

Metal-Free Photochemistry

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Photochemical Carbene Transfer Reactions of Aryl/Aryl Diazoalkanes—Experiment and Theory**

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Abstract: Controlling the reactivity of carbene intermediates is a key parameter in the development of selective carbene transfer reactions and is usually achieved by metal complexes via singlet metal-carbene intermediates. In this combined experimental and computational studies, we show that the reactivity of free diaryl carbenes can be controlled by the electronic properties of the substituents without the need of external additives. The introduction of electron-donating and -withdrawing groups results in a significant perturbation of singlet triplet energy splitting of the diaryl carbene intermediate and of activation energies of consecutive carbene transfer reactions. This strategy now overcomes a long-standing paradigm in the reactivity of diaryl carbenes and allows the realization of highly chemoselective carbene transfer reactions with alkynes. We could show that free diaryl carbenes can be readily accessed via photolysis of the corresponding diazo compounds and that these carbenes can undergo highly chemoselective cyclopropanation, cascade, or C–H functionalization reactions. Experimental and theoretical mechanistic analyses confirm the participation of different carbene spin states and rationalize for the observed reactivity.

Introduction

Carbenes are one of the key reactive intermediates in synthesis to leverage a broad variety of important transformations, ranging from cycloaddition towards site-selective C–H functionalization reactions.^[1–6] Since the initial discovery of metal-catalyzed carbene transfer reactions in 1950,^[3] it is regarded a necessity to use transition metal catalysts to access, stabilize and control the carbene intermediate and to make them viable intermediates for synthesis applications.^[4,5] Research in this area has been devoted to the development of new catalysts and ligand design to implement reactions of

metal-stabilized carbene intermediates, which in the vast majority exist as singlet carbenes.^[7] Latest developments demonstrate the importance of modern metal carbene chemistry to access site- and enantioselective C–H functionalization reactions of unreactive hydrocarbon frameworks.^[8] On the contrary, the triplet carbene, bearing two unpaired electrons, has only received little attention in carbene transfer reactions due to the requirements of specific metal complexes^[9] and as such the reactivity of triplet carbenes in organic synthesis is vastly underdeveloped.

The spin state of free carbene intermediates is an important area of research in physical organic chemistry and of prime importance to understand the chemical properties and reactivity of carbenes.^[10] Matrix-isolation, ultrafast spectroscopy, or latest developments in computational chemistry represent important state-of-the-art techniques to characterize such short-lived intermediates.^[11–17] These studies demonstrated that the electronic properties of the carbene substituents significantly impact on the spin state of carbenes and their singlet triplet splitting. For example, donor/acceptor carbenes exhibit a singlet ground state in chlorinated solvent as demonstrated both experimentally and computationally.^[12] This free singlet carbene can be selectively accessed via the photolysis of donor/acceptor diazoalkanes and utilized in singlet carbene transfer reactions, as demonstrated only recently (Scheme 1 a).^[6,18] Contrarily, the spin state of diaryl carbenes is much more dependent on the nature of the electronic properties of the substituents of the aromatic ring. While for diphenyl carbene **5b** the triplet state is favored over the singlet state by 4.6 kcal mol^{−1},^[17] the energies of the singlet and triplet state of electron-rich *bis*(4-methoxyphenyl)carbene **5c** are almost degenerate with the singlet state being 0.3 kcal mol^{−1} energetically favored.^[13] Moreover, **5c** can be selectively switched from triplet to singlet state at 3 K by irradiation with 450 nm blue light and reverted back with 365 nm light. This intersystem crossing can already occur under thermal conditions at very low temperature by heating of the singlet carbene **5c** to 25 K.^[13] In 1976, Rabinow already concluded that rapidly occurring ISC prevents the separation of singlet and triplet diaryl carbene intermediates and—as a consequence—the application in synthesis.^[19]

The development of chemoselective and efficient synthesis methods via free diaryl carbenes would thus overcome a long-standing paradigm and represents an important advancement in modern carbene chemistry. We hypothesized that the electronic properties of the carbene intermediate could serve as a suitable handle to address this challenge. Specifically, we assumed that the introduction of electron-donating or -withdrawing groups to the aromatic rings of diaryl carbenes influences the spin state and thus allows for

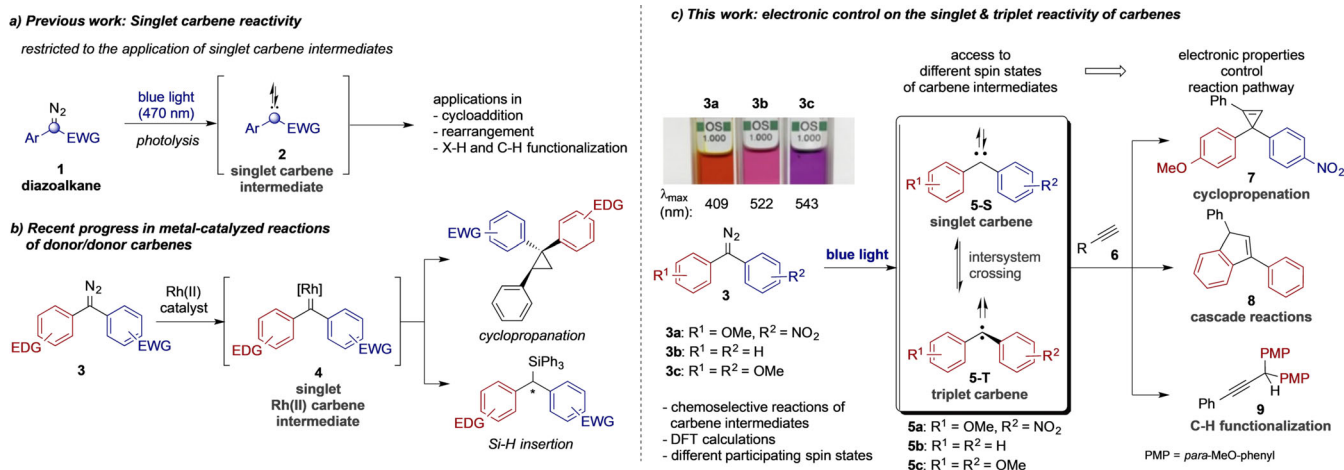
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Scheme 1. Carbene Transfer Reactions. a) and b) singlet reactivity vs. c) electronic control on singlet and triplet carbenes.

spin-dependent reactions of photochemically generated, free carbene intermediates. This approach should thus enable orthogonal reaction pathways of carbene intermediates that can be controlled by the electronic properties under otherwise identical conditions (Scheme 1 c).

