of 1,5-diaryl tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-enes, the same products that we observe in the photochemistry of the pyrazinyl enediyne **3**, Scheme 8 and Table 2. The tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-ene products can be easily identified by a characteristic set of <sup>1</sup>H NMR signals which include a doublet

**Table 2.** Conditions and Yields for the Photochemical Cycloaddition of Pyrazinyl Acetylenes to 1,4-Cyclohexadiene<sup>a,b</sup>

entry	reactants	product	Ar <sub>1</sub>	Ar <sub>2</sub>	irradiation time (h) <sup>c</sup>	% yield <sup>d</sup>
1a	<b>11</b>	<b>27</b>	Pyra-2-Cl	TFP	7	23
1a'	<b>11</b>	<b>29</b>	Pyra-2-Cl	TFP	7	40
1b <sup>e</sup>	<b>11</b>	<b>27</b>	Pyra-2-Cl	TFP	47	90 <sup>f</sup>
1c	<b>27</b>	<b>29</b>	Pyra-2-Cl	TFP	1.5	>99 <sup>f</sup>
2a	<b>12</b>	<b>30</b>	Pyra	TFP	2	38
2b	<b>12</b>	<b>28</b>	Pyra	TFP	2	g
2c	<b>28</b>	<b>30</b>	Pyra	TFP	0.75	>99 <sup>f</sup>
3	<b>16</b>	<b>31</b>	Pyra	Ph	48	10 <sup>h</sup>
4	<b>3</b>	<b>4</b>	Pyra-TFPE	TFP	5	20

<sup>a</sup> Irradiation was performed in CH<sub>3</sub>CN at 313 nm in acetonitrile at 25 °C; initial [acetylenes] = 1.0 × 10<sup>-3</sup> M with 100-fold excess [1,4-CHD] = 0.1 M; 1b, 1c, 2b, and 2c were performed in CD<sub>3</sub>CN in an NMR tube (see Experimental Section in Supporting Information). <sup>b</sup> Ph = phenyl, Py = pyridinyl, Pyra = pyrazinyl, TFP = tetrafluoropyridinyl, TFPE = tetrafluoropyridinylethynyl. <sup>c</sup> Irradiation time until total consumption of the acetylene according to TLC analysis. <sup>d</sup> Isolated yields, unless stated otherwise. <sup>e</sup> Irradiation at 330 nm. <sup>f</sup> Yields estimated by <sup>1</sup>H NMR. <sup>g</sup> The product was present in small amounts but could not be isolated from the reaction mixture. <sup>h</sup> Unreacted acetylene was recovered, and product yield was estimated by <sup>1</sup>H NMR of the crude reaction mixture.

in the vinylic region, a doublet of triplets at 3 ppm, and two signals (dd at 1.8 ppm and a doublet at 1.1 ppm) of hydrogens of the two diastereotopic CH<sub>2</sub> groups.

An important question was whether the tricyclooctene pathway is mechanistically independent of homoquadricyclane formation. In particular, we sought to determine whether tetracyclooctanes and tricyclooctenes were related as primary and secondary photochemical products or were formed through branching from a common intermediate. In the first case, one of these products should be transformed into the other upon further photolysis, while in the second case no such interconversion would be observed.

Fortunately, introduction of a chlorine atom in the pyrazine moiety of acetylene **11** modifies photochemical reactivity in a way where both types of photoproducts are formed at the same time and their interconversion during photolysis at 313 nm can be monitored with NMR. These products were isolated and identified, first spectroscopically and later by X-ray crystallography, as tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-ene **29** and 1-tetrafluoropyridyl-5-(2-chloro-3-pyrazinyl)tetracyclo[3.3.0.0<sup>2,8</sup>.0<sup>4,6</sup>]octane **27** (Figure 1).

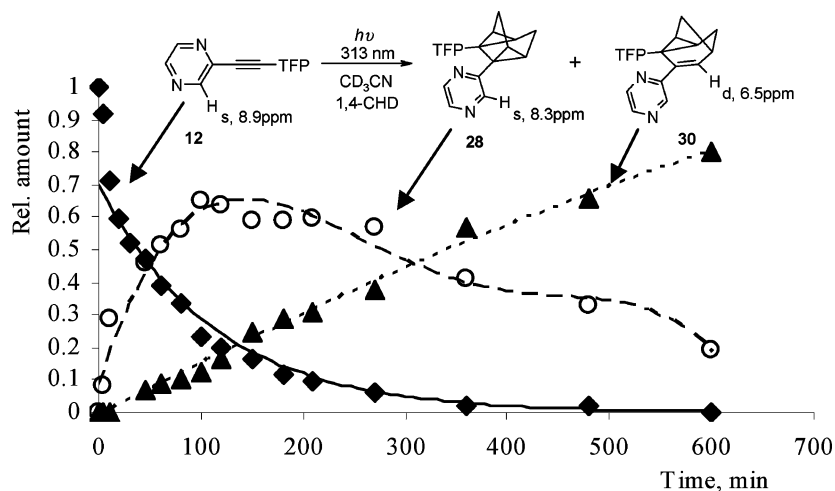
Taking advantage of the observation that, unlike the starting acetylene, the homoquadricyclane product **27** does not absorb light at  $\lambda > 330$  nm, we repeated the photolysis under these conditions. <sup>1</sup>H NMR monitoring of the reaction progress clearly showed that only tetracyclooctane **27** is formed in ca. 90% yield after 47 h of irradiation. No secondary photochemistry of **27** was observed under these conditions. On the other hand, when the tetracyclooctane was separated from the starting acetylene and subjected to further irradiation at 313 nm, the homoquadricyclane **27** was cleanly converted into the rearranged tricyclooctene product **29** (see Figure S2 in the Supporting Information for the spectra). As expected, 1,4-CHD was not needed for the latter step. Thus, in this case, the unusual tricyclooctene adduct formation is a result of a photochemical cascade proceeding through the homoquadricyclane intermediate.

Moreover, the homoquadricyclane intermediate can also be detected in the reaction with the pyrazinyl-TPF acetylene **12** when a less powerful and more tunable light source<sup>25</sup> was used

(22) This effect can be attributed either to the loss of conjugation with a strong electron acceptor or, to some extent, to the change in orientation of the two aromatic rings which places the pyridine ring in the vicinity of the aromatic current of the TFP ring.

(23) For a recent fascinating example of a dramatic effect on excited state nature in photochemistry of cyclohexenones, see: Zimmerman, H. E.; Nesterov, E. E. *J. Am. Chem. Soc.* **2003**, *125*, 5422.

(24) El-Sayed, M. *J. Chem. Phys.* **1962**, *36*, 573.



**Figure 3.** Time evolution of the relative amounts of acetylene **12** (◆), homoquadricyclane **28** (○), and tricyclooctene **30** (▲) during photolysis at 313 nm. Slight deviations from the ideal A→B→C kinetics are explained by the differences in the absorbance between compounds **12** and **28** and by the quenching effect of **30**.

**Table 3.** Quantum Yields for the Disappearance of Acetylene and Formation of Polycyclic Photoadducts<sup>a</sup>

acetylenes	$\phi_{\text{-acetylenes}} \times 10^2$	$\phi_{\text{-tricyclooctane}} \times 10^2$
2-Py-TFP, <b>6</b>	33.0 ± 0.8 (15.2 ± 0.4)	32.5 ± 0.2 (6.5 ± 0.1)
4-Py-TFP, <b>8</b>	31.9 ± 0.7 (21.5 ± 0.6)	30.5 ± 0.4 (19.6 ± 0.2)
3-Py-TFP, <b>7</b>	18.6 ± 0.5 (6.7 ± 0.5)	8.3 ± 0.1 (2.9 ± 0.1)
Ph-TFP, <b>10</b>	17.8 ± 0.6 (6.0 ± 0.2)	5.2 ± 0.1 (1.2 ± 0.1)
TFP-TFP, <b>9</b>	22.5 ± 0.8 (50.2 ± 0.9)	18.4 ± 0.3 (51.2 ± 0.7)
4-Py-4-Py, <b>14</b>	2.6 ± 0.9	2.8 ± 0.2
2-Py-PFB, <b>13</b>	1.2 ± 0.4	0.52 ± 0.05
4-Py-Ph, <b>15</b>	<0.5	<0.5

<sup>a</sup> Degassed solution in acetonitrile irradiated at 313 nm, 25.0 °C; [Acetylene] =  $1.0 \times 10^{-3}$  M; [1,4-CHD] =  $1.0 \times 10^{-1}$  M except for the values in parentheses which correspond to [1,4-CHD] =  $2.0 \times 10^{-3}$  M; error limits are average deviation from the mean of several GC traces.

for the photolysis. According to the NMR analysis of the reaction mixture, ca. 60% of the homoquadricyclane **28** is formed after 2 h of irradiation at  $\lambda > 313$  nm under these conditions, whereas further irradiation (the total of 10 h of photolysis) led to the reaction mixture which contained ca. 80% of the tricyclooctene **30** (Figure 3).

**Quantum Efficiency for Formation of Homoquadricyclanes.** To get further insight into reaction mechanism and effects of substituents on the efficiency of this process, we determined quantum yields for the formation of the photochemical products and disappearance of the starting material. Quantum yields for the loss of acetylenes and formation of tetracyclooctane and tricyclooctene adducts were determined for 1 mM acetylene solutions using *trans*-stilbene isomerization in benzene as the actinometer ( $\phi = 0.5$ ).<sup>26</sup> The results are summarized in Table 3 (pyridines) and Table 4 (pyrazines).

The quantum yields in the presence of 1,4-CHD (0.1 M) correlate well with the time necessary to complete the reaction (Table 1). Reaction efficiency increases in parallel with the electron acceptor ability of the substituents. 2-Py and 4-Py are more efficient than 3-Py and Ph, but the TFP moiety in

nonsymmetric acetylenes is, by far, the most effective in increasing quantum efficiency. In this context, the only seemingly surprising observation is that the quantum yield for the formation of homoquadricyclane from the bis-TFP acetylene is only half of that for 4-Py-TFP acetylene (we will comment on this observation later).

The cases of 2-pyridinyl-TFP, 4-pyridinyl-TFP, and bis-4-pyridinyl acetylenes **6**, **8**, and **14**, respectively, are especially interesting. The relative quantum efficiencies for the three acetylenes are drastically different; substitution of TFP for Ph decreases the quantum yield by a factor of 12, Table 3. This suggests that the highly polarized 4-Py-TFP triplet attacks 1,4-CHD noticeably faster. However, the quantum yields for the disappearance of the reactant and the appearance of the product are the same within experimental error. This indicates that formation of the tetracyclic product is the *only* photochemical pathway operating for both of these acetylenes and that *every excited molecule of these substrates which is not deactivated through competing radiative and radiationless decay options but undergoes a photochemical reaction follows an exclusive path to the homoquadricyclane product*. In other words, every molecule which enters a reactive path is efficiently converted into the respective homoquadricyclane product.

