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# NHC and visible light-mediated photoredox co-catalyzed 1,4-sulfonylacylation of 1,3-enynes for tetrasubstituted allenyl ketones†

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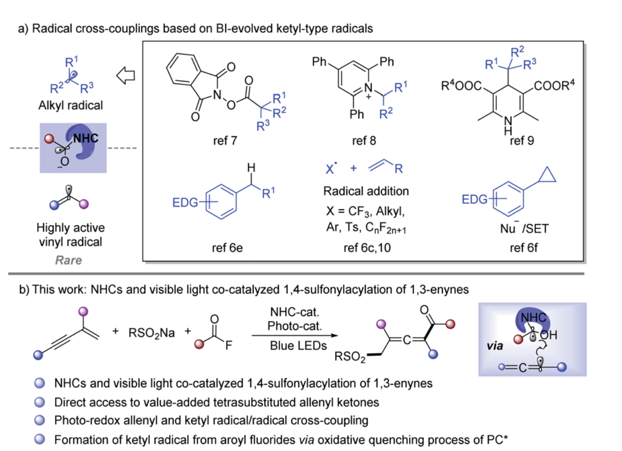
The modulation of selectivity of highly reactive carbon radical cross-coupling for the construction of C–C bonds represents a challenging task in organic chemistry. N-Heterocyclic carbene (NHC) catalyzed radical transformations have opened a new avenue for acyl radical cross-coupling chemistry. With this method, highly selective cross-coupling of an acyl radical with an alkyl radical for efficient construction of C–C bonds was successfully realized. However, the cross-coupling reaction of acyl radicals with vinyl radicals has been much less investigated. We herein describe NHC and visible light-mediated photoredox co-catalyzed radical 1,4-sulfonylacylation of 1,3-enynes, providing structurally diversified valuable tetrasubstituted allenyl ketones. Mechanistic studies indicated that ketyl radicals are formed from aroyl fluorides *via* the oxidative quenching of the photocatalyst excited state, allenyl radicals are generated from chemo-specific sulfonyl radical addition to the 1,3-enynes, and finally, the key allenyl and ketyl radical cross-coupling provides tetrasubstituted allenyl ketones.

## Introduction

Radical cross-coupling between two carbon radicals has emerged as a powerful platform for constructing C–C bonds and has received increasing attention.[1] Since the radical–radical coupling reactions proceed in a diffusion-controlled manner, selectivity modulation is the critical challenge.[1b] Through radical addition to the unsaturated bond to form a C–C bond, acyl radicals have been utilized in preparing diverse carbonyl compounds.[2] However, radical-coupling reactions between acyl and other carbon-centered radicals are rare. N-Heterocyclic carbene (NHC) catalysis has emerged as an attractive strategy in synthetic chemistry to access value-added organics *via* the formation of the key Breslow intermediate (BI).[3] Recently, the single-electron-transfer (SET) of BI was found to provide ketyl-type radical species, which opens a new avenue for acyl radical chemistry.[4–13] As a result, NHC catalyzed radical-coupling has attracted great attention after the pioneering work of Ohmiya in 2019.[7a] Alkyl radical sources such as redox-active esters,[7] Katritzky pyridinium salts,[8] Hantzsch ester,[9] benzylic C–H bonds,[6e] alkylborates,[10g] olefins[6c,10] and cyclopropanes[6f] could be used to perform cross-coupling reactions with ketyl radicals to form C–C bonds under thermal or photoredox conditions (Scheme 1a). Despite those innovative approaches, NHC catalyzed radical transformations have mainly been focused on coupling with alkyl radical species, while cross-coupling between highly active vinyl radicals and ketyl radicals though being extremely attractive is still largely underdeveloped.[11]

On the other hand, radical 1,4-difunctionalization[14,15] of 1,3-enynes provides an elegant and versatile strategy for




Scheme 1 Radical C–C bond formation based on BI-derived ketyl-type radicals.

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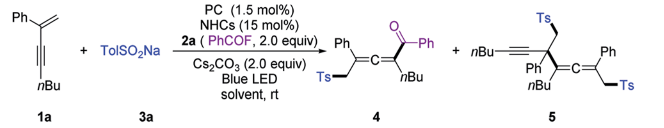
tetrasubstituted allenes from easily available feedstocks. In this regard, *in situ* generated allene radicals undergo cyanation,[15a–d] arylation,[15e–i] halogenation,[15j] alkynylation,[15k] trifluoromethylation,[15l] or intramolecular cyclization[15m] to afford functionalized allenes. Radical acylation of 1,3-enynes may provide straightforward access to value-added allenyl ketone units,[11] which are a crucial core in important nature products[16] and synthetic intermediates.[17] However, radical acylation of 1,3-enynes has been much less developed and is limited to carboacylation,[11] mainly due to the lack of an efficient acyl transfer approach. Recently, Studer *et al.* developed acylative difunctionalization of olefins[6c]/cyclopropanes[6f] and formal alkenyl[6d]/benzylic[6e] C–H acylation by employing aroyl fluorides as ketyl-type radical precursors *via* photo-induced SET. Inspired by those elegant approaches, we speculated that an NHC and visible light co-catalyzed system[6c–f,9,12,13] might enable the generation of allenyl radicals and NHC stabilized ketyl radicals under extremely mild conditions, which may provide an opportunity for radical acylation of 1,3-enynes. Sulfone-containing compounds found widespread applications in organic synthesis, medicinal chemistry, and materials science.[18] As part of our continued interest in radical chemistry[19a–g] and NHC catalysis,[19h] we now describe the development of NHC and photocatalysis co-catalyzed three-component radical 1,4-sulfonylacylation of 1,3-enynes, providing direct access to structurally diversified tetrasubstituted allenyl ketones (Scheme 1b).