Results and Discussion

As part of our ongoing research interest in photochemical applications of diazoalkanes,^[18c,20] we observed a marked dependency of the visual appearance and absorption properties of aryl/aryl diazoalkanes on their electronic properties (Scheme 1 c). While the electron-poor, *para*-NO₂-substituted aryl/aryl diazoalkane **3a** absorbs visible light in the purple light region ($\lambda_{\text{max}} = 409$ nm), the absorption maxima of electron-neutral diphenyl diazomethane **3b** is red-shifted towards the dark green light region ($\lambda_{\text{max}} = 522$ nm).^[21] Introduction of electron-donating groups results in a further bathochromic shift towards the light green region of the visible part of the electromagnetic spectrum ($\lambda_{\text{max}} = 543$ nm). This observation prompted us to further study aryl/aryl diazoalkanes to access donor/donor carbene intermediates via photolysis reactions. The carbene intermediates themselves differ in their electronic properties that we hypothesize to be applicable in chemoselective, orthogonal organic transformations (5-S, 5-T, Scheme 1 c).^[5]

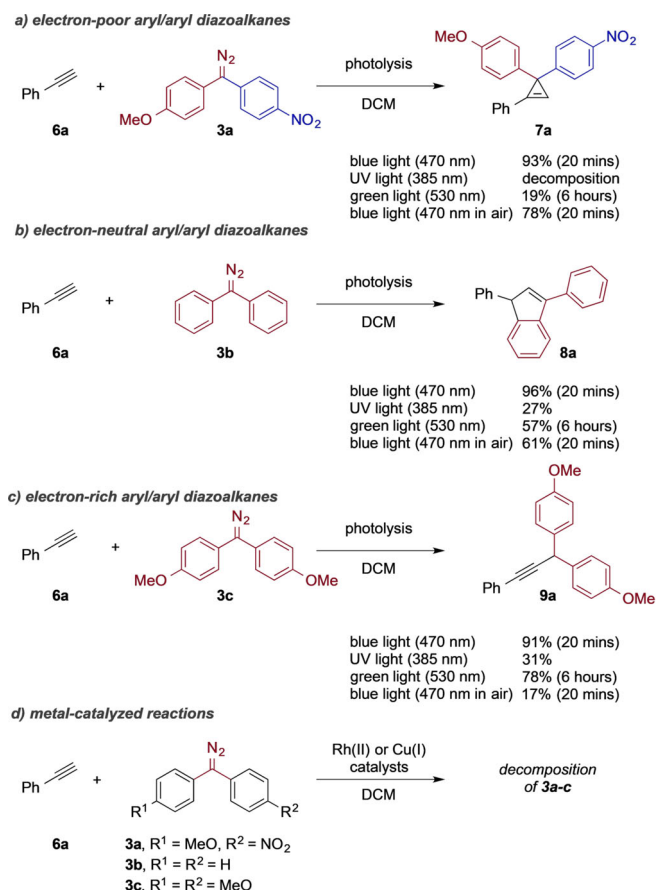
In a similar context, yet using transition metal catalysts,^[22,23] the Davies group recently reported on the effect of electron-donating and -withdrawing groups on the reactivity of aryl/aryl diazoalkanes in Rh^{II}-catalyzed stereoselective cyclopropanation reactions.^[24] Shortly thereafter, the Zhou and Franz groups reported on similar observations in Rh^{II}-catalyzed Si-H insertion reactions.^[25,26] In these cases the reactivity of the carbene intermediate is controlled by the Rh^{II} catalyst and thus represents the singlet carbene reactivity (Scheme 1 b).

Experimental Studies

We initiated our studies by exploring the reaction of aryl/aryl diazoalkanes with phenyl acetylene (**6a**) and evaluated the reaction of electron-poor aryl/aryl diazoalkane **3a** first.^[21] We assumed that the introduction of one electron-withdrawing group could be utilized to control the reactivity of the carbene intermediate and that this carbene more resembles a classic donor/acceptor carbene. Indeed, under blue light conditions the cyclopropene product **7a** was obtained in excellent yield after only 20 minutes reaction time (Scheme 2 a), which is in line with the reactivity of donor/acceptor carbenes.^[18c] Noteworthy, the synthesis of diaryl cyclopropenes represents even today a challenge in cyclopropene chemistry and only singular examples are known in the literature.^[27]

We next turned our attention towards electron-neutral aryl/aryl diazoalkane **3b** in the reaction with phenyl acetylene (Scheme 2 b). No cyclopropanation reaction occurred under identical conditions, instead a highly selective cascade reaction occurred and indene product **8a** was obtained in excellent yield as the sole product. Finally, we probed the reactivity of electron-rich aryl/aryl diazoalkane **3c** (Scheme 2 c). Neither the cyclopropene nor the indene product was observed, instead a selective C–H functionalization of the terminal alkynyl C(sp)–H bond (**9a**) occurred with excellent yield, which represents an intriguing reactivity of free carbenes, which can otherwise only be accessed from *N*-heterocyclic carbenes.^[28]

To probe, if the absorption properties of diazoalkanes **3a–c** (cf. Scheme 1 c) influence the efficiency and synthetic applicability of this photochemical carbene transfer reaction, we studied all above reactions under green or UV light conditions. Under UV light conditions, the cyclopropene product **7a** was not observed and **3a** underwent decomposition to a complex mixture. In the case of diazoalkanes **3b** and **3c** the yield of indene **8a** and C(sp)–H functionalization product **9a**, respectively, was significantly decreased and a complex mixture of by-products was observed. Photochemical decomposition pathways of either the diazoalkane



Scheme 2. Carbene transfer reactions of electronically distinct aryl/aryl diazoalkanes with phenyl acetylene. *Reaction conditions:* In an oven dried reaction tube the diazoalkane (0.2 mmol, 1 equiv.) was added and DCM was added. Phenyl acetylene (2 mmol, 10 equiv.) was dissolved in 0.5 mL of DCM and added to the reaction tube by syringe and then irradiated as indicated at room temperature. The crude reaction mixture was purified by silica gel column chromatography.