Smaller quantum yields for product formation in the case of other acetylenes may indicate the presence of an intermediate undergoing a slower secondary photochemical process or simply formation of byproducts along the thermal reaction paths. The highest observed values of quantum yields of ca. 0.5 indicate that the transformation involves no more than two photochemical steps. In other words, when all information about quantum yields is taken together, it suggests a stepwise process where all steps except for one or two are thermally activated. In the case of a sequential two-photon process, the intermediate should successfully compete for light with the starting material and react efficiently.

We have also measured the dependence of the quantum yields on the concentration of 1,4-CHD. In the case of the more reactive 4-Py-TFP acetylene **8**, a 50-fold decrease in the 1,4-CHD concentration leads to only a ca. 30% decrease in the quantum yields. The photocycloaddition of the less reactive 3-Py-TFP and Ph-TFP acetylenes **7** and **10** is more sensitive to

(25) 200 W Hg–Xe lamp (Spectra-Physics, Laser & Photonics Oriel Instrument) and Corning glass filter # 7380 (C.S. 0–52) that transmits light above 340 nm.

(26) Saltiel, J.; Marinari, A.; Chang, D. W. L.; Mitchener, J. C.; Megarity, D. *J. Am. Chem. Soc.* **1979**, *101*, 2982. Acetylenes with low reactivity required extended irradiation times. Thus, the conversion of *trans*-stilbene to the *cis*-isomer was more than 10%, and correction for the back reaction was required; Lamola, A. A.; Hammond, G. S. *J. Chem. Phys.* **1965**, *43*, 2129.

**Table 4.** Quantum Yields for the Disappearance of Acetylene and Formation of Polycyclic Photoadducts in Pyrazinyl Acetylenes<sup>a</sup>

acetylenes	$\phi_{\text{-acetylenes}} \times 10^2$	$\phi_{\text{-tetracyclooctane}} \times 10^2$	$\phi_{\text{-tricyclooctene}} \times 10^2$
Pyra-2,3-TFP, <b>3</b>	10.0 ± 0.4	<i>b</i>	0.76 ± 0.04 <sup>c</sup>
Pyra-2-Cl-3-TFP, <b>11</b>	28.3 ± 1.1 (8.1 ± 0.1)	18.8 ± 0.4 (4.3 ± 0.1)	8.0 ± 0.1 <sup>d</sup>
Pyra-2-TFP, <b>12</b>	27.3 ± 0.3	13.6 ± 0.3	7.7 ± 0.1 <sup>d</sup>

<sup>a</sup> Degassed solution in acetonitrile irradiated at 313 nm, 25.0 °C; [Acetylenes] =  $1.0 \times 10^{-3}$  M; [1,4-CHD] =  $1.0 \times 10^{-1}$  M except values in parentheses are for [1,4-CHD] =  $2.0 \times 10^{-3}$  M; error limits are average deviation from the mean of several GC traces. <sup>b</sup> Photoproduct not detectable,  $\phi < 5 \times 10^{-3}$ . <sup>c</sup> The overall quantum yield for acetylene/CHD–tricyclooctene transformation. <sup>d</sup> Quantum yields determined for the photorearrangement of homoquadricyclane to tricyclooctene adduct.

**Table 5.** Quantum Yields for the Consumption of Bis-TFP Acetylene **9** and Formation of Polycyclic Photoadducts<sup>a</sup>

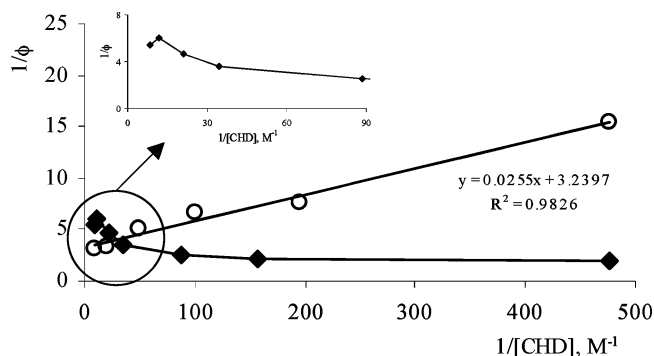
solvent	diene	$\phi_{\text{-acetylenes}} \times 10^2$	$\phi_{\text{-tetracyclooctane}} \times 10^2$
acetonitrile	1,4-CHD	22.5 ± 0.8 (50.2 ± 0.9)	18.4 ± 0.3 (51.2 ± 0.7)
	1,5-dimethoxy-1,4-CHD	9.0 ± 0.1 (40.5 ± 0.3)	7.71 ± 0.07 (34.0 ± 0.1)
cyclohexane	1,4-CHD	31.5 ± 1.7 (49.5 ± 0.9)	8.5 ± 0.5 (13.3 ± 0.2)

<sup>a</sup> Degassed solution irradiated at 313 nm, 25.0 °C; initial [Acetylenes] =  $1.0 \times 10^{-3}$  M; initial [1,4-CHDs] =  $1.0 \times 10^{-1}$  M except for the values in parentheses which are for [1,4-CHDs] =  $2.0 \times 10^{-3}$  M; the error limits are average deviations from the mean of several GC traces.

the concentration of the diene, and the same decrease in the 1,4-CHD concentration leads to ca. 60% decreases in the quantum efficiency. However, the most surprising behavior is displayed by the bis-TFP acetylene **9** where the 50-fold decrease in the concentration of 1,4-CHD leads to more than a 30% increase in the quantum yield for the disappearance of the acetylene and to more than a 3-fold increase in the quantum yield for the formation of the respective homoquadricyclane product. To understand this peculiar behavior, we have investigated the effect of 1,4-CHD concentration on the reaction with 2-Py-TFP and TFP-TFP acetylenes in more detail and determined the limiting quantum yields for these processes (vide infra).

In the case of 2-Py-TFP acetylene **6**,  $\phi_{\text{lim}}$  for the consumption of acetylene and the formation of tetracyclooctane adduct were  $0.32 \pm 0.03$  and  $0.31 \pm 0.05$ , respectively (Figure 4 and Supporting Information). A linear relationship obtained when  $1/\phi$  were plotted against  $1/[1,4\text{-CHD}]$  indicates that the mechanism does not change when higher concentrations of CHD are used.

In sharp contrast, in the case of bis-TFP acetylene **9** the analogous relationship between  $1/\phi$  and  $1/[1,4\text{-CHD}]$  is clearly nonlinear (Figure 4). At a 1 mM concentration of the acetylene, the quantum efficiency of the photoaddition reaches its maximum at a 2–5-fold molar excess of 1,4-CHD. The lower quantum yields at the higher 1,4-CHD/acetylene molar ratios suggest a change in mechanism. GC analysis shows that new products are formed at higher concentrations of 1,4-CHD at the expense of the tetracyclooctane adduct.



**Figure 4.** Limiting quantum yields for the formation of the tetracyclooctane products from 2-Py-TFP (○) and TFP-TFP (◆) acetylenes. The results are tabulated in the Supporting Information.

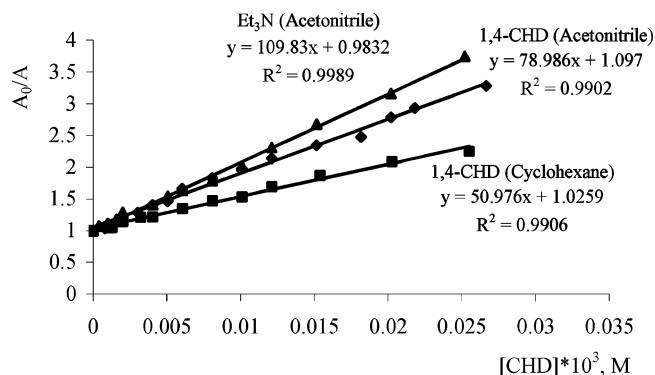
**Dependence of the Quantum Yields on the Nature of 1,4-Diene and Solvent.** To understand further the anomalous behavior of bis-TFP acetylene **9**, we compared the quantum yields of the reaction of 1,4-CHD and a more electron-rich 1,5-dimethoxy-1,4-cyclohexadiene and found that the unusual trend in the concentration dependence in the quantum yield is even more pronounced. On the other hand, when the reaction is carried out in a nonpolar solvent (cyclohexane), the effect of 1,4-CHD concentration on the quantum yields is smaller (Table 5). These data strongly suggest that photoinduced electron transfer (PET) plays a role in the concentration effects on the cycloaddition efficiency in the case of the highly electron-acceptor acetylenes.

**Quantum Efficiency for Formation of Tricyclooctenes.** Quantum yields were determined similarly for the photochemical reactions of TFP-pyrazine acetylenes (Table 4). The overall quantum yield for the formation of tricyclooctene from enediyne **3** is rather low (less than 0.01). We also determined the quantum yields for the two sequential steps of acetylene→homoquadricyclane→tricyclooctene transformation separately. The first step is comparable in efficiency to photocycloaddition of pyridinyl acetylenes and has a similar dependence from the diene concentration as in the case of nonsymmetric Ar-TFP acetylenes. The quantum yields for the secondary transformation are in the order of 0.1, indicating a moderately efficient process.

**Nature of Excited States.** The spin multiplicity of the excited state involved in the formation of polycyclic photoadducts and their subsequent rearrangement was determined using quenching and sensitization experiments. Whereas the homoquadricyclane→tricyclooctene rearrangement is not affected by triplet sensitizers and quenchers and, thus, should proceed through a singlet excited state, formation of homoquadricyclanes can be sensitized by benzophenone ( $E_T = 68$  kcal/mol) and acetophenone ( $E_T = 74$  kcal/mol) and quenched by azulene ( $E_T = 39$  kcal/mol) and molecular oxygen.<sup>27</sup> The latter observation is important from a practical point of view because, due to the quenching effect of oxygen, degassing is essential for reaching high conversions and reaction yields. Interestingly, despite the accelerating effects of the acceptor groups mentioned above, the reaction can be performed not only in polar solvents

(27) Nondegassed samples showed 50% less conversion than degassed samples under identical conditions; see Figure *i* in the Supporting Information.