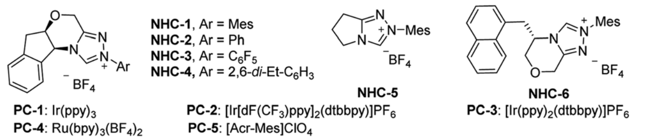
## Results and discussion

We commenced our investigation by employing a 1,3-enyne (**1a**), benzoyl fluoride (**2a**), and $TolSO_2Na$ (**3a**) as the prototype substrates, and **PC-1** (1.5 mol%) and **NHC-1** (15 mol%) as catalysts. Pleasingly, in dichloromethane (DCM), under irradiation with a blue LED at room temperature for 4 h, the expected allenyl ketone **4** was obtained in 10% yield in combination with competitive byproduct **5** (10%).[20] Ir-based photocatalysts **PC-2** and **PC-3** improved the reactivity and selectivity (Table 1, entries 2 and 3), while **PC-4** and **PC-5** were inefficient for this reaction (Table 1, entries 4 and 5). The employment of other solvents such as $CH_3CN$, $PhCF_3$, or THF provided **4** in relatively lower yields (entries 6–8). The structure of NHCs was crucial for chemo-selectivity control (entries 11–15). **NHC-2** and **NHC-3** were unsatisfactory (entries 11 and 12). The *N*-2,6-diethyl phenyl substituted catalyst **NHC-4** afforded **4** with a slightly diminished yield compared to **NHC-1** (entry 13). For **NHC-5** or **NHC-6**, decreased yield was observed (entries 14 and 15). Other bases, such as CsOAc and $K_2CO_3$, were applicable, with slightly lower yields (entries 9 and 10). To our delight, the yield could be further improved by running the reaction at lower concentration (Table 1, entries 16 and 17), affording **4** in 80% isolated yield with negligible yield of **5** in 4 mL DCM (entry 17). The desired 1,4-sulfonylacylation product **3aa** was isolated in 75% yield when the reaction was run at 0.2 mmol scales (entries 18 and 19) by employing chiral or racemic **NHC-1** as the catalyst, and these conditions were thus defined as the standard reaction conditions for subsequent investigations. Finally, benzoic

Table 1 Conditions optimization[a,b]




| Entry | NHCs (15 mol%) | PCs (1.5 mol%) | Solvent (mL) | Yields (%) 4 | 5 |
|---|---|---|---|---|---|
| 1 | **NHC-1** | **PC-1** | DCM (2) | 10 | 10 |
| 2 | **NHC-1** | **PC-2** | DCM (2) | 45 | 14 |
| 3 | **NHC-1** | **PC-3** | DCM (2) | 65 | 12 |
| 4 | **NHC-1** | **PC-4** | DCM (2) | 16 | 15 |
| 5 | **NHC-1** | **PC-5** | DCM (2) | <5 | <5 |
| 6 | **NHC-1** | **PC-3** | $CH_3CN$ (2) | 22 | 17 |
| 7 | **NHC-1** | **PC-3** | $CF_3Ph$ (2) | 56 | 8 |
| 8 | **NHC-1** | **PC-3** | THF (2) | 36 | 12 |
| 9[c] | **NHC-1** | **PC-3** | DCM (2) | 37 | 25 |
| 10[d] | **NHC-1** | **PC-3** | DCM (2) | 51 | 20 |
| 11 | **NHC-2** | **PC-3** | DCM (2) | 15 | 14 |
| 12 | **NHC-3** | **PC-3** | DCM (2) | <5 | 20 |
| 13 | **NHC-4** | **PC-3** | DCM (2) | 60 | 17 |
| 14 | **NHC-5** | **PC-3** | DCM (2) | 40 | 12 |
| 15 | **NHC-6** | **PC-3** | DCM (2) | 53 | 6 |
| 16 | **NHC-1** | **PC-3** | DCM (1) | 29 | 9 |
| 17 | **NHC-1** | **PC-3** | DCM (4) | 80 | <5 |
| 18[e] | **NHC-1** | **PC-3** | DCM (8) | 75 | <5 |
| **19**[e] | *rac*-**NHC-1** | **PC-3** | **DCM (8)** | 75 | <5 |
| 20[f] | *rac*-**NHC-1** | **PC-3** | DCM (8) | 26 | 8 |




[a] Unless otherwise noted, all the reactions were carried out with **1a** (0.1 mmol), **2a** (0.2 mmol), **3a** (0.2 mmol), NHCs (0.015 mmol), $Cs_2CO_3$ (0.2 mmol), and PCs (0.0015 mmol) in anhydrous solvent, and irradiation with a blue LED (453.5 nm, 10 W) at room temperature for 4 h. [b] Isolated yields. [c] CsOAc (0.2 mmol) was used as a base. [d] $K_2CO_3$ (0.2 mmol) was used as a base. [e] 0.2 mmol scale reaction was conducted. [f] Benzoic anhydride (0.4 mmol) was used instead of **2a**.

anhydride was employed as an acyl radical precursor, and **3aa** was obtained in 26% yield (entry 20).