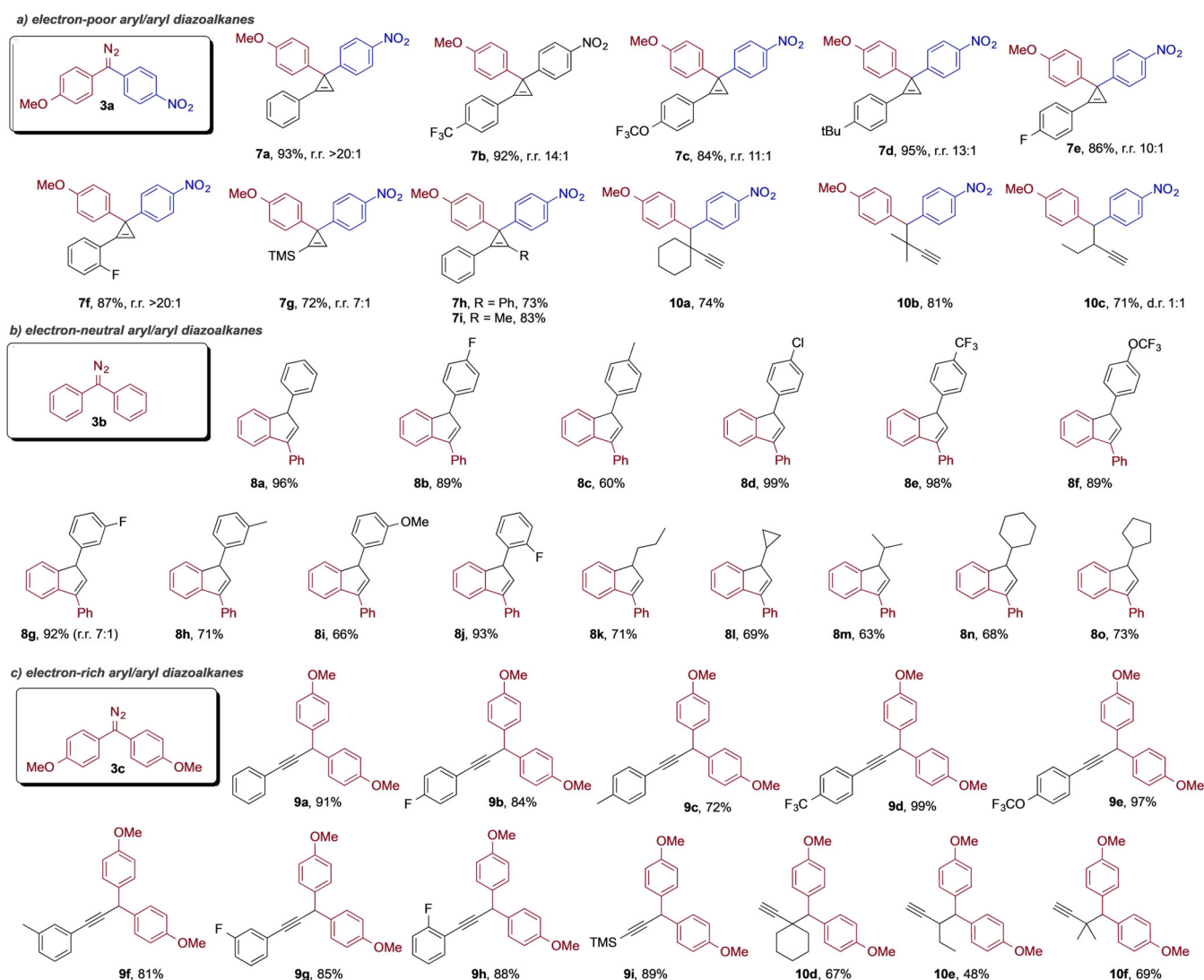
itself or of reaction products can reason the by-product formation and reduced efficiency under UV light conditions. When irradiated with green light, a considerable influence of the absorption properties of the diazoalkanes on the reaction yield was observed. Electron-poor aryl/aryl diazoalkanes, which absorb only poorly in the green light range, reacted in low yield to the corresponding cyclopropene. In contrast, electron-neutral and electron-rich aryl/aryl diazoalkanes absorb in the green light range (Scheme 1 c) and significantly higher yields were obtained, with the best yields for the most red-shifted and electron-rich aryl/aryl diazoalkane **3c**. Last, it should be noted that no reaction between the aryl/aryl diazoalkane and phenylacetylene was observed in the dark.

In contrast to the reaction of donor/acceptor diazoalkanes,^[6,18,20] the photolysis of aryl/aryl diazoalkanes needs to be performed under an inert atmosphere and exclusion of air and moisture are required to obtain high reaction yields. However, it should be noted that electron-poor diazoalkane **3a** reacts in reasonable yield (78%) to the cyclopropene product in air, while electron-rich substrate **3c** requires strict exclusion of air.