**Figure 5.** Stern–Volmer plots for fluorescence quenching of bis-TFP acetylene with 1,4-CHD in acetonitrile (◆) and cyclohexane (■) and with Et<sub>3</sub>N in acetonitrile (▲).

(acetonitrile) but also in nonpolar solvents (cyclohexane).<sup>28</sup> Together, these results clearly suggest that the photocycloaddition step proceeds through an acetylene triplet excited state without formation of charged intermediates.

**Competition between Triplet and Photoelectron Transfer (PET) Pathways.** Fast intersystem crossing (ISC) to the triplet excited state (vide infra) is likely to be responsible for the absence of radical-anionic C1C5 cyclization in the case of enediyne **3**. Fast ISC rate in this molecule is consistent with the drastically reduced quantum yield of fluorescence in the pyrazine enediynes (0.01 for **3** vs 0.90 for **1**).<sup>29</sup> Electron transfer from cyclohexadiene to the lower energy triplet excited state of enediynes is less favorable than PET to the singlet excited state of enediyne **3**. The thermodynamics of the PET can be calculated using the Rehm–Weller equation:<sup>30</sup>

$$\Delta G_{\text{ET}} = 23.06[E_{1/2}(\text{D}^+/\text{D}) - E_{1/2}(\text{A}/\text{A}^-)] - w_p - \Delta G_{00}$$

where  $\Delta G_{\text{ET}}$  is the energy of electron transfer (ET) process,  $E_{1/2}$  values are oxidation and reduction potentials for the donor (D) and acceptor (A), and  $\Delta G_{00}$  is the excited-state energy;  $E_{1/2}$  (1,4-CHD) = 1.74 V (vs SCE),<sup>31</sup>  $E_{1/2}$ (**3**) = -1.07 V (vs SCE),  $E_{1/2}$ (**1**) = -1.22 V (vs SCE). According to this estimate,  $\Delta G_{\text{ET}}$  is equal to -26 and +3 kcal/mol, respectively, for the singlet and triplet excited states of enediynes **3** (taking  $E_S = 90$  kcal/mol and  $E_T = 61$  kcal/mol). To estimate efficiency of PET in these systems, quenching of fluorescence of bis-TFP acetylenes **9** with 1,4-CHD was investigated in acetonitrile and cyclohexane.

Stern–Volmer plots for the quenching are linear with slopes of  $k_q\tau = 79$  and 51 M in acetonitrile and cyclohexane, respectively (Figure 5). Since the excited states of 1,4-CHD are higher in energy than the respective excited states of the acetylene, electron transfer should be the main photophysical mechanism for the fluorescence quenching. Consistent with this notion, the quenching is ca. 5 times less efficient in cyclohexane than in acetonitrile (assuming that the lifetimes are similar in the two solvents). A Stern–Volmer plot for a much stronger

(28) The quantum yields for the loss of 2-tetrafluoropyridylethynyl pyrazine **12** in acetonitrile,  $(27.3 \pm 0.4) \times 10^{-2}$ ; in cyclohexane,  $(26.9 \pm 0.3) \times 10^{-2}$ .

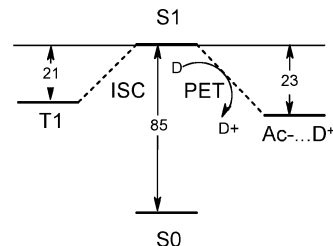
(29) Measured by Professor J. Kauffman at the University of Missouri-Columbia.

(30) Rehm, D.; Weller, A. *Isr. J. Chem.* **1970**, *8*, 59.

(31) Shono, T.; Ikeda, A.; Hayashi, J.; Hakozi, S. *J. Am. Chem. Soc.* **1975**, *97*, 4261.

(32) Nagano, Y.; Ikoma, T.; Akiyama, K.; Tero-Kubota, S. *J. Chem. Phys.* **2001**, *114*, 1775.

**Scheme 9.** Competing Photophysical Pathways for the Reaction of 1,4-CHD (D = donor) and Diaryl Acetylenes (Ac)<sup>a</sup>



<sup>a</sup> Energies of states relative to S<sub>0</sub> are given in kcal/mol for the case of bis-TFP acetylene **9** in acetonitrile.

electron donor, Et<sub>3</sub>N ( $\Delta G_{\text{ET}} = -30$  kcal/mol), shows a 40% increase in the efficiency of fluorescence quenching indicating that PET in the case of 1,4-CHD is very fast but not diffusion controlled.

These results provide an explanation for the “anomalous” plot in Figure 4 and show that reaction efficiency is a compromise between the rate of intersystem crossing forming the reacting triplet and unproductive interception of the singlet excited state through electron transfer from 1,4-cyclohexadiene (Scheme 9). In the case of the strongly acceptor bis-TFP acetylene **9** and high concentrations of 1,4-CHD, PET successfully competes with ISC leading to the observed decrease in cycloaddition efficiency. For the less electron-deficient acetylenes, this competition is less important and triplet reactivity is observed (Table 6).

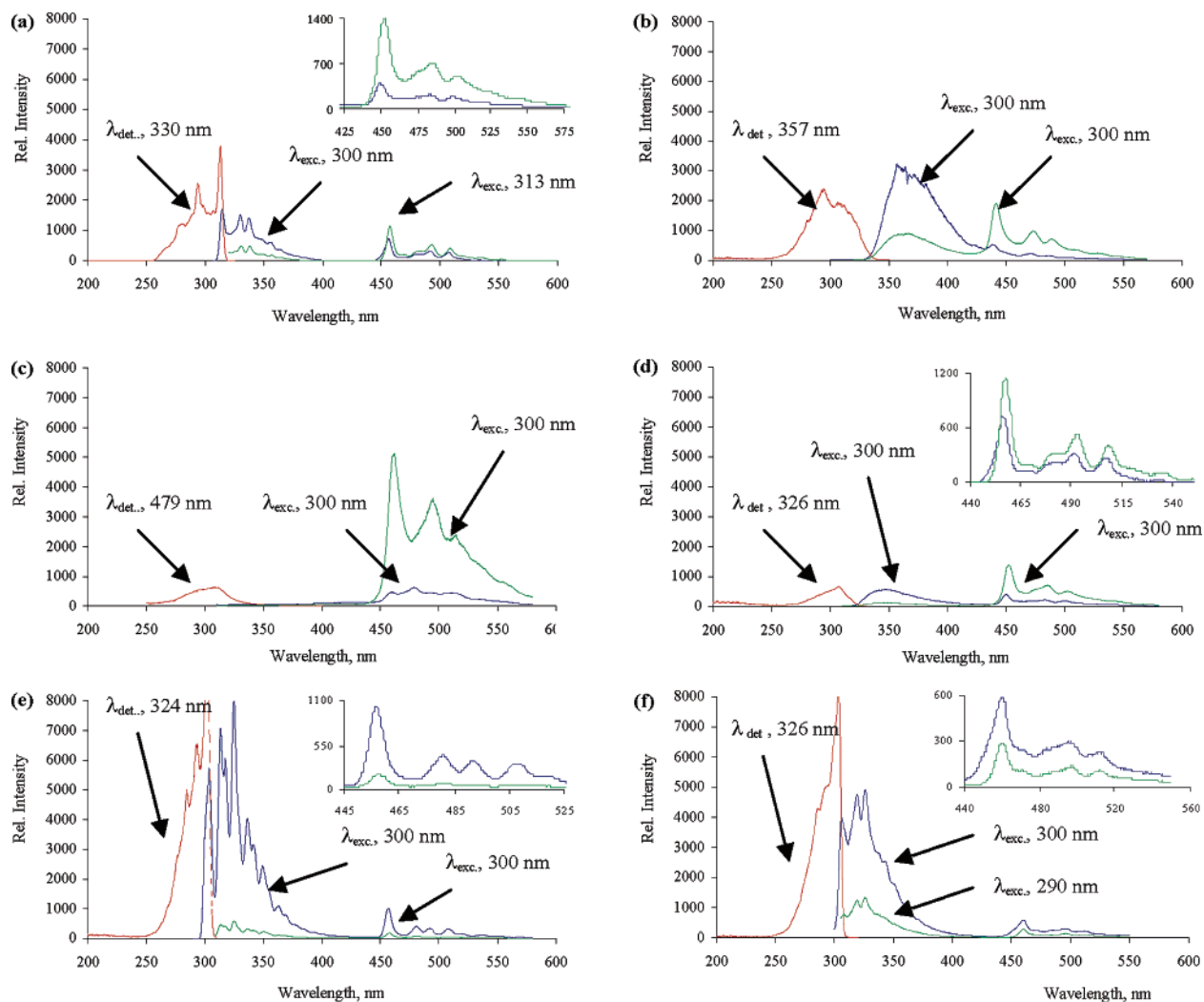
**Phosphorescence of Diaryl Acetylenes at Low Temperature.** Further insight into the nature of triplet excited states of diaryl acetylenes was obtained by spectroscopic studies. Low-temperature emission spectra of six acetylenes (four reactive and two unreactive) were recorded at 77 K in Pyrex NMR tubes in methylcyclohexane glass after three freeze/pump/thaw degassing cycles. Under these conditions, emission spectra of the acetylenes show two sets of signals (Figure 6). The set at the shorter wavelengths is a mirror image of the excitation spectrum and corresponds to the fluorescence spectrum, whereas the second set of peaks at lower energy ( $\lambda > 450$  nm) corresponds to phosphorescence. Importantly, both the strong 0–0 band and the vibronic structure in the phosphorescence spectra of all acetylenes are almost identical to each other and to the literature spectrum of toluene **17**.<sup>32</sup> Such spectral similarity suggests that the electronic structures of the lowest triplet excited states are close as well.

Although phosphorescence could not be sensitized in glassy methylcyclohexane through triplet energy transfer using conventional triplet sensitizers (benzophenone,  $E_T = 68$  kcal/mol;

**Table 6.** Reduction Potentials, Energies of Singlet and Triplet Excited States and PET Free Energies for Selected Diaryl Acetylenes

acetylenes	$E_{\text{pc}} \text{A}/\text{A}^-$ (V) <sup>a</sup>	$E_S^{\text{b}}$	$E_T^{\text{b}}$	$\Delta G_{\text{ET}, \text{S}}^{\text{c}}$	$\Delta G_{\text{ET}, \text{T}}^{\text{c}}$
Ph-PFB, <b>18</b>	-2.1	93	62	-5.7	25.2
2-Py-TFP, <b>6</b>	-1.4	88	63	-16.9	8.1
Ph-TFP, <b>10</b>	-1.6	90	62	-15.4	14.6
TFP-TFP, <b>9</b>	-1.0	85	64	-23.1	-2.1
Pyra-TFP, <b>12</b>	-1.2	89	61	-21.4	6.6

<sup>a</sup> The reduction is irreversible, peak potentials are measured vs SCE in DMF, [acetylene] =  $1 \times 10^{-2}$  M. <sup>b</sup> Values in kcal/mol estimated from low-temperature fluorescence and phosphorescence spectra. <sup>c</sup> Values in kcal/mol calculated from the Rehm–Weller equation taking  $w_p = 1.3$  kcal/mol, and  $E_{1/2}(\text{D}^+/\text{D}) = 1.74$  (vs SCE) for 1,4-CHD.