With the optimized reaction conditions, the scope of 1,3-enynes was explored. As shown in Scheme 2a, 1,3-enynes bearing various electron-donating or -withdrawing substituents at the *ortho* (**6–9**), *meta* (**10** and **11**), or *para* (**12–16**) positions of the 2-phenyl rings, such as alkyl, methoxyl, halogen, methoxycarbonyl, trifluoromethyl, and trifluoromethoxy groups, were fully tolerated affording the corresponding products **6–16** smoothly. 1,3-Enynes bearing naphthalene, fluorene, and pyridine were also compatible with the transformation, and corresponding products **17–19** were formed in 50–93% yields. The functional groups linked to the alkyne triple bond could also be diversified. As shown in Scheme 2a, 1,3-enynes with *n*-hexyl (**4–21**), cyclohexyl (**25**), cyclopropyl (**27**), and chloroalkyl (**26**) groups were tolerated for this transformation. Moreover, good coupling

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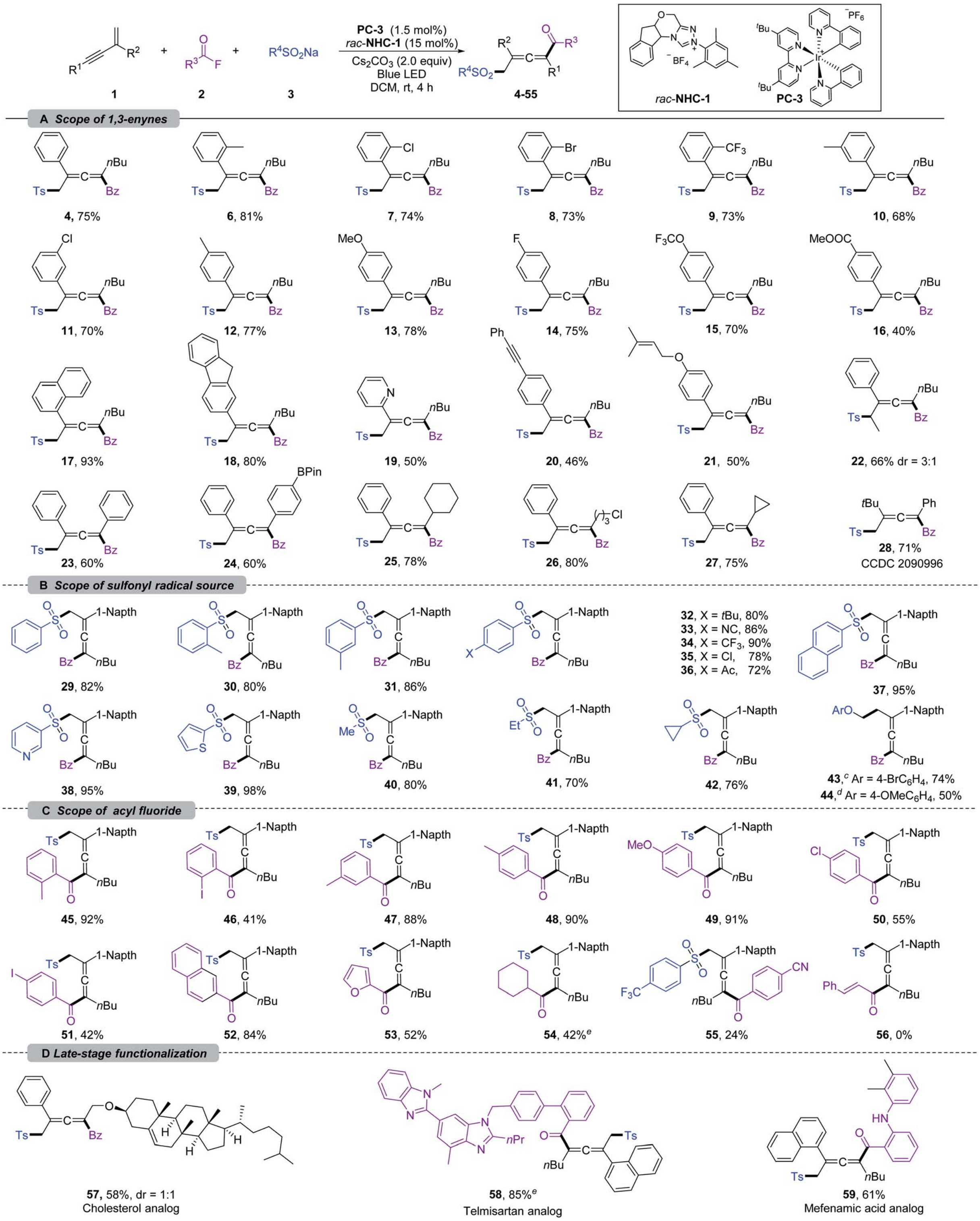

Scheme 2 Substrate scope for 1,4-sulfonylacylation of 1,3-enynes.[a,b] [a] Reaction conditions: unless otherwise noted, all the reactions were carried out with **1** (0.2 mmol), **2** (0.4 mmol), **3** (0.4 mmol), *rac*-**NHC-1** (0.03 mmol), **PC-3** (0.003 mmol) and $Cs_2CO_3$ (0.4 mmol) in DCM (8 mL) at rt under $N_2$, and irradiation with a blue LED (453.5 nm, 10 W) for 4 h. [b] Isolated yield. [c] $4\text{-BrC}_6H_4OCH_2BF_4K$ was used as a radical source. [d] $4\text{-OMeC}_6H_4OCH_2BF_4K$ was used as a radical source. [e] Reactions were carried out with *in situ* generated acyl fluoride; see the ESI† for detailed reaction conditions.

efficiencies were maintained for 2,4-diaryl substituted 1,3-enynes (**23** and **24**). It should be noted that the vulnerable Bpin (**24**), insular alkyne (**20**), and olefin (**21**) units have been preserved after transformation. Furthermore, internal 1,3-enynes and 2-alkyl substituted 1,3-enynes were applicable, affording **22** and **28** in 66% (3 : 1 dr) and 71% yields,