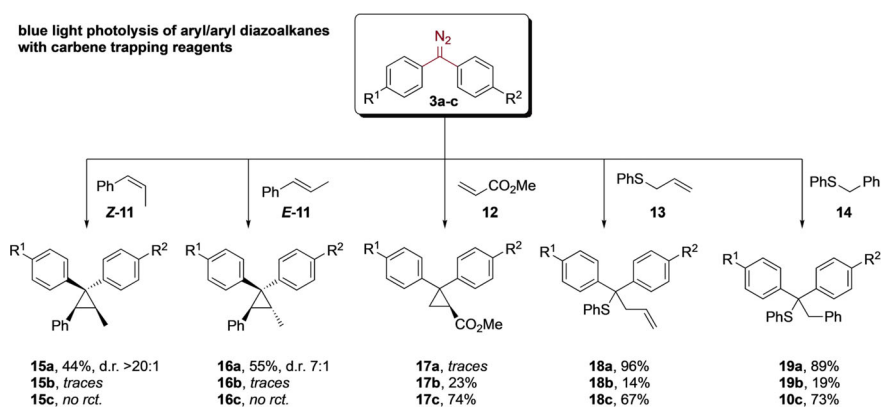
Further studies on the compatibility of solvent showed a strong solvent dependency and only chlorinated solvents are compatible with the present reaction conditions. In all other solvent either decomposition of the diazoalkane or significantly reduced yields were observed (please see Table S1 in Supporting Information). Importantly, when studying the reaction of aryl/aryl diazoalkanes **3a–c** with phenyl acetylene in the presence of Rh^{II}- or Cu^I-based catalysts only the decomposition of diazoalkane was observed (Scheme 2 d), which showcases the complementarity and orthogonality of photochemical and metal-catalyzed carbene transfer reactions.

We subsequently studied the application of the photolysis reaction of aryl/aryl diazoalkanes in electronic-controlled carbene transfer reactions with alkynes (Scheme 3). Different terminal aromatic alkynes smoothly reacted with electron-poor aryl/aryl diazoalkane **3a** in a very efficient cyclopropanation reaction, with diminutive amounts of indene as by-product (**7a–i**, r.r. up to > 20:1). Contrarily, aliphatic alkynes reacted in selective C–H functionalization of the propargylic C–H bond in high yield (**10a–c**). We then turned our attention to the reaction of electron-neutral aryl/aryl diazoalkane **3b** with aryl and alkyl alkynes. An almost quantitative yield of the corresponding indene products (**8a–j**) were obtained in the case of aryl acetylenes bearing halogen or electron-withdrawing groups in all positions of the aromatic ring. Slightly reduced yields were obtained, when electron-donating groups, such as alkyl- or methoxy-groups were introduced (**8c**, **8h**, **8i**). In all cases the indene products were obtained as the only reaction product. Similarly, aliphatic, terminal alkynes gave indene products (**8k–o**). Finally, we studied electron-rich aryl/aryl diazoalkane **3c** that underwent C(sp)–H insertion reaction into a variety of different terminal aryl alkynes in very good to almost quantitative yield (**9a–i**). Under the present reaction conditions, TMS-acetylene smoothly reacted to give the C–H functionalization product in excellent yield (**9i**). Aliphatic alkynes however, did not undergo C(sp)–H insertion, instead a highly efficient C(sp³)–H insertion in the propargylic position was observed in high yields (**10d–f**). It should be noted that this C(sp³)–H functionalization can be readily applied to install a quaternary carbon center in the direct proximity of an alkyne group that are valuable building blocks for further derivatization.

This observation prompted us to study the electronic properties of diaryl carbenes experimentally (Scheme 4 and Scheme 5). First, we investigated the reaction of *E*-β-methyl styrene and *Z*-β-methyl styrene with aryl/aryl diazoalkanes (Scheme 4). **3a** reacted under the present reaction conditions in a fully stereospecific reaction with both *E*-β-methyl styrene and *Z*-β-methyl styrene without loss of stereochemical information of the olefin geometry in the starting material (**15a**, **16a**). Contrarily, the reaction of electron-neutral and electron-rich aryl/aryl diazoalkanes was significantly hampered for both *E*-β-methyl styrene and *Z*-β-methyl styrene. The electron-poor methyl acrylate reacted preferentially with electron-rich or electron-neutral diaryl carbenes and no reaction was observed with electron-poor diazoalkane **3a**. Next, we studied the reaction of aryl/aryl diazoalkanes with sulfides in rearrangement reactions. An excellent yield of the



Scheme 3. Investigations on the photochemical reaction of aryl/aryl diazoalkanes with alkynes. *Reaction conditions:* In an oven dried reaction tube the diazoalkane (0.2 mmol, 1 equiv.) was added and the reaction tube was purged with argon for three times then 0.5 mL of degassed and dry DCM was added. Alkyne (2 mmol, 10 equiv.) was dissolved in 0.5 mL of degassed and dry DCM and added to the reaction tube by syringe and then irradiated with blue LED (470 nm, 3 W) for 30 minutes at room temperature under argon atmosphere. The crude reaction mixture was purified by silica gel column chromatography.



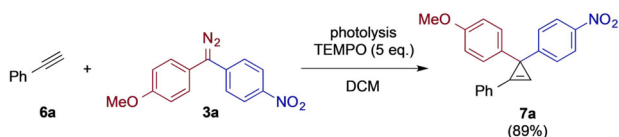
Scheme 4. Reactions with different carbene trapping reagents; for compounds **a** $R^1 = \text{OMe}$, $R^2 = \text{NO}_2$; **b** $R^1 = R^2 = \text{H}$; **c** $R^1 = R^2 = \text{OMe}$.

rearrangement products **18a** and **19a** were obtained for electron-poor aryl/aryl diazoalkane **3a** in the reaction with allyl phenyl sulfide **13** and phenyl benzyl sulfide **14**. A significantly reduced yield of **18b** and **19b** was observed for the electron-neutral aryl/aryl diazoalkane **3b**. Electron-rich diazoalkane **3c** gave the products **18c** and **19c** in good isolated yield.

In a second set of control experiments, we probed the reaction of diazoalkanes **3a-c** with terminal alkynes in the presence of TEMPO as a trapping reagent. In the presence of TEMPO all of the photochemical carbene transfer reactions were (al-

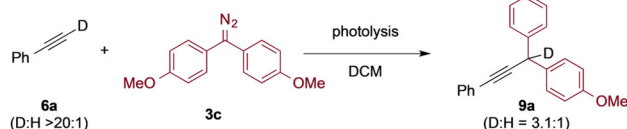


a) Reaction in the presence of TEMPO



Note: Reactions of **3b** and **3c** are inhibited.
Reactions with aliphatic, terminal alkynes are inhibited for **3a-c**.

b) Reaction with deuterated alkynes



Note: Reactions of **3b** and **3c** and reactions with aliphatic, terminal alkynes give D:H >20:1

Scheme 5. Reactions with a carbene trapping reagent and with deuterium-labeled alkynes.

most) completely inhibited for both phenyl acetylene and 3-methyl-1-butyne (for details, please see Scheme S4 in Supporting Information).^[21] The only exception was observed for the reaction of diazoalkane **3a** with phenyl acetylene; in this case only a slightly reduced yield (89%) of the cyclopropene product was observed (Scheme 5a).