**Figure 6.** Excitation (dotted red line) and emission (solid blue line) spectra from  $10^{-5}$  M of acetylene solutions in the absence and presence of methyl iodide (dashed green line): (a) Ph-TFP **10**; (b) TFP-TFP **9**; (c) Pyra-TFP **12**; (d) 2-Py-TFP **6**; (e) Ph-Ph **17**; (f) Ph-PFB **18** in frozen methylcyclohexane glass (77 K). Both excitation and detection wavelengths are shown.

acetophenone,  $E_T = 74$  kcal/mol; and xanthone,  $E_T = 74$  kcal/mol), we found it to be sensitive to the presence of MeI (Figure 6).<sup>33</sup> Remarkably, adding MeI to the methylcyclohexane glasses enhanced initially very weak phosphorescence of reactive acetylenes **6**, **9**, **10**, and **12** (at the expense of their fluorescence) but did not lead to a similar phosphorescence enhancement in the case of unreactive Ph-PFB **18** and Ph-Ph acetylenes **17**.<sup>33</sup> These differences between reactive and unreactive acetylenes further suggest that ISC efficiency and the dynamics of triplet state formation are important for the homoquadricyclane formation.

The phosphorescence spectra also give triplet energies of acetylenes **6**, **9**, **10**, **12**, and **18**. Values estimated from the onset of the phosphorescence peaks are given in Table 6. These values are in a good agreement with the results of triplet quenching and sensitization experiments discussed above and with the computational data provided in Table 8.

**Laser Flash Photolysis Studies.** Transient absorption of diaryl acetylenes under laser flash photolysis (LFP) using 266 nm excitation was monitored at 450 nm. The triplet lifetimes were determined by fitting the decays with a single or (when

**Table 7.** Lifetimes of Excited Species Determined by LFP,  $\text{CH}_3\text{CN}$ , 25 °C in Argon-Saturated (Left) and Oxygen-Saturated (Right) Solutions

acetylene	argon-saturated		oxygen-saturated	
	$\tau_1$ ( $\mu\text{s}$ )	$\tau_2$ ( $\mu\text{s}$ )	$\tau_1$ ( $\mu\text{s}$ )	$\tau_2$ ( $\mu\text{s}$ )
2-Py-TFP, <b>6</b>	71.8		24.0	
Ph-TFP, <b>10</b>	4.06		<1.5	
Ph-PFB, <b>18</b>	25.6	5.2	<1.5	
Pyra-TFP, <b>12</b>	22.6	4.36	10.8	<1.5
TFP-TFP, <b>9</b>	1.82		<1.5	
4-Py-4-Py, <b>14</b>	1.72		<1.5	

necessary) a double exponential function (further details are given in the Supporting Information). The results for selected acetylene triplet states with and without oxygen in acetonitrile are shown in Table 7.

Interestingly, 2-Py-TFP acetylene **6** which has the longest lived triplet excited state has the highest cycloaddition quantum yield, *vide supra*. In all of the cases, saturation of solutions with oxygen leads to a noticeable decrease in the lifetime of the excited species.<sup>34</sup> Interestingly, the triplet states of more electron-deficient 2-Py-TFP **6** and Pyra-TFP **12** acetylenes are quenched by oxygen rather inefficiently compared to the triplet of Ph-PFB **18** acetylene. The slower quenching is consistent with

(33) 20  $\mu\text{l}$  of MeI was added to 1.0 mL of acetylene solution.

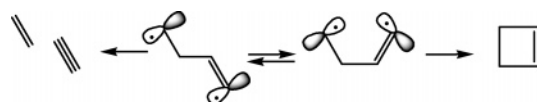
different electronic properties of the respective triplet states, e.g., higher electrophilicity and greater oxidative potential of the TFP triplets.<sup>35</sup> Unfortunately, the two symmetric acetylenes have lifetimes shorter than our instrument response which precluded us from estimating the efficiency of triplet quenching with oxygen using available instrumentation.<sup>36</sup> The efficiency of singlet oxygen formation has been used in the literature as a tool to study electronic properties and nature of T<sub>1</sub> states.<sup>37</sup> For example, these efficiencies vary from 0.3 to 0.5 for n- $\pi^*$  excited ketones,<sup>38</sup> whereas in the cases of  $\pi$ - $\pi^*$  excited ketones and  $\pi$ - $\pi^*$  excited aromatic hydrocarbons, these values are generally close to unity (0.8–1).<sup>39</sup>

These data suggest that, besides the ISC efficiency, sufficiently long triplet lifetime and electron deficiency of triplet state are the two conditions favoring the photocycloaddition. In the ideal case of 2-Py-TFP acetylene, both of these conditions are satisfied. In the case of short-lived triplets, the role of electrophilicity becomes essential as illustrated by comparison of the results for the two symmetric acetylenes **9** and **14**: although the lifetimes of bis-TFP **9** and bis-4-Py **14** triplets are very close, the quantum yield for the formation of homoquadricyclane product is considerably higher in the case of the more electron-deficient and, thus, more reactive bis-TFP acetylene.

**Reaction Mechanisms. A. Formation of Homoquadricyclanes.** Literature reports describing the photochemical transformation of acetylenes into homoquadricyclanes are scarce, and there are no mechanistic studies aimed at elucidation of factors controlling efficiency of this reaction as well as the nature of excited states (singlet vs triplet) involved in this transformation. The reaction yields are generally low, and quantum yields for the formation of the products were never measured. The only conclusion regarding the reaction mechanisms which could be derived from the earlier literature data is that formation of homoquadricyclanes from acetylenes requires the presence of a C=O moiety in the excited reagent (either the diene or the acetylene). This observation supports the notion that the presence of a long-lived and electron-deficient triplet excited state (vide supra) is essential for these photocycloadditions and agrees well with our experimental data for diarylacetylenes.

One can also speculate that the other key requirements are efficient formation of the triplet state upon excitation and inefficient ISC of the triplet 1,4-diradical intermediate formed by addition of excited acetylene to alkene to its singlet counterpart (vide infra). Depending on their conformation,

**Scheme 10.** Most Common Reactions of Singlet 1,4-Biradicals<sup>40</sup>



singlet 1,4-diradicals are expected either to undergo the Grob fragmentation or to close into the cyclobutene products (Scheme 10).

**Computational Analysis of Triplet Excited States of the Diaryl Acetylenes.** Although the phosphorescence studies suggest that all diaryl acetylenes have lowest excited states of the similar nature, the oxygen quenching in LFP experiments and contrasting MeI effects on phosphorescence suggest that differences in dynamics and electronic properties exist between reactive and unreactive acetylenes. In the next section of the paper, we describe a computational study aimed to determine how the nature of aryl group influences the electronic structure of the T<sub>1</sub> state of diaryl acetylenes.

The results of computational analysis of these species using unrestricted B3LYP/6-31(d,p) methods are shown in Table 8. Although the energies of all of the excited triplet states of acetylenes are quite close and all of the triplet states are dominated by a  $\pi_x$ - $\pi_x^*$  configuration,<sup>41,42</sup> some differences in their electronic structures are noticeable. Comparison of nitrogen-containing acetylenes **10** and **15** with Ph-PFB acetylene **18** is especially interesting. Polarization of the triple bond in the ground state is quite similar for the Ph-TFP and Ph-PFB acetylenes, and in both cases, electron density is shifted to the acceptor group. As a result, the acetylenic carbon adjacent to this group acquires a small negative charge, whereas the acetylenic carbon remote from the acceptor attains a positive charge. Although electron density is moved from the central carbons in all of the triplets, only in the case of 4-Py-Ph **15** and Ph-TFP **10** triplet states polarization of the triple bond is inverted relative to the respective ground state (“umpolung” by light). In contrast, the *relative* polarization of the triple bond in the triplet of Ph-PFB acetylene does not change relative to the ground state. Interestingly, in the nitrogen-containing triplets, the carbon atom adjacent to the pyridyl groups bears a larger positive charge and is more electrophilic. Although T<sub>1</sub> triplets at the UB3LYP level are still dominated by a  $\pi$ , $\pi^*$  configuration, this change may suggest a slight increase in the n, $\pi^*$  character in pyridine triplets with electron density being transferred from the nitrogen lone pair to the  $\pi^*$  orbital delocalized throughout the molecule.

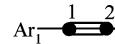
At the UB3LYP/6-31G(d,p) level, the differences between the electronic structures of reactive and unreactive acetylenes are not dramatic (Table 9) and, when taken alone, are not likely to explain the sharp divergence in reactivity of TFP- and PFB-substituted acetylenes. Calculations including the self-consistent reaction field (SCRF) solvation model (CH<sub>3</sub>CN) confirm the general trend found by the gas-phase computations.<sup>43</sup> Solvation effects slightly *enhance* the change in polarization upon triplet

- (34) Interestingly, argon-saturated solutions of acetylenes changed color after flash photolysis (yellowish in the case of Ph-TFP and even yellow reddish in the case of 2-Py-TFP). The color change is less pronounced in oxygen saturated solutions. This indicates that the acetylenes reacted when irradiated with the laser pulse and that the reactive species, presumably the triplet excited state of the acetylene, is quenched with oxygen.
- (35) Oxygen quenching rate correlates with oxidation potential of fluorenes: Mehrdad, Z.; Noll, A.; Grabner, E. W.; Schmidt, R. *Photochem. Photobiol. Sci.* **2002**, *1*, 263. Biphenyls: Schmidt, R.; Shafii, F. *J. Phys. Chem. A* **2001**, *105*, 8871. Wilkinson, F.; Abdel-Shafii, A. A. *J. Phys. Chem. A* **1999**, *103*, 5425. For a detailed review, see: Schweitzer, C.; Schmidt, R. *Chem. Rev.* **2003**, *103*, 1685.
- (36) It is interesting that the decay is biexponential in the cases of Ph-PFB **18** and Pyra-TFP **12** acetylenes.
- (37) Darmanyan, A. P.; Foote, C. S. *J. Phys. Chem.* **1993**, *97*, 4573.
- (38) Gorman, A. A.; Lovering, G.; Rodgers, M. A. J. *J. Am. Chem. Soc.* **1978**, *100*, 4527. Chattopadhyay, S. K.; Kumar, C. V.; Das, P. K. *J. Photochem.* **1985**, *30*, 81. Redmond, R. W.; Braslavsky, S. E. *Chem. Phys. Lett.* **1988**, *148*, 523. Wang, B.; Ogilby, P. R. *J. Photochem. Photobiol., A* **1995**, *90*, 85. Mehrdad, Z.; Schweitzer, C.; Schmidt, R. *J. Phys. Chem. A* **2002**, *106*, 228.
- (39) Marti, C.; Jurgens, O.; Cuenca, O.; Casals, M.; Nonell, S. *J. Photochem. Photobiol., A* **1996**, *97*, 11.