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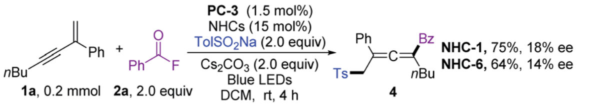
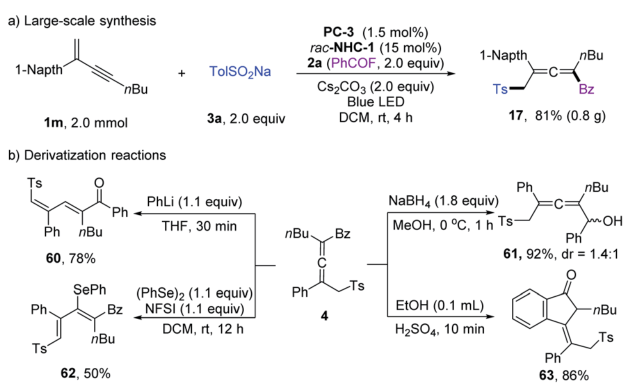


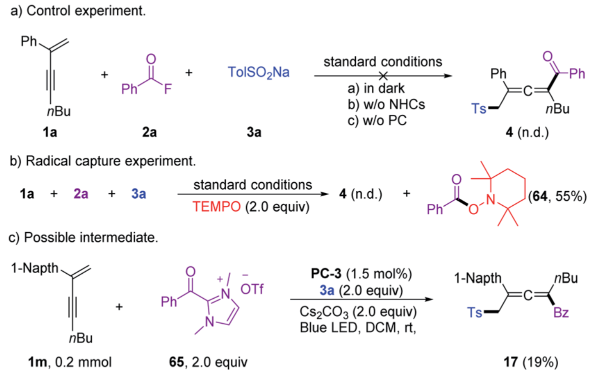

Scheme 3 Attempts at asymmetric 1,4-sulfonylacylation of 1,3-enynes.

respectively. The structure of **28** was confirmed by X-ray single-crystal diffraction (CCDC 2090996).[21] Next, we turned our attention to the scope of the sulfonyl radical source; various β-sulfonated allenyl ketones **29–40** could be obtained in good yields (Scheme 2b). Sodium arylsulfinates with methyl substituents in *ortho*- and *meta*-positions were well compatible under the reaction conditions, delivering **30** and **31** in 80 and 86% yields, respectively. The functional group tolerances and electronic effects were next investigated based on *para*-substituted sodium arylsulfinates. An array of electron-donating (*t*-Bu), -withdrawing (cyano, trifluoromethyl, and carbonyl), and halogen groups were tolerated under the standard conditions, affording **32–36** in 72–90% yields. Sodium arylsulfinates containing naphthalene (**37**), pyridine (**38**), and thiophene (**39**) proved to be viable substrates. Notably, methyl, ethyl and cyclopropyl substituted sodium sulfite could also deliver difunctionalization products **40–42** in 70–80% yield.

Very recently, the Du[11a] and Huang[11b] groups developed 1,4-alkylacylation of 1,3-enynes under thermal conditions by employing an electrophilic alkyl radical precursor. It should be noted that our NHC and PC co-catalyzed system could be extended to alkyl trifluoroborates. By employing Scheidt's aryloxymethyl trifluoroborates,[10h] the desired 1,4-alkylacylation products **43** and **44** were obtained in 74 and 50% yields, respectively. These exciting results encouraged us to evaluate the scope of acyl fluorides (Scheme 2c). This sulfonylacylation reaction was insensitive to the steric hindrance of benzoyl fluoride (**45–53**). The electron-donating aryl acyl fluorides showed excellent reactivities (**45** and **48–50**), while the presence of strong electron-deficient groups (**55**) led to low efficiency. Remarkably, the iodine group, which is sensitive in most metal-catalyzed coupling reactions, did not inhibit the reaction (**46** and **51**), providing an opportunity for further transformations.




Scheme 4 Large-scale synthesis and derivatization reactions.




Scheme 5 Mechanism investigation.

The aryl groups have been extended to naphthalene and heterocycles, providing **52** and **53** in acceptable yields. Importantly, an alkyl acyl fluoride could be used as well in this transformation, affording the corresponding allene **54** in 42% yield. Unfortunately, cinnamoyl fluoride (**56**) was not suitable for this conversion. Taking advantage of the mild reaction conditions as well as broad functional group tolerances, the 1,4-sulfonylacylation of enynes could be applied at a late-stage functionalization. As shown in Scheme 2d, the 1,3-enynes derived from cholesterol could participate in this reaction, delivering **57** in 58% (1 : 1 dr) yield. Furthermore, the fluorides derived from natural products such as telmisartan and mefenamic acid were successfully converted into **58** and **59** in 85% and 61% yields, respectively.

Considering the mild reaction conditions as well as tolerance with chiral NHC catalysts, we attempted the challenging chiral allene synthesis. Unfortunately, unsatisfactory enantioselectivity was observed for both chiral **NHC-1** and **NHC-6** (Scheme 3).

Large-scale synthesis and derivatization reactions were performed to showcase the synthetic applications (Scheme 4). Scale-up synthesis of **17** has been achieved at a 2.0 mmol scale, and a comparable yield was obtained (Scheme 4a). When employing PhLi as a base, the tetrasubstituted allenyl ketone **4** could isomerize to diene product **60** in 78% yield. **4** could undergo reduction of the ketone unit with $NaBH_4$. The allenyl ketone **4** could easily be transformed into conjugated viny selenyl ether **62** in 50% yield with excellent *Z*/*E* selectivity. When treated with concentrated $H_2SO_4$, Nazarov cyclization product **63** was isolated in 86% yield.