This observation is now indicative of a singlet carbene intermediate in the cyclopropanation reaction, while triplet carbenes are viable intermediates in indene formation or C–H functionalization reactions.

We next examined the reaction of deuterium-labeled alkyne substrates with diazoalkanes **3a–c** under the optimized reaction conditions. Importantly, the deuterium label was preserved with > 95% for most substrates (for details, please see S5 in Supporting Information);^[21] only in the case of the C(sp)–H functionalization reaction of the electron-rich diazoalkane **3c** with phenyl acetylene, a significant erosion of the deuterium label was observed (Scheme 5b), which suggests either proton or hydrogen atom transfer to occur in the C(sp)–H functionalization reaction. This observation can now rationalize for the missing reactivity of **3c** with phenyl acetylene in the presence of spin trapping reagents due to side-reactions of ionic intermediates with the trapping reagent.

The above experimental evidence is suggesting the participation of either singlet or triplet carbene intermediates in this photochemical carbene transfer reaction. For further validation of the above data, additional experiments using time-resolved spectroscopy would provide important additional insight. In contrast to the Rabinow report from 1976, we could show that the reaction of diaryl carbenes can be differentiated by electronic properties to enable a high chemoselectivity in the reaction with terminal alkynes.

Theoretical Studies

To gain a better understanding of the underlying reaction mechanism and the involvement of singlet or triplet carbene intermediates, we performed computational studies on the

reaction of carbene intermediates **5a–c** with phenyl acetylene and 3-methyl but-1-yne.

We set out our investigations by studying geometrical and electronic properties of carbenes **5a–c**. Specifically, we performed calculations using the B3LYP-D3 functional to obtain a first data set on the singlet triplet energy splitting, which could provide a reasonable approximation for subsequent investigations on the reaction mechanism.^[29] For benchmarking of B3LYP-D3 calculations, we next performed coupled cluster calculations with the DLPNO-CCSD(T) method^[30] that was recently demonstrated as a viable method to obtain an accurate singlet triplet energy splitting.^[31,32]

With the B3LYP-D3 functional, we observed a significant difference in the singlet triplet energy splitting of carbenes **5a–c**, which strongly depends on the substitution pattern of the aromatic ring (Table 1). For diphenyl carbene (**5b**), this

Table 1: Theoretical calculations on the singlet triplet splitting.

# ^[a]	Functional/ method	$\Delta E_{ST}/ \Delta G_{ST}$ (kcal mol ^{−1})
5b (Ph/Ph)	B3LYP-D3	3.0 (4.5)
	DLPNO-CCSD(T)	4.6 (4.0)
	CCSD(T)	3.2 ^[13]
	Experimental	4.6 ^[17]
5c (4-MeOPh/4-MeOPh)	B3LYP-D3	−1.5 (0.4)
	DLPNO-CCSD(T)	1.1 (0.1)
	CCSD(T)	−0.3 ^[13]
5a (4-NO ₂ Ph/4-MeOPh)	B3LYP-D3	−0.8 (−0.3)
	DLPNO-CCSD(T)	3.3 (1.7)
	CCSD(T)	0.3 (−1.4)

[a] Calculations were performed at the following levels of theory: B3LYP-D3/def2-tzvp(DCM)//B3LYP-D3/def2-svp(DCM); DLPNO-CCSD(T)/cc-PVDZ// B3LYP-D3/def2-tzvp; CCSD(T)/cc-PVDZ//B3LYP-D3/def2-tzvp. Positive values indicate an energetically favored triplet state, negative values indicate an energetically favored singlet state. ΔG_{ST} is the Gibbs energy gap calculated in DCM.

energy gap was calculated to be 4.5 kcal mol^{−1}, which is close to the CCSD(T) calculations that showed an energy gap of 3.2 kcal mol^{−1}.^[13] The data obtained on B3LYP-D3 level is reasonably close to the experimentally observed energy gap of 4.6 kcal mol^{−1}.^[17] For the more electron-rich *bis*(4-methoxyphenyl)carbene a smaller energy gap of only 0.4 kcal mol^{−1} (0.1 kcal mol^{−1} for DLPNO-CCSD(T)) was calculated, which is an overestimation of the calculation using CCSD(T).^[13] In the case of the (4-nitrophenyl)(4-methoxyphenyl)carbene **5a**, an energy gap of −0.3 kcal mol^{−1} was calculated with the B3LYP functional, while a slightly larger ΔG_{ST} was obtained when using the DLPNO-CCSD(T) method (ΔG_{ST} = 1.7 kcal mol^{−1}).

Although singlet triplet splitting energies from calculations using the B3LYP-D3 functional do not perfectly reflect experimentally observed or high level CCSD(T) calculations, an important aspect can be deduced: In the case of diphenyl carbene **5b**, ΔG_{ST} is the largest and can thus provide a rationale for the observed reactivity. For carbenes **5a** and **5c** the singlet triplet splitting is significantly smaller, which can rationalize for the coexistence of both spin states in solution and a facile intersystem crossing and thus for the markedly different reactivity of **5a** and **5c**. In this context,