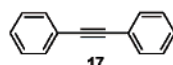
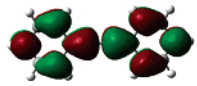
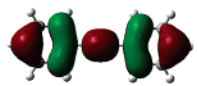

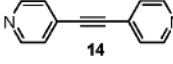
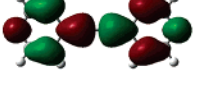
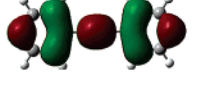

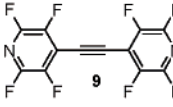
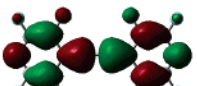
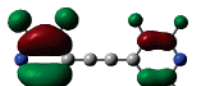
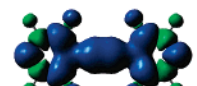
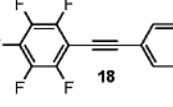
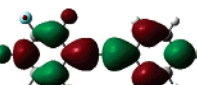
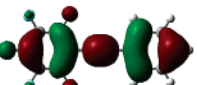
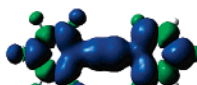
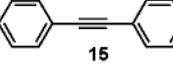
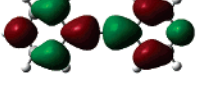
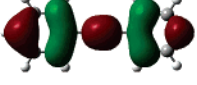

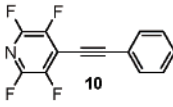
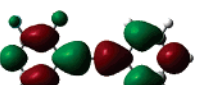


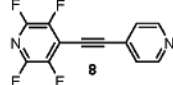
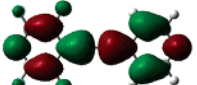
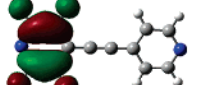
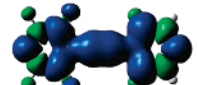
- (40) Differences in hybridization of nonbonding orbitals at sp<sup>3</sup> and sp<sup>2</sup> carbon centers are neglected.
- (41) These results are consistent with those reported in a recent combined experimental and theoretical study of phenylene-acetylenes: Magyar, R. J.; Tretiak, S.; Gao, Y.; Wang, H. L.; Shreve, A. P. *Chem. Phys. Lett.* **2005**, *401*, 149.
- (42) Our computational results also strongly support conclusions of Tero-Kubota and co-workers (ref 32) who, based on experimental observations, suggested that T<sub>1</sub> states of diphenyl acetylene and related molecules are planar and have a  $\pi_x$ - $\pi_x^*$  configuration.



**Table 8.** C≡C Distances (Å), Charges (au) at the “Alkyne” Carbon Atoms (Values for Triplet Excited State are Given in Parentheses), and Energies (kcal/mol<sup>-1</sup>) for the T<sub>1</sub> States of Diarylacetylenes in CH<sub>3</sub>CN at the UB3LYP/6-31G(d,p) Level (See Supporting Information for Computational Details)

Ar <sub>1</sub> —  —Ar <sub>2</sub>	C <sub>1</sub> –C <sub>2</sub>	q <sub>C1</sub>	q <sub>C2</sub>	T <sub>1</sub> energy
Ar <sub>1</sub> = Ar <sub>2</sub> = Ph, <b>17</b>	1.2167 (1.2645)	0.001 (0.031)	0.001 (0.031)	61.2
Ar <sub>1</sub> = Ar <sub>2</sub> = 4-Py, <b>14</b>	1.2150 (1.2663)	0.019 (0.072)	0.019 (0.072)	62.8
Ar <sub>1</sub> = Ar <sub>2</sub> = TFP, <b>9</b>	1.2120 (1.2631)	0.042 (0.097)	0.042 (0.097)	62.5
Ar <sub>1</sub> = Ph, Ar <sub>2</sub> = PFB, <b>18</b>	1.2151 (1.2612)	0.055 (0.060)	-0.029 (0.029)	60.4
Ar <sub>1</sub> = Ph, Ar <sub>2</sub> = 4-Py, <b>15</b>	1.2162 (1.2639)	0.028 (0.018)	-0.010 (0.076)	61.6
Ar <sub>1</sub> = Ph, Ar <sub>2</sub> = TFP, <b>10</b>	1.2154 (1.2604)	0.084 (0.039)	-0.040 (0.079)	60.2
Ar <sub>1</sub> = 4-Py, Ar <sub>2</sub> = TFP, <b>8</b>	1.2138 (1.2643)	0.072 (0.093)	-0.010 (0.076)	62.4

**Table 9.** Singly Occupied Molecular Orbitals (SOMOs) and Spin Density Distribution for the Lowest Triplet States of Diarylacetylenes Optimized at the UB3LYP/6-31G(d,p) Level

Compound	SOMO <sub>1</sub>	SOMO <sub>2</sub>	Spin density
			
			
			
			
			
			
			

excitation in pyridinyl acetylenes and *decrease* such a change in Ph-PFB acetylene.

#### Role of n,π\* States in Homoquadricyclane Formation.

Since the lowest energy triplets in both reactive and unreactive diaryl acetylenes in this study have a dominant π,π\* configuration, one has to ask the question about the origin of the dramatic difference in reactivity of pyridinyl and pyrazinyl acetylenes and whether the presence of a higher energy n,π\* state in azaheterocycles play any role in this phenomenon.

Since <sup>3</sup>n,π\* is not the lowest triplet state, it should undergo fast radiationless decay into the lowest energy <sup>3</sup>π,π\* state in accordance with Kasha's rules<sup>44,45</sup> and, thus, is unlikely to play a direct role in photochemical reactivity. However, its presence

plays an important role in the *efficiency* of <sup>3</sup>π,π\* triplet excited state formation. In seminal studies, El-Sayed had shown that the first-order spin-orbit coupling (SOC) is forbidden between states of the same configuration and developed the set of selection rules (commonly known as El-Sayed rules) for ISC in compounds possessing π-π\* and n-π\* states.<sup>24</sup> This work found that transition between <sup>1</sup>π,π\* and <sup>3</sup>n,π\* states in N-heterocyclic molecules proceeds up to three orders of magnitude faster (~10<sup>-9</sup> s) in pyridines than ISC between <sup>1</sup>π,π\* and <sup>3</sup>π,π\* states (~10<sup>-6</sup> s) and radiative decay back to the ground state (~10<sup>-7</sup> s). Since transitions between <sup>3</sup>π,π\* and <sup>3</sup>n,π\* are known to be very fast (~10<sup>-11</sup> s), the overall effect of the <sup>3</sup>n,π\* state presence is a dramatic increase in the efficiency of S<sub>1</sub>→T<sub>1</sub> triplet state formation, Scheme 11. This increase effectively “blocks” side reactions associated with singlet excited-state reactivity.

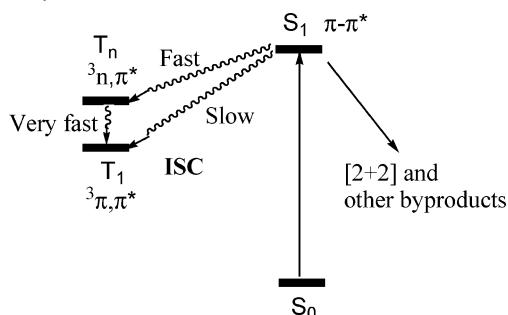
**Competing Pathways for the Homoquadricyclane Formation.** Several photochemical routes summarized in Scheme 12 can account for the formation of homoquadricyclane adducts.

(43) Calculations including the self-consistent reaction field (SCRf) in the gas-phase computations are included in the Supporting Information.

(44) Kasha, M. *Discuss. Faraday Soc.* **1950**, *9*, 14.

(45) For the interesting consequences of the presence of n,π\* states in pyridines and other azaheterocycles, see: ref 44 and Kasha, M. *Radiat. Res. Suppl.* **1960**, *2*, 243. Goodman, L. *J. Mol. Spectrosc.* **1961**, *6*, 109. Lower, S. K.; El-Sayed, M. A. *Chem. Rev.* **1966**, *66*, 199.



**Scheme 11.** Role of a “Phantom”  $^3n,\pi^*$  State in Enhancing ISC in Diaryl Acetylenes

In every case, the initially formed first singlet excited state of diaryl acetylenes ( $S_1$ ) undergoes intersystem crossing (ISC) to the first triplet excited state ( $T_1$ ). High efficiency of ISC is consistent with the drastically reduced fluorescence and with the observed lack of photochemical reactivity (C1C5 cyclization)<sup>4</sup> derived from PET from 1,4-CHD to the enediyne moiety of **3**.<sup>46</sup> In contrast with the earlier photochemical reactions of enediynes where 1,4-CHD serves as a source of *electrons and/or hydrogen atoms*,<sup>4</sup> the triplet excited state of enediyne **3** and related monoacetylenes finds yet another way to engage 1,4-CHD in a photochemical reaction by attacking one of the two *double bonds* of cyclohexadiene moiety. Although lack of PET from 1,4-CHD is readily explained by the lower energy of the triplet state, the switch from H-atoms abstraction to the attack on the  $\pi$ -system provides a direct insight into the electronic structure of the triplet acetylenes and deserves an additional comment.