A series of control experiments were performed to unravel the reaction mechanism. Light, NHCs, and photoredox catalysis were indispensable for this 1,4-sulfonylacylation reaction (Scheme 5a). When the radical scavenger 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) was added, the reaction was suppressed, and TEMPO-trapped product **64** was separated in 55% yield (Scheme 5b), thus suggesting the formation of ketyl radicals. Furthermore, a trace amount of 4,4′-dimethyl-1,1′-biphenyl (**66**) was isolated under standard conditions, indicating the involvement of a sulfonyl radical. The intermediacy of acyl azoliums has been confirmed by coupling of acyl azolium

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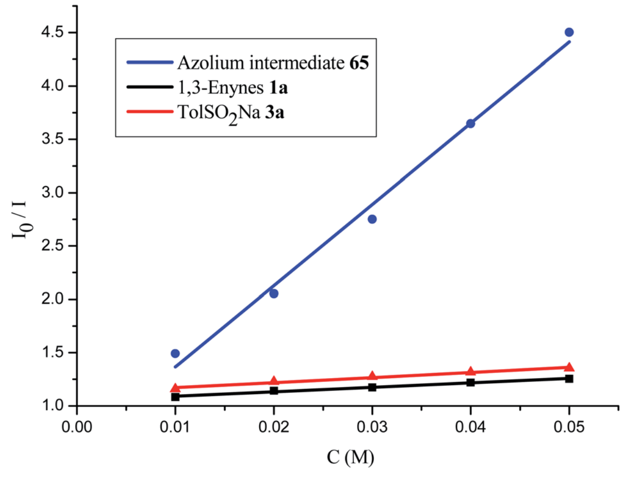
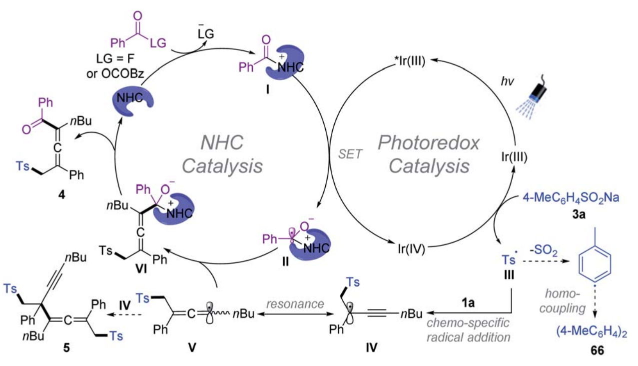



Scheme 6 Stern–Volmer quenching studies.




Scheme 7 Proposed catalytic cycle.

ion **65** with 1,3-enyne **1a** and sodium benzenesulfinate **3a** in the absence of NHCs (Scheme 5c). The radical chain process could be ruled out based on light/dark experiments (Fig. S4, see the ESI†). Then Stern–Volmer quenching studies were conducted to clarify the plausible photoredox mechanism (Scheme 6). 1,3-Enynes **1a** and sodium benzenesulfinate **3a** do not show a significant luminescence quenching effect on the excited state of Ir*(III). In contrast, the Ir*-complex was effectively quenched by acyl azolium ion **65**, pointing to the oxidative quenching process.

Based on a series of experimental studies and previous reports, a plausible catalytic cycle for the 1,4-sulfonylacylation is proposed in Scheme 7. The acyl fluoride or *in situ* generated bisacyl carbonate intermediate[6f] could react with NHCs providing acylazolium intermediate **I**. Upon visible light irradiation, the excited state of $[Ir(ppy)_2(dtbbpy)]PF_6$ undergoes an oxidative quenching[22] by **I** to yield the $Ir^{IV}$-complex and ketyl radical **II**. Single-electron transfer between the $Ir^{IV}$-complex and aryl sulfinate provides an aryl sulfonyl radical **III** while regenerating the ground-state photocatalyst ($Ir^{III}$), closing the photoredox cycle. The sulfonyl radical then adds to the olefin unit of the 1,3-enyne **1** delivering the propargyl radical **IV**, which could undergo reversible resonance to generate trisubstituted allenyl radical **V**.[15] Subsequently, chemo-specific radical/radical cross-coupling between the persistent ketyl radical **II** and transient allenyl radical **V** affords NHC-bound intermediate **VI**. The exclusive coupling selectivity might be regulated by the persistent radical effect[1b] as well as the steric exclusion of propargyl radical **IV** with ketyl radical **II**. **VI** disintegrates to give rise to the final product **4**, while the NHC is regenerated for the next NHC cycle. Meanwhile, $SO_2$ fragments of the sulfonyl radical produced aryl radicals, which undergo homocoupling affording biaryl **66**. Radical–radical cross-coupling of **V** and **IV** affords the byproduct **5**.[1b,20] Meanwhile, direct homo-coupling of **V** or **IV** was not detected in our reaction system, which might be due to the persistent radical effect.[1b]

## Conclusions

In summary, we have realized an efficient 1,4-sulfonylacylation of 1,3-enynes by merging photocatalysis with NHCs. This transformation provided a facile and direct access to tetrasubstituted allenyl ketones under mild conditions with broad functional group tolerance and excellent chemo- and regioselectivity. Mechanistic studies indicated that the key step of the transformation is allenyl and ketyl radical cross-coupling, proving a new avenue for NHC catalyzed radical chemistry. The ketyl radical was formed from aroyl fluorides *via* the oxidative quenching of the photocatalyst excited state. Further extension of this cross-coupling system to other destabilized transient radicals is ongoing in our laboratory.

## Data availability

Data for all compounds in this manuscript are available in the ESI,† which includes experimental details, characterization and copies of $^{1}H$ and $^{13}C$ NMR spectra. Crystallographic data for compound **28** has been deposited at the CCDC under CCDC 2090996.