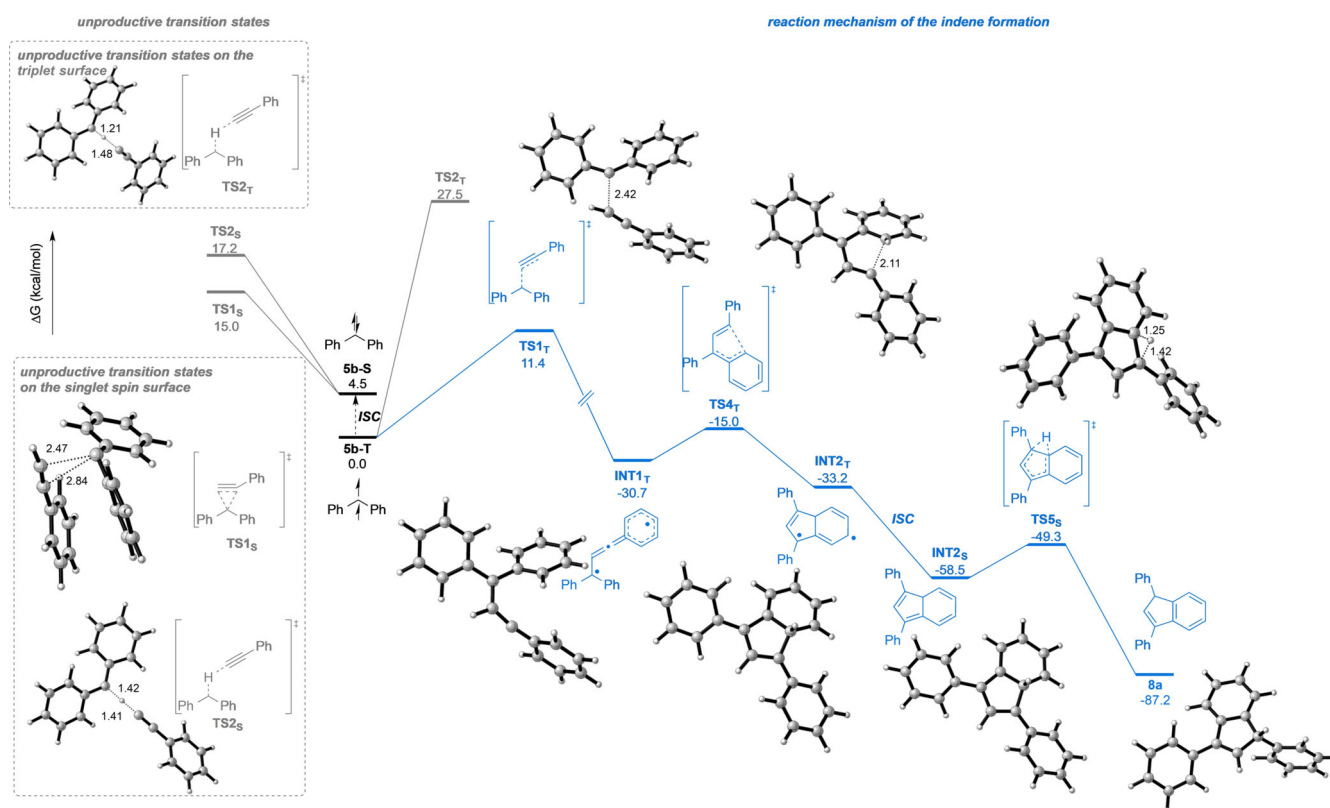
Sander reported on the reversible switching of spin states of **5c** by different light sources or temperature annealing in Ar matrices at temperatures between 3 and 25 K.^[13] However, it is important to note that thermal relaxation at temperatures as low as 25 K resulted in an equilibrium shift towards the singlet carbene of **5c**. We therefore consider that thermally induced intersystem crossing via a low intersystem crossing barrier ($\Delta G^\ddagger = 1.4 \text{ kcal mol}^{-1}$ for **5c**)^[13] rationalizes for the observed reactivity of **5a** and **5c**. While the low barrier for **5c** was already determined experimentally in argon matrices,^[13] similar experimental evidence is not yet available for **5a**.

As part of these calculations, we also studied the geometric properties and electron-distribution by NBO analysis of all possible carbene intermediates. The geometries of the triplet state of all carbene intermediates **5a–c** are remarkably close and only small deviations in bond or torsion angles were observed. However, in singlet state the influence of the electron-withdrawing nitro group in (4-nitrophenyl)(4-methoxy-phenyl)carbene **5a–S** leads to a rotation of the electron-poor 4-nitrophenyl group to a near orthogonal position, while the other aryl ring rotates to a near-coplanar orientation with the carbene empty p-orbital. It is remarkable that this free singlet carbene now shows similar structural features as the singlet donor/acceptor carbenes (**20**, Table S7 in the Supporting Information)^[21] or aryl/aryl carbenes in the corresponding Rh-carbene complexes as recently described by Davies and co-workers.^[24] NBO analysis of these carbene intermediates shows that singlet carbene **5c–S** is significantly more nucleophilic than **5a–S** and **5b–S**. Furthermore, **5a–S** has a more

positive charge on the singlet carbene carbon, which indicates that it is more electrophilic and thus facilitates cyclopropanation, similar to a phenyl-(carbomethoxy)carbene singlet carbene **20** (Table S7 in the Supporting Information)^[21] or the 2-naphthyl-(carbomethoxy)carbene, which was studied by McMahon.^[16]

Calculations on the Reaction of Diphenyl Carbene

We next studied both spin states of the diphenyl carbene intermediate in the reaction with terminal alkynes on the B3LYP-D3 level of theory. In the reaction of singlet diphenyl carbene **5b–S** with phenyl acetylene, two transition states were identified that lead to the direct formation of the cyclopropane (via **TS1_s**, $\Delta G^\ddagger = 10.5 \text{ kcal mol}^{-1}$) and the insertion into the C(sp)–H (via **TS2_s**, $\Delta G^\ddagger = 12.7 \text{ kcal mol}^{-1}$). In the case of triplet diphenyl carbene **5b–T** two further transition states could be located. The relatively high lying **TS2_T** ($27.5 \text{ kcal mol}^{-1}$) can account for C(sp)–H functionalization, yet is not feasible due to its high barrier. The addition of triplet carbene **5b–T** to the distal acetylene carbon atom proceeds via the lowest-lying transition state **TS1_T** ($\Delta G^\ddagger = 11.4 \text{ kcal mol}^{-1}$) to give **INT1_T**. As the triplet carbene intermediate is energetically favored over the singlet carbene intermediate, the addition pathway via **INT1_T** leading to the indene product is energetically preferred. **INT1_T** further undergoes a radical cyclization via **TS4_T** followed by intersystem crossing to give **INT2_s**. Final [1,2]-hydrogen shift and



Scheme 6. Theoretical calculations on the reaction mechanism of diphenyl carbene with phenyl acetylene and analysis of all possible reaction pathways. Level of theory: B3LYP-D3/def2-tzvp(PCM)// B3LYP-D3/def2-svp(PCM).



rearomatization gives the desired indene product as the preferred reaction product in the reaction of diphenyl carbene with aromatic alkynes (Scheme 6, right part), which is consistent with the experimental data.