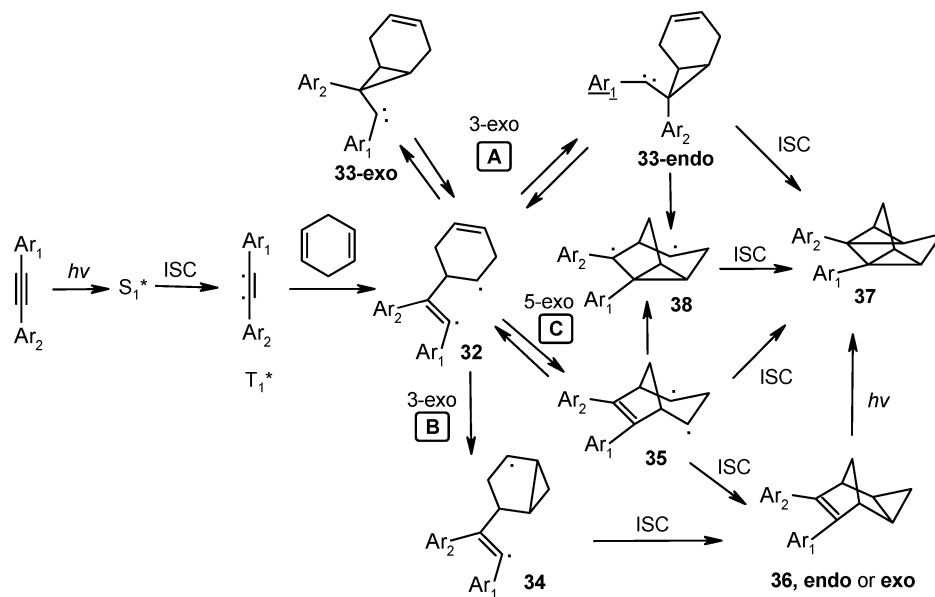
In general, such a competition between hydrogen atom abstraction and addition to a double bond is a typical feature of radical processes. Although radicals can participate in both of the above reactions, they often exhibit a preference toward a particular pathway depending on their nucleophilic or electrophilic character.<sup>47</sup> The fact that triplet acetylenes choose for the attack a position of increased electron density (the  $\pi$ -bond) rather than the partially positive hydrogen atom of C–H bonds strongly suggests the *electrophilic nature of the triplet diaryl acetylenes*,

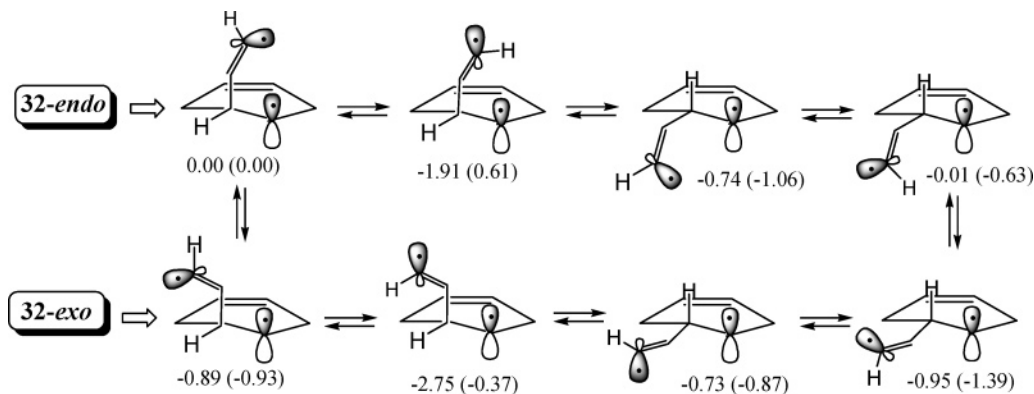
a notion which is in perfect agreement with the observed quantum yield increase for acetylenes with electron-acceptor substituents (Table 3).

After addition of the triplet acetylene to the double bond, the initially formed diradical intermediate **32** can undergo three different intramolecular cyclizations. In the most “economic” mechanism **A**, the radical on the cyclohexenyl moiety “comes back” to the former acetylenic moiety in a 3-exo-trig fashion<sup>49</sup> with formation of a carbene **33**. Insertion of the carbene into the remaining double bond will lead directly to the tetracyclooctane adduct **37**. The insertion can be either stepwise or concerted depending on the multiplicity of the carbene (triplet or singlet), which, in turn, is determined by the relative ISC timing. The carbene mechanism is supported by an earlier finding that the photochemical reaction of dimethyl acetylene dicarboxylate with ethylene<sup>50</sup> resulted in a 9:1 mixture of cyclobutene and dicyclopropane adducts where the latter product was suggested to be formed through a similar cyclopropane–carbene intermediate.

The main problem with extending this mechanism to our system is that in the intramolecular version of this process the first cyclization step should lead to formation of a mixture of two carbene isomers (exo- and endo-) shown in Scheme 12, and according to the simple geometric considerations, only one of these isomers can insert into the double bond. Although the “unreactive” isomer **33-exo** can be “recycled” back to the 1,4-diradical **32**, one would expect that if carbene **33** and diradical **32** were in an equilibrium, the latter would sooner or later undergo ISC to a ground state 1,4-diradical which should close to the cyclobutene product of formal [2+2] cycloaddition. We do not observe such a product as well as any other products derived from **33-exo** carbene in reactions with cyclohexadiene.<sup>51</sup> In a recent work, Tomioka et al. had shown that triplet diaryl carbenes readily abstract hydrogen from 1,4-CHD.<sup>52</sup>

In a second possible mechanism **B**, the radical at the cyclohexene moiety of **32** reacts via another 3-exo-trig pathway with the remaining double bond of 1,4-CHD to give a new diradical **34**. The newly formed radical centers can combine after ISC to give a stable intermediate **36**.<sup>53</sup> This intermediate

**Scheme 12.** Possible Mechanisms of the Homoquadricyclanes Formation in Photocycloaddition of Diaryl Acetylenes to 1,4-CHD<sup>48</sup>



**Figure 7.** Relative energies (UB3LYP/6-31G\*\*) from ground ( $S_0$ ) and triplet ( $T_1$ , in parentheses) states for conformers of diradical intermediates **32-endo** and **32-exo**.

would require further photochemical excitation in order to undergo a  $[2\pi+2\sigma]$  transformation to the homoquadricyclane product.<sup>54,52</sup>

The final possibility **C** is the 5-exo-trig cyclization of the vinyl radical **32** leading to a 1,3-diradical **35**. According to the empirical “rule of five”<sup>55</sup> which is a paraphrase of the Baldwin rules,<sup>56</sup> this should be the most likely pathway. This cyclization opens two new directions. In the first of them, the diradical undergoes ISC and closes to form the cyclopropane **36** which needs to absorb another photon for the transformation to the final product **37** as described in the previous paragraph. Alternatively, one of the radical centers of **35** reacts with the double bond to give diradical **38**, and the two radical centers recombine only at the final stage providing the homoquadricyclane product **37**. In this process, each of the two unpaired electrons generated at the triple bond by photochemical excita-

tion eventually comes back to the same carbon atoms as a boomerang. Again, ISC is needed somewhere along this reaction path to arrive at the final product.

The partitioning between the alternative cyclization pathways will depend on the conformational landscape of the diradical **32** potential energy surface. For the parent version of this diradical, this landscape is rather flat<sup>57</sup> at the triplet hypersurface with the “equatorial” conformers suitable for the 5-exo cyclization being among the lowest energy conformers (Figure 7). In contrast, the singlet hypersurface is biased toward the two conformers where both radical orbitals are parallel to the bridge C–C bond. This arrangement results in a stabilizing interaction transferred through the  $\sigma^*$  bridge orbital.<sup>58</sup> Such interactions received a lot of attention in the chemistry of 1,4-diradicals produced in the Bergman and related cycloaromatization reactions<sup>59</sup> where they are estimated to be typically on the order of 3–5 kcal/mol.<sup>60,61</sup> Most importantly, the lower energy conformers for the singlet 1,4-diradical are predisposed for the  $[2+2]$ -adduct formation, the Grob fragmentation regenerating the starting acetylene and 1,4-CHD or 3-exo cyclization leading to **33-exo**. Thus, it is not surprising that the homoquadricyclane formation only proceeds through a triplet excited state.

**Computational Analysis of Reaction Hypersurface for the Formation of Homoquadricyclane.** Since all of the mechanisms involve the similar steps (if one agrees to consider the carbene insertion as a formal addition of 1,1-diradical to a double bond) and differ only in their sequence, it is difficult to choose between the different mechanisms without additional information.

To gain this information, we performed computational analysis of the potential energy reaction hypersurfaces for the singlet and triplet reactions of acetylene and 1,4-CHD at the

(46) Unlike the highly exothermic PET to the singlet excited state, PET from 1,4-CHD to the triplet excited state becomes endothermic due to the lower energy of the latter state.

(47) A particularly thorough study: Pryor, W. A.; Tang, F. Y.; Tang, R. H.; Church, D. F. *J. Am. Chem. Soc.* **1982**, *104*, 2885. Zipse, H.; He, J.; Houk, K. N.; Giese, B. *J. Am. Chem. Soc.* **1991**, *113*, 4324. Tararov, V. I.; Kuznetsov, N. Y.; Bakmutov, V. I.; Ikonnikov, N. S.; Bubnov, Y. N.; Khrustalev, V. N.; Saveleva, T. F.; Belokon, Y. N. *J. Chem. Soc., Perkin Trans. 1* **1997**, *20*, 3101. Heberger, K.; Lopata, A. *J. Org. Chem.* **1998**, *63*, 8646. Arnaud, R.; Bugaud, N.; Vetere, V.; Barone, V. *J. Am. Chem. Soc.* **1998**, *120*, 5733. Roberts, B. P.; Smits, T. M. *J. Chem. Soc., Perkin Trans. 2* **1999**, *12*, 2691. Lalevee, J.; Allonas, X.; Fouassier, J. *J. Phys. Chem. A* **2004**, *108*, 4326.

(48) Note that ISC should occur somewhere along the reaction hypersurface in order to reach the final product **37**. The lack of  $[2+2]$  adducts suggests that ISC occurs after the initially formed diradical **32** undergoes one of the further steps in the cyclization cascade. Five possible ISC points are shown, but it is possible that ISC occurs even before these points.

(49) For recent examples of 3-exo-trig cyclizations, see: Journet, M.; Malacria, M. *J. Org. Chem.* **1994**, *59*, 718. Srikrishna, A.; Danieloss, S. *J. Org. Chem.* **1997**, *62*, 7863. Lange, G. L.; Merica, A. *Tetrahedron Lett.* **1999**, *40*, 7897. The first step of di- $\pi$ -methane rearrangement can also be considered to be a 3-exo-trig cyclization when the excitation is mostly concentrated on one of the double bonds: Zimmerman, H. E.; Armesto, D. *Chem. Rev.* **1996**, *96*, 3065.