## Author contributions

L. W., R. M., and J. S. performed the experiments. G. Z. and Q. Z. conceived the concept, directed the project and wrote the paper.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

1 (*a*) J. Xie, H. Jin and A. S. K. Hashmi, *Chem. Soc. Rev.*, 2017, **46**, 5193–5203; (*b*) D. Leifert and A. Studer, *Angew. Chem., Int. Ed.*, 2020, **59**, 74–108; (*c*) A. Bhunia and A. Studer, *Chem*, 2021, **7**, 1–41; (*d*) J. D. Bell and J. A. Murphy, *Chem. Soc. Rev.*, 2021, **50**, 9540–9685; (*e*) Y. Sohtome, K. Kanomata and M. Sodeoka, *Bull. Chem. Soc. Jpn.*, 2021, **94**, 1066–1079; (*f*) Y. Yuan, J. Yanga and A. Lei, *Chem. Soc. Rev.*, 2021, **50**, 10058–10086.

2 (*a*) C. Chatgilialoglu, D. Crich, M. Komatsu and I. Ryu, *Chem. Rev.*, 1999, **99**, 1991–2069; (*b*) A. Banerjee, Z. Lei and M. Ngai, *Synthesis*, 2019, 303–333; (*c*) Y. Liu, Y. Ouyang, H. Zheng, H. Liu and W. Wei, *Chem. Commun.*, 2021, **57**, 6111–6120.

3 (*a*) D. Enders, O. Niemeier and A. Henseler, *Chem. Rev.*, 2008, **107**, 5606–5655; (*b*) X. Bugaut and F. Glorius, *Chem. Soc. Rev.*, 2012, **41**, 3511–3522; (*c*) M. N. Hopkinson, C. Richter, M. Schedler and F. Glorius, *Nature*, 2014, **510**, 485–496; (*d*) J. Mahatthananchai and J. W. Bode, *Acc. Chem. Res.*, 2014, **47**, 696–707; (*e*) R. S. Menon, A. T. Biju and V. Nair, *Chem. Soc. Rev.*, 2015, **44**, 5040–5052; (*f*) D. M. Flanigan, F. Romanov-Michailidis, N. A. White and T. Rovis, *Chem. Rev.*, 2015, **115**, 9307–9387; (*g*) C. Zhang, J. F. Hooper and D. W. Lupton, *ACS Catal.*, 2017, **7**, 2583–2596; (*h*) X.-Y. Chen, Q. Liu, P. Chauhan and D. Enders, *Angew. Chem., Int. Ed.*, 2018, **57**, 3862–3873; (*i*) K. J. R. Murauski, A. A. Jaworski and K. A. Scheidt, *Chem. Soc. Rev.*, 2018, **47**, 1773–1782; (*j*) S. Mondal, S. R. Yetra, S. Mukherjee and A. T. Biju, *Acc. Chem. Res.*, 2019, **52**, 425–436; (*k*) X. Chen, Z. Gao and S. Ye, *Acc. Chem. Res.*, 2020, **53**, 690–702; (*l*) P. Bellotti, M. Koy, M. N. Hopkinson and F. Glorius, *Nat. Rev. Chem.*, 2021, **5**, 711–725.

4 (*a*) I. Nakanishi, S. Itoh, T. Suenobu and S. Fukuzumi, *Chem. Commun.*, 1997, 1927–1928; (*b*) J. K. Mahoney, D. Martin, C. E. Moore, A. L. Rheingold and G. Bertrand, *J. Am. Chem. Soc.*, 2013, **135**, 18766–18769; (*c*) V. Regnier, E. A. Romero, F. Molton, R. Jazzar, G. Bertrand and D. Martin, *J. Am. Chem. Soc.*, 2019, **141**, 1109–1117.

5 (*a*) K. Zhao and D. Enders, *Angew. Chem., Int. Ed.*, 2017, **56**, 3754–3756; (*b*) R. Song and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2019, **58**, 8628–8630; (*c*) T. Ishii, K. Nagao and H. Ohmiya, *Chem. Sci.*, 2020, **11**, 5630–5636; (*d*) Q. Liu and X.-Y. Chen, *Org. Chem. Front.*, 2020, **7**, 2082–2087; (*e*) H. Ohmiya, *ACS Catal.*, 2020, **10**, 6862–6869; K.-Q. Chen, H. Sheng, Q. Liu, P.-L. Shao and X.-Y. Chen, *Sci. China: Chem.*, 2021, **64**, 7–16. (*f*) Q.-Z. Li, R. Zeng, B. Han and J.-L. Li, *Chem.–Eur. J.*, 2021, **27**, 3238–3250; (*g*) Y. Sumoda and H. Ohmiya, *Chem. Soc. Rev.*, 2021, **50**, 6320–6332.

6 (*a*) J. Guin, S. D. Sarkar, S. Grimme and A. Studer, *Angew. Chem., Int. Ed.*, 2008, **47**, 8727–8730; (*b*) J. Zhao, C. Mück-Lichtenfeld and A. Studer, *Adv. Synth. Catal.*, 2013, **355**, 1098–1106; (*c*) Q.-Y. Meng, N. Döben and A. Studer, *Angew. Chem., Int. Ed.*, 2020, **59**, 19956–19960; (*d*) K. Liu and A. Studer, *J. Am. Chem. Soc.*, 2021, **143**, 4903–4909; (*e*) Q.-Y. Meng, L. Lezius and A. Studer, *Nat. Commun.*, 2021, **12**, 2068; (*f*) Z. Zuo, C. G. Daniliuc and A. Studer, *Angew. Chem., Int. Ed.*, 2021, **60**, 25252–25257.