In the reaction with 3-methyl but-1-yne we considered all of the above transition states and identified two additional transition states that can account for C(sp³)-H functionalization.^[21] In this case, calculations with the B3LYP-D3 functional gave data that is partially in line with the experimental results. These calculations gave consistent results regarding transition states on the singlet spin surface, which are high in activation free energy and do not account for product formation.^[21] Contrarily, calculations on the triplet spin surface gave slightly contradictory results, which suggest C(sp³)-H functionalization ($\Delta G^\ddagger = 12.7 \text{ kcal mol}^{-1}$) being slightly favored by $0.9 \text{ kcal mol}^{-1}$ over indene formation ($\Delta G^\ddagger = 13.6 \text{ kcal mol}^{-1}$), which can be attributed to spin contamination in the triplet state (Table 2).^[31]

To better rationalize for the reaction pathways of diphenyl carbene on the triplet spin surface, we performed calculations using the DLPNO-CCSD(T) method. These provide more accurate calculations in the case of unpaired electrons and indeed provide a good rationale on the reaction of triplet diphenyl carbene **5b-T** with 3-methyl but-1-yne and show that transition state **TS1_T** that leads to indene formation is $0.8 \text{ kcal mol}^{-1}$ lower in energy compared to the C(sp³)-H functionalization ($\Delta G^\ddagger = 14.0 \text{ kcal mol}^{-1}$ for indene vs. $\Delta G^\ddagger = 14.8 \text{ kcal mol}^{-1}$ for C(sp³)-H functionalization).

Calculations on the Reaction of Bis(4-methoxyphenyl) Carbene and (4-Nitrophenyl)(4-methoxyphenyl)carbene

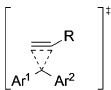
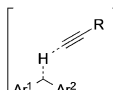
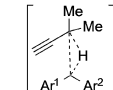
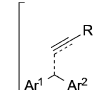
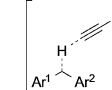
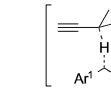
A significant perturbation of transition state free energies was observed when studying the reaction of bis(4-methoxyphenyl)carbene **5c**. This variation in the electronic structure of the carbene intermediate and the almost degenerate singlet and triplet state result have a major effect on the activation free energy of the first bond-forming event for most reaction pathways and as a result, different reaction pathways are

preferred, depending on the alkyne reaction partner (Table 2).^[21] The presence of two electron-donating methoxy groups leads to a significant increase of electron density at the carbene atom (please also see the NBO analysis in Supporting Information) and thus facilitates a formal C-H functionalization mechanism via the low lying transition state **TS2_s** ($\Delta G^\ddagger = 9.8 \text{ kcal mol}^{-1}$) to give a carbocation and acetylide ion pair **INT1_s** that is stabilized by weak hydrogen-bonding and π - π stacking between alkynyl anion and diaryl cation. Subsequent, barrierless nucleophilic addition results in the formation of the new C-C bond (Scheme 7a). Transition states leading to cyclopropene or C(sp³)-H functionalization are disfavored on the singlet spin surface. Similarly, transition states leading to formation of the indene or C-H functionalization are disfavored on the triplet spin surface (Table 2).

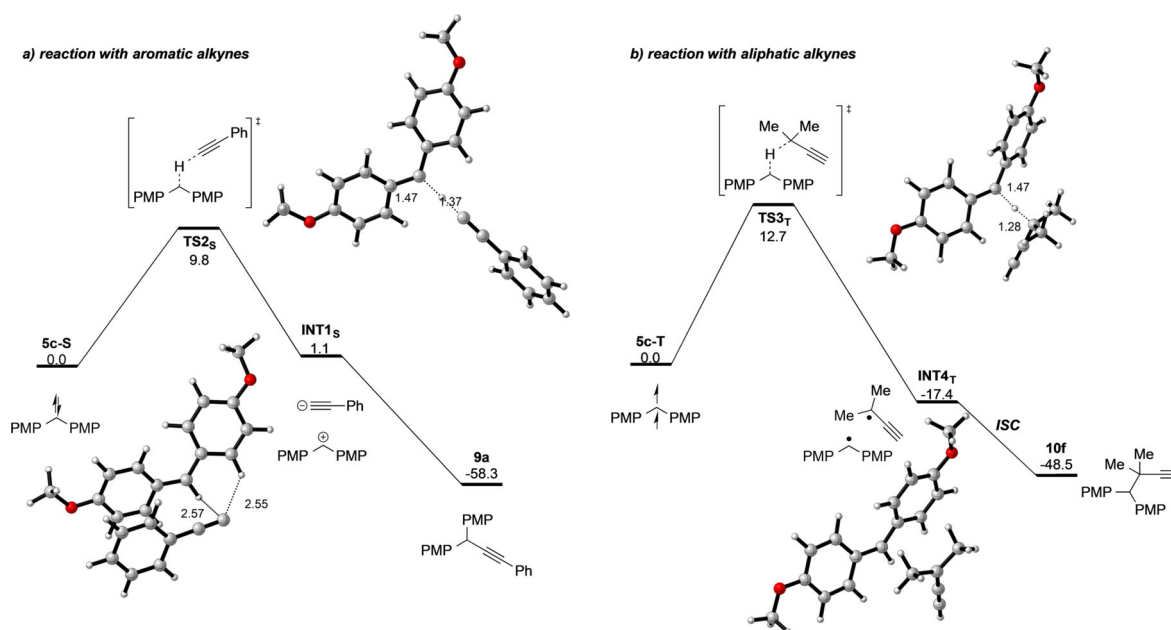
The reaction profile with 3-methyl but-1-yne is similarly influenced.^[21] In this case, bis(4-methoxyphenyl)carbene reacts on the triplet spin surface via **TS3_T** ($\Delta G^\ddagger = 12.7 \text{ kcal mol}^{-1}$) and hydrogen atom abstraction to give two radicals (**INT4_T**) that undergo a radical recombination and intersystem crossing to the C(sp³)-H functionalization product (Scheme 7b). Importantly, other reaction pathways are disfavored and proceed via relatively high lying transition states (See Table 2 and Supporting Information).