(50) Owsley, D. C.; Bloomfield, J. *J. Am. Chem. Soc.* **1971**, *93*, 782.

(51) The  $[2+2]$  adducts are readily formed in reactions with alkenes such as cyclohexene and tetramethyl ethylene.

(52) Monguchi, K.; Itoh, T.; Hirai, K.; Tomioka, H. *J. Am. Chem. Soc.* **2004**, *126*, 11900.

(53) Control experiments ruled out a thermal homo-Diels–Alder reaction between 1,4-CHD and acetylene which is the other way to form compound **36**.

(54) Srinivasan, R.; Ors, J. A.; Brown, K. H.; Baum, T.; White, L. S.; Rossi, A. R. *J. Am. Chem. Soc.* **1980**, *102*, 5297.

(55) Srinivasan, R.; Carlough, K. H. *J. Am. Chem. Soc.* **1967**, *89*, 4932. See also: Turro, N. J. *Molecular Photochemistry*; University Science Books: 1991; p 430. For MO and state correlation diagrams for the formation of five-membered biradicals in cyclizations of 1,4-pentadiene and 1,5-hexadiene, see: Gleiter, R.; Sander, W. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 566. For the role of sigma bridge in these processes, see: Verhoeven, J. W. *Recl. Trav. Chim. Pays-Bas* **1980**, *99*, 375.

(56) Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734.

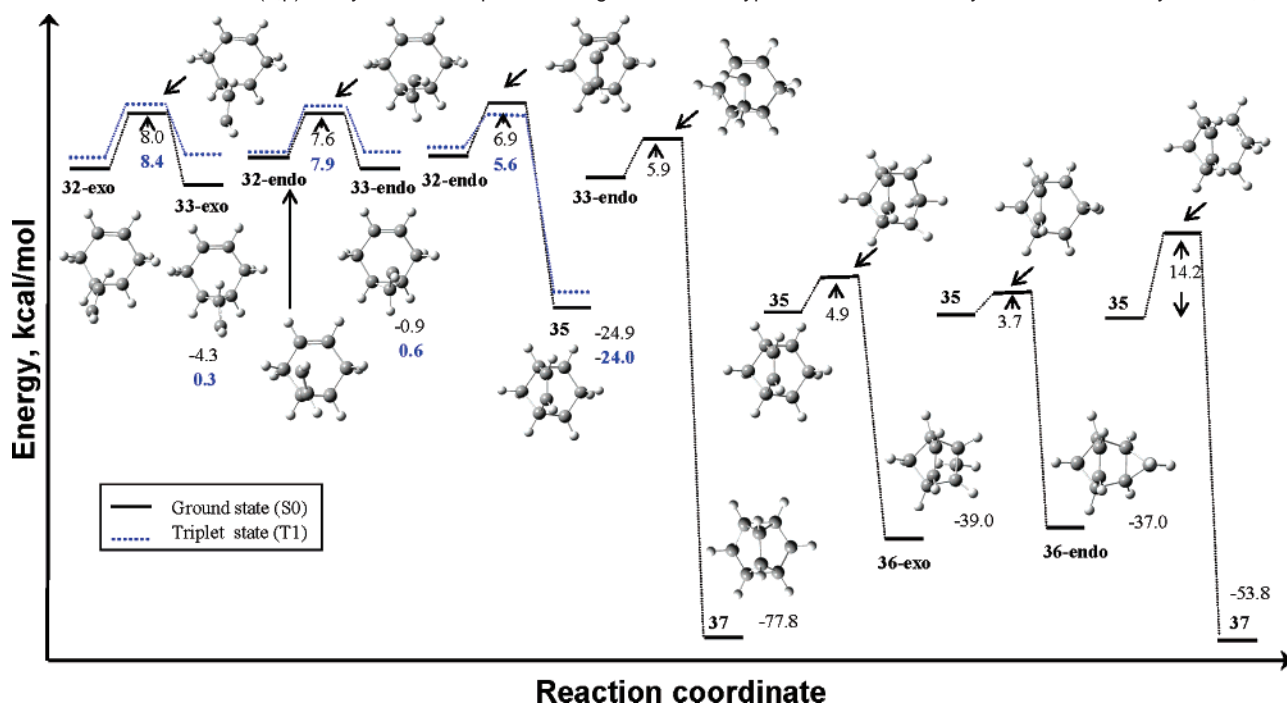
(57) This is a typical situation for diradical species. For a recent discussion and references, see: Doering, W. v. E.; Barsa, E. A. *J. Am. Chem. Soc.* **2004**, *126*, 12353. See also: Doering, W. v. E.; DeLuca, J. P. *J. Am. Chem. Soc.* **2003**, *125*, 10608. von Doering, W.; Cheng, X.; Lee, K.; Lin, Z. *J. Am. Chem. Soc.* **2003**, *124*, 11642.

(58) The seminal study: (a) Hoffmann, R.; Imamura, A.; Hehre, W. J. *J. Am. Chem. Soc.* **1968**, *90*, 1499. (b) Hoffmann, R. *Acc. Chem. Res.* **1971**, *4*, 1–9. (c) Paddon-Row, M. N. *Acc. Chem. Res.* **1982**, *15*, 245. (d) Gleiter, R.; Schafer, W. *Acc. Chem. Res.* **1990**, *23*, 369–375. (e) Brodskaya, E. I.; Ratovskii, G. V.; Voronkov, M. G. *Russ. Chem. Rev.* **1993**, *62*, 975.

(59) Logan, C. F.; Chen, P. *J. Am. Chem. Soc.* **1996**, *118*, 2113. Schottelius, M. J.; Chen, P. *J. Am. Chem. Soc.* **1996**, *118*, 4896. Kraka, E.; Cremer, D. *J. Am. Chem. Soc.* **2000**, *122*, 8245. Alabugin, I. V.; Manoharan, M. *J. Am. Chem. Soc.* **2003**, *125*, 4495.

(60) For the most thorough recent discussion, see: Squires, R. R.; Cramer, C. J. *J. Phys. Chem. A* **1998**, *102*, 9072.

(61) Antiperiplanar arrangement of the two radical centers strengthens their interaction even further: Prall, M.; Wittkopp, A.; Schreiner, P. R. *J. Phys. Chem. A* **2001**, *105*, 9265.

**Scheme 13.** UB3LYP/6-31G(d,p) Analysis of the Triplet and Singlet Reaction Hypersurfaces for Photocycloaddition of Acetylene to 1,4-CHD

UB3LYP/6-31G(d,p) level (Scheme 13). According to this analysis, both 5-exo and 3-exo cyclizations of diradical **32** proceed through low energy transition states but formation of intermediate **35** through the 5-exo pathway is the most favorable pathway, both kinetically and thermodynamically. The kinetic preference for 5-exo cyclization is greater in the triplet state than in the singlet state (2.3 vs 0.7 kcal/mol), but in both cases the cyclization is ca. 24–25 kcal/mol exothermic and essentially irreversible. Two new possibilities arise at this point. In the first, recombination of the two radical centers of **35** leads to the formation of the strained intermediate **36**. Two isomers of **36** (exo- and endo-) can be formed via relatively low barriers (ca. 5 and 4 kcal/mol, respectively). Transformation of this intermediate to the final product **37** through  $[2\sigma-2\pi]$  cyclization releases ca. 15 kcal/mol of strain energy and should be essentially irreversible.<sup>62</sup> High photochemical reactivity of intermediate **36** may explain its absence in the reaction mixtures and the quantum yields for the formation of homoquadricyclane products which reach the upper limits of 0.5, the maximum possible value for a sequential two-photon process. The second possibility which cannot be eliminated at this moment is that the diradical remains a triplet and reacts with the remaining triple bond to give **38**. The latter intermediate finally undergoes ISC to form the homoquadricyclane product.

The 3-exo cyclizations of **32** into cyclopropyl carbenes **33-exo** and **33-endo** is less likely but still a viable possibility. In contrast to the 5-exo pathway, these transformations are almost thermoneutral and should be readily reversible. This is especially important in the case of the exo-isomer which does not possess a readily accessible intramolecular reaction path. On the other hand, the endo-isomer can be readily and irreversibly trapped through intramolecular cyclopropanation of the remaining

**Table 10.** UB3LYP/6-31G(d,p) Analysis of Possible Cycloaddition Reaction Intermediates: Relative Energies (RE) to the Ground State Acetylene and 1,4-Cyclohexadiene, Singlet–Triplet Gaps, and Spin–Orbit Coupling (SOC) Values

compound	RE(S <sub>0</sub> ) kcal/mol <sup>-1</sup>	RE(T <sub>1</sub> ) kcal/mol <sup>-1</sup>	E <sub>ST</sub> , kcal/mol <sup>-1</sup>	SOC, <sup>a</sup> cm <sup>-1</sup>
<b>32-exo</b>	36.2	36.9	0.7	0.2
<b>32-endo</b>	37.1	37.8	0.7	0.2
<b>33-exo</b>	31.9	37.2	5.3	12.8
<b>33-endo</b>	36.2	38.4	2.2	12.8
<b>34-exo</b>	44.5	45.4	0.8	0.0
<b>34-endo</b>	45.9	46.0	0.2	0.0
<b>35</b>	12.2	13.8	1.6	0.1
<b>36-exo</b>	-26.7	43.2	69.9	na
<b>36-endo</b>	-24.8	47.9	72.6	na
<b>37</b>	-41.6	na	na	na

<sup>a</sup> A single-point calculation at the CASSCF level on the UB3LYP/6-31G(d,p) triplet geometries.

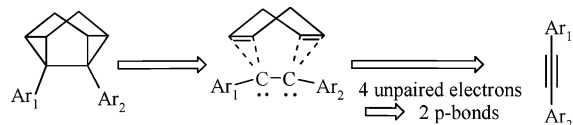
double bond. The spin–orbit coupling (SOC) values in Table 10 suggest that both triplet carbenes **33** should readily undergo ISC to their singlet counterparts unlike the **32** → **35** → **38** sequence which may occur at the triplet hypersurface.