7 (*a*) T. Ishii, Y. Kakeno, K. Nagao and H. Ohmiya, *J. Am. Chem. Soc.*, 2019, **141**, 3854–3858; (*b*) Y. Kakeno, M. Kusakabe, K. Nagao and H. Ohmiya, *ACS Catal.*, 2020, **10**, 8524–8529.

8 L. Kim, H. Im, H. Lee and S. Hong, *Chem. Sci.*, 2020, **11**, 3192–3197.

9 (*a*) A. V. Davies, K. P. Fitzpatrick, R. C. Betori and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2020, **59**, 9143–9148; (*b*) A. A. Bayly, B. R. McDonald, M. Mrksich and K. A. Scheidt, *Proc. Natl. Acad. Sci. U. S. A.*, 2020, **117**, 13261–13266; (*c*) A. V. Bay, K. P. Fitzpatrick, G. A. González-Montiel, A. O. Farah, P. H. Cheong and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2021, **60**, 17925–17931; (*d*) S.-C. Ren, W.-X. Lv, X. Yang, J.-L. Yan, J. Xu, F.-X. Wang, L. Hao, H. Chai, Z. Jin and Y. R. Chi, *ACS Catal.*, 2021, **11**, 2925–2934.

10 (*a*) T. Ishii, K. Ota, K. Nagao and H. Ohmiya, *J. Am. Chem. Soc.*, 2019, **141**, 14073–14077; (*b*) K. Ota, K. Nagao and H. Ohmiya, *Org. Lett.*, 2020, **22**, 3922–3925; (*c*) Y. Matsuki, N. Ohnishi, Y. Kakeno, S. Takemoto, T. Ishii, K. Nagao and H. Ohmiya, *Nat. Commun.*, 2021, **12**, 3848; (*d*) H.-B. Yang, Z.-H. Wang, J.-M. Li and C. Wu, *Chem. Commun.*, 2020, **56**, 3801–3804; (*e*) J.-L. Li, Y.-Q. Liu, W.-L. Zou, R. Zeng, X. Zhang, Y. Liu, B. Han, Y. He, H.-J. Leng and Q.-Z. Li, *Angew. Chem., Int. Ed.*, 2020, **59**, 1863–1870; (*f*) B. Zhang, Q. Peng, D. Guo and J. Wang, *Org. Lett.*, 2020, **22**, 443–447; (*g*) Y. Sato, Y. Goto, K. Nakamura, Y. Miyamoto, Y. Sumida and H. Ohmiya, *ACS Catal.*, 2021, **11**, 12886–12892; (*h*) P. Wang, K. P. Fitzpatrick and K. A. Scheidt, *Adv. Synth. Catal.*, 2022, **364**, 518–524.

11 (*a*) C. Lei, C. Lin, S. Zhang, X. Zhang, J. Zhang, L. Xing, Y. Guo, J. Feng, J. Gao and D. Du, *ACS Catal.*, 2021, **11**, 13363–13373 (During our preparation of this manuscript, Feng, Du and co-workers reported 1,4-alkylacylation of 1,3-enynes under thermal conditions); (*b*) Y. Cai, J. Chen and Y. Huang, *Org. Lett*, 2021, **23**, 9251–9255 (During our submission, Chen, Huang and co-workers reported 1,4-alkylacylation of 1,3-enynes under thermal conditions); (*c*) L. Wang, R. Ma, J. Sun, G. Zheng and Q. Zhang, *ChemRxiv*, 2021, DOI: 10.33774/chemrxiv-2021-5c17 (preprint).

12 (*a*) A. Mavroskoufis, M. Jakob and M. N. Hopkinson, *ChemPhotoChem*, 2020, **4**, 5147–5153; (*b*) J. Liu, X.-N. Xing, J.-H. Huang, L.-Q. Lu and W.-J. Xiao, *Chem. Sci.*, 2020, **11**, 10605–10613.

13 (*a*) D. A. DiRocco and T. Rovis, *J. Am. Chem. Soc.*, 2012, **134**, 8094–8097; (*b*) L. Dai, Z.-H. Xia, Y.-Y. Gao, Z.-H. Gao and S. Ye, *Angew. Chem., Int. Ed.*, 2019, **58**, 18124–18130; (*c*) A. Mavroskoufis, K. Rajes, P. Golz, A. Agrawal, V. Ruß, J. P. Götze and M. N. Hopkinson, *Angew. Chem., Int. Ed.*, 2020, **59**, 3190–3194.

14 L. Fu, S. Greßies, P. Chen and G. Liu, *Chin. J. Chem.*, 2020, **38**, 91–100.

15 (*a*) F. Wang, D. Wang, Y. Zhou, L. Liang, R. Lu, P. Chen, Z. Lin and G. Liu, *Angew. Chem., Int. Ed.*, 2018, **57**, 7140–7145; (*b*) X. Zhu, W. Deng, M.-F. Chiou, C. Ye, W. Jian, Y. Zeng, Y. Jiao, L. Ge, Y. Li, X. Zhang and H. Bao, *J. Am.