The introduction of the electron-withdrawing group in the case of (4-nitrophenyl)(4-methoxyphenyl)carbene **5a-S** and **5a-T** (Table 2) had a similar influence on the energies of transition states.^[21] In this case, calculations on the singlet triplet splitting with the B3LYP-D3 functional suggest a more stabilized singlet state (cf. Table 2). Indeed, for the reaction with phenyl acetylene, the calculated energies of transition states suggest that cyclopropene formation is almost identical to indene formation. However, as the singlet carbene is the energetically preferred intermediate, the cyclopropene is thus formed as the main reaction product. Contrarily, in the reaction with 3-methyl but-1-yne, the lowest activation free energy was calculated for C(sp³)-H functionalization via a similar pathway as for the reaction of bis(4-methoxyphenyl)carbene and is thus the favored pathway on the triplet spin surface (Table 2).

Table 2: Activation free energies of the first transition state in the reaction of bis(4-methoxyphenyl)carbene and (4-nitrophenyl)(4-methoxyphenyl)carbene with phenyl acetylene or 3-methyl but-1-yne.

		Singlet spin state intermediates			Triplet spin state intermediates		
							
		TS1 _s cyclopropene	TS2 _s C(sp ³)-H	TS3 _s C(sp ³)-H	TS1 _t indene	TS2 _t C(sp ³)-H	TS3 _t C(sp ³)-H
		Singlet spin state			Triplet spin state		
Carbene ^[a] (Ar ¹ /Ar ²)	R	TS1 _s Cyclopropene	TS2 _s C(sp ³)-H	TS3 _s C(sp ³)-H	TS1 _t indene	TS2 _t C(sp ³)-H	TS3 _t C(sp ³)-H
5a (4NO ₂ /4MeO)	Ph	10.6	17.2	—	10.2	27.4	—
	iPr	15.5	20.4	14.0	12.9	33.5	12.3
5c (4,4'-MeO)	Ph	12.0	9.8	—	11.3	27.5	—
	iPr	15.7	13.0	13.8	14.1	33.1	12.7

[a] Calculations were performed at the following levels of theory: B3LYP-D3/def2-tzvp(PCM)//B3LYP-D3/def2-svp(PCM). The relative Gibbs energies are shown in kcal mol⁻¹ as $\Delta G^\ddagger$ against the respective carbene intermediate.



Scheme 7. Theoretical calculations on the reaction mechanism of bis(4-methoxyphenyl)carbene with phenyl acetylene and 3-methylbut-1-yne at the B3LYP-D3/def2-tzvp(DCM)//B3LYP-D3/def2-svp(DCM) level of theory.

These computational studies now provide a rationale for the observed reactivity. The distinct reactivity of aryl/aryl diazoalkanes **3a–c** under photochemical conditions with alkynes can be reasoned by two factors: First, singlet triplet energy splitting of diaryl carbene intermediates **5a–c** is significantly affected by the introduction of electron-donating or electron-withdrawing groups, leading to almost degenerate energies of both carbene intermediates in the case of **5a** and **5c**. Moreover, the electronic properties of the diaryl carbene intermediates influences the transition state energies and can facilitate for example, C(sp)–H functionalization via a deprotonation/addition reaction mechanism or cyclopropanation via a classic cyclopropanation reaction mechanism similar to a donor/acceptor carbene. Thus both the singlet triplet splitting energies and electronics result in distinct reaction pathways and allow the access of orthogonal reaction pathways of diaryl carbene intermediates, for which further experimental support of highly reactive intermediate species, for example, by time-resolved spectroscopy, would be beneficial to experimentally validate the above theoretical calculations.

Conclusion

We herein report on the photochemical reaction of aryl/aryl diazoalkanes with alkynes via diaryl carbene intermediates. Visible light photolysis furnishes the diaryl carbene intermediate that, depending on the electronic properties of the substituents, selectively reacts in cyclopropanation, C–H functionalization, or cascade reactions. We could show by detailed computational and experimental studies that electronic properties of the diaryl carbene intermediate have a significant influence on the singlet triplet energy splitting,

the geometric and electronic properties of the diaryl carbene intermediate, and on the activation free energy in the reaction with alkynes. This strategy now overcomes classic limitations in the reaction of diaryl carbenes and now enables applications of aryl/aryl diazoalkanes in electronically controlled photochemical carbene transfer reactions via singlet and triplet spin states. Future studies are expected to concern mechanistic details and at the experimental identification of intermediate species involved in these reactions, for example, by time-resolved spectroscopy.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: carbene · DFT calculations · photochemistry · singlet · triplet

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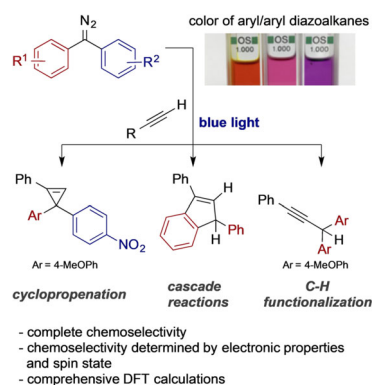


Metal-Free Photochemistry

S. Jana, C. Pei, C. Empel,
R. M. Koenigs*



Photochemical Carbene Transfer
Reactions of Aryl/Aryl Diazoalkanes—
Experiment and Theory



Aryl/aryl diazoalkanes undergo distinct, chemoselective reactions with alkynes upon blue light photolysis. This report showcases how electronic properties and spin state influence the reaction outcome of metal-free carbene transfer reactions by experimentation and theory.