**“Boomerang” Cycloaddition.** Even though, at this point, the computations do not give a definitive answer about the preferred reaction path and, at least, two converging pathways may be responsible for the formation of the observed products, the bulk of computational results does suggest that 5-exo cyclization at the triplet hypersurface is the most likely reaction pathway. Certainly, the presence of aryl substituents will influence the rather subtle differences between the alternative mechanisms, and further experimental and theoretical studies are needed to elucidate all of the mechanistic details of the (acetylene + diene) → homoquadricyclane transformation. It is possible that ISC may also be important in controlling the partitioning between the alternative mechanisms.<sup>63</sup> However, from a practical perspective, all of the mechanisms converge to the same product and differ only in a sequence of bond-forming steps, and thus,

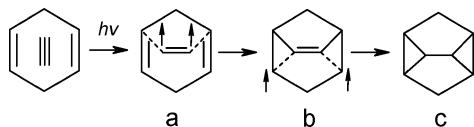
(62) Freeman and co-workers have shown that the endo-isomer reacts two times faster than the exo-isomer, a result which is consistent with the larger exothermicity computed in the former case: Freeman, P. K.; Kupur, D. G.; Mallikarjuna Rao, V. N. *Tetrahedron Lett.* **1965**, *37*, 3301.



**Scheme 14.** Retrosynthetic Analysis of the Photochemical Approach to Homoquadricyclanes Based on the Triplet Photocycloaddition of Diaryl Acetylenes and 1,4-CHD

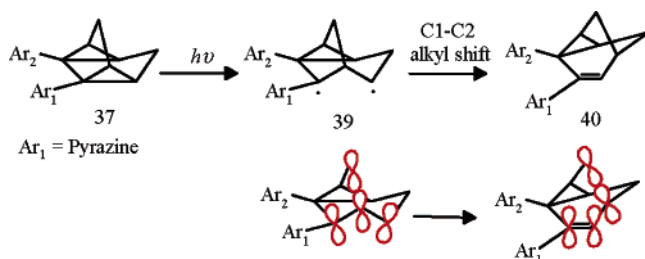


**Scheme 15.** Topological Analysis of the “Boomerang” Reaction of Vinyl-1,2-diyl with Two Double Bonds<sup>a</sup>



<sup>a</sup> (a) Triplet diradical is formed; (b) two new sigma bonds and two new radicals are formed at the expense of two  $\pi$ -bonds of 1,4-CHD; (c) the new radical centers complete the cyclic bond-forming route

**Scheme 16.** Secondary Photochemistry of Pyrazinyl Homoquadricyclanes



topologically, one can think about this transformation as cyclopropanation of both double bonds of a 1,4-diene by a 1,2-bicarbene synthon (Scheme 14). Mechanistically, this transformation occurs through a “boomerang” reaction of a vinyl-1,2-diyl diradical with two double bonds where the two radical centers “self-annihilate” after completing a circular cascade of bond-forming events (Scheme 15).

### B. Homoquadricyclane–Tricyclooctene Transformation.

Finally, the most probable mechanism for the transformation of homoquadricyclanes to the tricyclo[3.2.1.0<sup>4,6</sup>]oct-2-enes is shown in Scheme 16. Photochemical excitation of homoquadricyclane **37** results in the regioselective C–C rupture in the cyclopropyl group attached to the pyrazinyl ring and formation of 1,3-diradical **39**. The source of this selectivity is unknown at this moment<sup>64</sup> but is perfectly consistent with the absence of homoquadricyclane–tricyclooctene rearrangement in the case of pyridinyl-substituted homoquadricyclanes. This process is not affected by triplet sensitizers and quenchers and is likely to proceed through a singlet excited state.<sup>65</sup> This transformation is followed by a 1,2-carbon shift directly leading to tricyclooctene **40**.

**Practical Outlook.** Although it is known that strained alkynes sometimes react like bicarbenes,<sup>66</sup> the use of simple diaryl acetylenes in their triplet excited states as synthetic equivalents of 1,2-bicarbenes is interesting from a fundamental point of view. This process also opens new practical possibilities which we intend to explore in future studies.<sup>67</sup> A particularly interesting structural feature of homoquadricyclane products is that the two aryl groups defining the hydrophobic cavity are oriented in an almost perfect 60° angle. In the context, it is interesting to quote a recent paper by Stang and co-workers: “The relative dearth of triangles synthesized to-date can be explained by the difficulty in finding the appropriate corner unit... there exist no single-center complex that possesses a 60° angle between coordinated ligands.”<sup>68</sup> 1,5-(4,4'-Dipyridyl)homoquadricyclanes may be suitable corner units for such supramolecular triangles or rhomboids.<sup>69</sup>

### Conclusions

Although this paper started as a curiosity driven project, it evolved into a detailed mechanistic study of two scarcely studied photochemical transformations. This study significantly expanded the utility of the photochemical conversion of acetylenes to homoquadricyclanes and, for the first time, provided a mechanistic rationale for this intriguing and atom-economical cascade transformation. Photoirradiation of pyridine-substituted acetylenes in the presence of 1,4-CHD yielded 1,5-diaryl-substituted tetracyclo[3.3.0.0<sup>2,8</sup>.0<sup>4,6</sup>]octanes in good yields. The spin multiplicity of the excited state involved in the formation of polycyclic photoadducts and their subsequent photorearrangement was determined using quenching and sensitization experiments. These experiments unambiguously confirmed that formation of homoquadricyclanes proceeds through a triplet excited state. An electron-accepting substituent increases the efficiency of the reaction by enhancing electrophilic character of the triplet acetylene moiety. However, electron-acceptor properties of the acetylene moiety must be balanced in such a way that ISC to the triplet excited state would proceed faster than electron transfer between excited acetylene and 1,4-diene moieties. Lack of such balance can lead to the situation when, in the case of larger concentrations of dienes, the singlet excited state of acetylene is intercepted through electron transfer before it is transformed into the triplet, and thus, efficiency of the triplet photocycloaddition decreases.

Sufficiently long triplet lifetime and electron deficiency of triplet state are the two conditions favoring the photocycloaddition. Acetylenes where both of these conditions are satisfied react with 1,4-CHD very efficiently. In the case of short-lived triplets, the role of electrophilicity becomes essential as illustrated by comparison of the results for the two symmetric acetylenes: although the lifetimes of TFP-TFP and 4-Py-4-Py

(63) For interesting observations on reactivity of singlet and triplet 1,4-diradicals in photochemical reactions, see: Scaiano, J. C. *Tetrahedron* **1982**, *38*, 819. Wagner, P. J. *Acc. Chem. Res.* **1989**, *22*, 83. Griesbeck, A. G.; Stadtmüller, S. *J. Am. Chem. Soc.* **1990**, *112*, 1281. Griesbeck, A. G.; Stadtmüller, S. *J. Am. Chem. Soc.* **1991**, *113*, 6923. Griesbeck, A. G.; Mauder, H.; Stadtmüller, S. *Acc. Chem. Res.* **1994**, *27*, 70. Zand, A.; Park, B. S.; Wagner, P. J. *J. Org. Chem.* **1997**, *62*, 2326. Giese, B.; Wetstein, P.; Stahelin, C.; Barnosa, F.; Neuburger, M.; Zehnder, M.; Wessig, P. *Angew. Chem., Int. Ed.* **1999**, *38*, 2586. Abe, M.; Kawakami, T.; Ohata, S.; Nozaki, K.; Nojima, M. *J. Am. Chem. Soc.* **2004**, *126*, 2838. A recent thorough theoretical study of SOC in 1,4-diradicals: Kutateladze, A. G. *J. Am. Chem. Soc.* **2001**, *123*, 9279. Authoritative review: Doubleday, C., Jr.; Turro, N. J.; Wang, J. F. *Acc. Chem. Res.* **1989**, *22*, 199.

(64) A different electronic nature of the singlet excited states in pyridines vs pyrazines ( $n,\pi^*$  vs  $\pi,\pi^*$  as discussed in ref 45) may provide an explanation.

(65) The photorearrangement is not sensitized by benzophenone, acetophenone, or xanthone.

(66) (a) Shim, S. C.; Lee, T. S. *J. Org. Chem.* **1988**, *53*, 2410. Lee, T. S.; Lee, S. J.; Shim, S. C. *J. Org. Chem.* **1990**, *55*, 4544. (b) Lee, S. J.; Shim, S. C. *Tetrahedron Lett.* **1990**, *31*, 6197. (c) Shim, S. C. *J. Chem. Soc., Chem. Commun.* **1996**, 2609. (d) Lu, P. J.; Pan, W.; Jones, M., Jr. *J. Am. Chem. Soc.* **1998**, *120*, 8315. (e) Laird, D. W.; Gilbert, J. C. *J. Am. Chem. Soc.* **2001**, *123*, 6704.

(67) Manuscript is in preparation.

(68) Kryschenko, Y. K.; Seidel, S. R.; Arif, A. M.; Stang, P. *J. Am. Chem. Soc.* **2003**, *125*, 5193.

(69) For a recent review of supramolecular coordination chemistry, see: Leininger, S.; Olenyuk, B.; Stang, P. *Chem. Rev.* **2000**, *100*, 853. See also: Khlöbstov, A. N.; Blake, A. J.; Chapness, N. R.; Lemenovskii, D. A.; Majouga, G.; Zyk, N. V.; Schroder, M. *Coord. Chem. Rev.* **2001**, *222*, 155.



triplets are very close, the quantum yield for the formation of homoquadricyclane product is considerably higher in the case of the more electron-deficient TFP–TFP acetylene.

In the triplet excited state produced from Ph-PFB acetylene **18**, relative polarization of the triple bond does not change compared to the ground state, whereas, in the case of 4-Py-Ph and Ph-TFP triplets, there is an inversion of the ground-state polarization of the triple bond (repolarization, or “umpolung” by light). Influence of these electronic effects on the observed trends in reactivity should also depend on the relative rates of ISC in the two types of acetylenes. El-Sayed rules suggest that the phantom  $n,\pi^*$  excited state plays an important role in accelerating ISC and blocking competing side reactions.

The reaction cascade is complicated, and several reasonable possibilities exist for the formation of the homoquadricyclanes. From these possibilities, the 5-exo cyclization of the initially formed 1,4-diradical seems the most likely.

In the case of pyrazyl-substituted aryl acetylenes, secondary photoreaction of the homoquadricyclane singlet excited state leads to a tricyclooctene adduct via a 1,2-carbon shift. These results provide the new insight needed for rational design and better control of this intriguing class of photochemical cycloadditions.

Finally, from a practical point of view such reactions are interesting because “capping” of the triple bond with the

polycyclic framework orients the terminal aryl (4-pyridyl, 4-tetrafluoropyridyl, phenyl, etc.) groups in an almost perfect  $60^\circ$  angle rendering such molecules promising supramolecular building blocks in the design and synthesis of metal coordination polymers.

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**Supporting Information Available:** Experimental procedures and spectral data including:  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{19}\text{F}$  NMR; IR, UV, MS, and X-ray crystallography data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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