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*Chem. Soc.*, 2019, **141**, 548–559; (*c*) Y. Zeng, M.-F. Chiou, X. Zhu, J. Cao, D. Lv, W. Jian, Y. Li, X. Zhang and H. Bao, *J. Am. Chem. Soc.*, 2020, **142**, 18014–18021; (*d*) Y. Chen, J. Wang and Y. Lu, *Chem. Sci.*, 2021, **12**, 11316–11321; (*e*) J. Terao, F. Bando and N. Kambe, *Chem. Commun.*, 2009, 7336–7338; (*f*) K.-F. Zhang, K.-J. Bian, C. Li, J. Sheng, Y. Li and X.-S. Wang, *Angew. Chem., Int. Ed.*, 2019, **58**, 5069–5074; (*g*) C. Ye, Y. Li, X. Zhu, S. Hu, D. Yuan and H. Bao, *Chem. Sci.*, 2019, **10**, 3632–3636; (*h*) Y. Chen, K. Zhu, Q. Huang and Y. Lu, *Chem. Sci.*, 2021, **12**, 13564–13571; (*i*) T. Xu, S. Wu, Q.-N. Zhang, Y. Wu, M. Hu and J.-H. Li, *Org. Lett.*, 2021, **23**, 8455–8459; (*j*) Y. Song, S. Song, X. Duan, X. Wu, F. Jiang, Y. Zhang, J. Fan, X. Huang, C. Fu and S. Ma, *Chem. Commun.*, 2019, **55**, 11774–11777; (*k*) X.-Y. Dong, T.-Y. Zhan, S.-P. Jiang, X.-D. Liu, L. Ye, Z.-L. Li, Q.-S. Gu and X.-Y. Liu, *Angew. Chem., Int. Ed.*, 2021, **60**, 2160–2164; (*l*) H. Shen, H. Xiao, L. Zhu and C. Li, *Synlett*, 2020, **31**, 41–44; (*m*) C. Alameda-Angulo, B. Quiclet-Sire and S. Z. Zard, *Tetrahedron Lett.*, 2006, **47**, 913–916; (*n*) H.-M. Huang, P. Bellotti, C. Daniliuc and F. Glorius, *Angew. Chem., Int. Ed.*, 2021, **60**, 2464–2471.

16 (*a*) A. Hoffmann-Roder and N. Krause, *Angew. Chem., Int. Ed.*, 2004, **43**, 1196–1216; (*b*) L. U. Dzhemileva, V. A. D'Yakonov, A. A. Makarov, E. K. Makarova, E. N. Andreev and U. M. Dzhemilev, *J. Nat. Prod.*, 2020, **83**, 2399–2409.

17 (*a*) A. S. Dudnik and V. Gevorgyan, *Angew. Chem., Int. Ed.*, 2007, **46**, 5195–5197; (*b*) C. Xue, X. Huang, S. Wu, J. Zhou, J. Dai, C. Fu and S. Ma, *Chem. Commun.*, 2015, **51**, 17112–17115; (*c*) M. Miao, Y. Luo, H. Xu, Z. Chen, J. Xu and H. Ren, *Org. Lett.*, 2016, **18**, 4292–4295; (*d*) M. Miao, H. Xu, Y. Luo, M. Jin, Z. Chen, J. Xu and H. Ren, *Org. Chem. Front.*, 2017, **4**, 1824–1828; (*e*) J. Teske and B. Plietker, *Org. Lett.*, 2018, **20**, 2257–2260.

18 (*a*) G. H. Whitham, *Organosulfur Chemistry*, Oxford University Press, Oxford, 1995; (*b*) M. Feng, B. Tang, S. H. Liang and X. Jiang, *Curr. Top. Med. Chem.*, 2016, **16**, 1200; (*c*) X. Jiang, *Sulfur Chemistry*, Springer, Berlin, 2019; (*d*) X. Chu, D. Ge, Y. Cui, Z. Shen and C. Li, *Chem. Rev.*, 2021, **121**, 12548–12680.

19 (*a*) H. Zhang, W. Pu, T. Xiong, Y. Li, X. Zhou, K. Sun, Q. Liu and Q. Zhang, *Angew. Chem., Int. Ed.*, 2013, **52**, 2529–2533; (*b*) H. Zhang, Y. Song, J. Zhao, J. Zhang and Q. Zhang, *Angew. Chem., Int. Ed.*, 2014, **53**, 11079–11083; (*c*) G. Zhang, T. Xiong, Z. Wang, G. Xu, X. Wang and Q. Zhang, *Angew. Chem., Int. Ed.*, 2015, **54**, 12649–12653; (*d*) G. Zheng, Y. Li, J. Han, T. Xiong and Q. Zhang, *Nat. Commun.*, 2015, **6**, 7011; (*e*) J. Sun, G. Zheng, T. Xiong, Q. Zhang, J. Zhao, Y. Li and Q. Zhang, *ACS Catal.*, 2016, **6**, 3674–3678; (*f*) S. Yang, L. Wang, H. Zhang, C. Liu, L. Zhang, X. Wang, G. Zhang, Y. Li and Q. Zhang, *ACS Catal.*, 2019, **9**, 716–721; (*g*) T. Qin, G. Lv, Q. Meng, G. Zhang, T. Xiong and Q. Zhang, *Angew. Chem., Int. Ed.*, 2021, **60**, 25949–25957; (*h*) Y. Wu, M. Li, J. Sun, G. Zheng and Q. Zhang, *Angew. Chem., Int. Ed.*, 2022, **61**, DOI: 10.1002/anie.202117340.

20 (*a*) F. Yang, G. Zhao, Y. Ding, Z. Zhao and Y. Zheng, *Tetrahedron Lett*, 2002, **43**, 1289–1293; (*b*) G. V. Karunakar and M. Periasamy, *Tetrahedron Lett.*, 2006, **47**, 3549–3552.

21 CCDC 2090996 (**28**) contains the supplementary crystallographic data for this paper.†

22 (*a*) J. Xuan and W. Xiao, *Angew. Chem., Int. Ed.*, 2012, **51**, 6828–6838; (*b*) C. K. Prier, D. A. Rankic and D. W. C. MacMillan, *Chem. Rev.*, 2013, **113**, 5322–5363; (*c*) J. D. Slinker, A. A. Gorodetsky, M. S. Lowry, J. Wang, S. Parker, R. Rohl, S. Bernhard and G. G. Malliaras, *J. Am. Chem. Soc.*, 2004, **126**, 2763–2767.