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Transition-metal-free radical cleavage of a hydrazonyl N−S bond: tosyl radical-initiated cascade C(sp³)−OAr cleavage, sulfonyl rearrangement and atropisomeric cyclopropanation†

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For the first time, the combination of catalytic 1,10-phenanthroline and potassium carbonate enables a radical cleavage of a hydrazonyl N−S bond to deliver a tosyl radical and a diazo compound, along with releasing molecular hydrogen spontaneously. The tosyl radical and hydrogen evolution are witnessed by radical trapping, EPR experiment and gas chromatography. An innovative application of this strategy into metal-free coupling of *N*-tosylhydrazone and phosphinyl allene provides a one-step synthesis of novel atropisomeric 3-tosyl-1-enyl-cyclopropyl-diphenylphosphine oxide derivatives with excellent diastereo-selectivity and *E*-selectivity. Moreover, these atropisomeric products, verified by ¹H-NMR, DFT calculations and X-ray crystallography, are controllably formed. Mechanistic studies indicate that the multistep cascade reaction occurs through radical hydrazonyl N−S bond cleavage, radical C(sp³)−OAr bond cleavage, sulfonyl rearrangement and atropisomeric cyclopropanation.
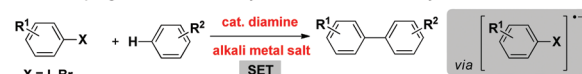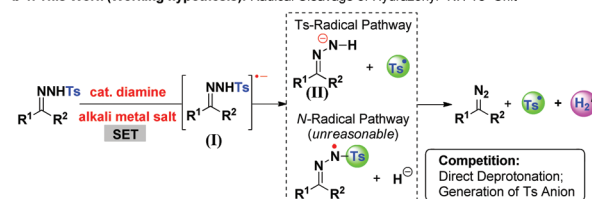
Introduction

In the past decade, the green and sustainable strategy for free-radical generation from a diamine/alkali metal salt system has contributed greatly to cross-coupling reactions, which received significant attention from scientific and industrial communities.[1] Contributions by Hayashi, Shi, Lei, Murphy and others have witnessed the blooming of this chemistry,[2] lately classified as base-promoted homolytic aromatic substitution (BHAS),[3] in various inter/intramolecular C–C couplings between aryl halides and arenes or olefins (Scheme 1a). Although potassium *t*-butoxide alone was reported to enable the couplings,[4] a wide range of organic additives including 1,10-phenanthroline derivatives, aliphatic 1,2-diamines, imines, amino acids, hydrazine derivatives, *N*-heterocyclic carbenes, and diphosphines have been used in initiating the radical chain process more efficiently.[2a–g,3b,5] From both experimental facts and theoretical calculation considerations,[2i]

a single electron transfer process has been verified, for example, 1,10-phenanthroline/*t*-BuOK initiated radical cleavage of the aryl–I bond will deliver an aryl radical and an iodide anion. We believe that this strategy should be ideally suitable for developing novel radical chain reactions other
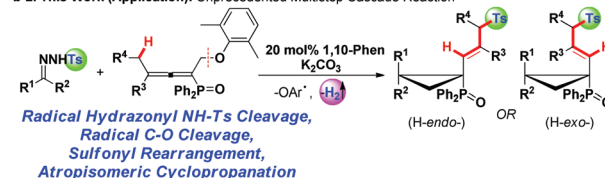

Scheme 1 Previous work with diamine/alkali metal salt combination (a) and this work (b-1, b-2).

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†Electronic supplementary information (ESI) available. CCDC 1573906, 1573907, 1573911 and 1573912. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c8qo00873f

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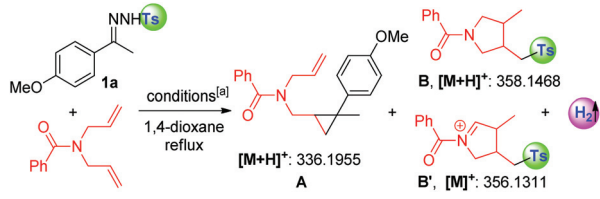*Org. Chem. Front.*, 2018, **5**, 3567–3573 | **3567**

than C–C couplings; however, to the best of our knowledge, this field remains untouched so far.

The pursuit of *N*-tosylhydrazone chemistry dates back to the mid-20th century, as well-known as the Bamford–Stevens reaction and Shapiro reaction.[6] Since the first report of palladium-catalyzed coupling of *N*-tosylhydrazones with arylbromides in 2007, this chemistry has been attracting extensive interest in providing diazo precursors in building versatile functionalities for synthetic compounds, led by the groups of Barluenga and Valdés,[7] Wang[8] and others.[9] Despite these great achievements, only a handful of methods have been established regarding free-radical generation from *N*-tosylhydrazone, albeit confined to a transition metal-catalysis system.[10] For example, Xiao's group has established a photocatalytic hydroamination of *N*-tosylhydrazones with intramolecular alkenes, in which *N*-radical formation from single-electron oxidation of deprotonated *N*-tosylhydrazones was involved.[10a,b] Very recently, cobalt[III]–carbene radicals, generated through metalloradical activation of *N*-tosylhydrazones by cobalt[II] complexes, were developed in the reactions of *N*-tosylhydrazones and olefins, alkynes or alkanes.[10d–f,10h–i] Inspired by the aforementioned studies and our previous studies,[11] we hypothesized that, a diamine/alkali metal salt excited hydrazonyl radical anion might undergo a probable Ts-radical pathway (N–S bond cleavage)[12] to furnish a diazo compound, tosyl radical and molecular hydrogen (Scheme 1b-1), and this unprecedented strategy should offer a powerful and important platform for discovering new radical chemistry of *N*-tosylhydrazones with allenes toward complex molecules.

Results and discussion

With an aim to rationalize our hypothesis, an EPR experiment for the reaction of 1-(1-(4-methoxyphenyl)ethylidene)-2-tosylhydrazine (**1a**), 20 mol% of 1,10-phen and 1.5 equivalents of *t*-BuOK was conducted to monitor the formation of radical species, which indicated the formation of the tosyl radical (see more details in the ESI†).[13] The tosyl radical could also be captured by TEMPO as monitored by HR-MS (in ESI†). As shown in Table 1, *N*,*N*-diallylbenzamide was subsequently applied to trap the fragments cleaved from *N*-tosylhydrazone (**1a**). In preliminary results, 20 mol% of 1,10-phen and 1.5 equivalents of *t*-BuOK or K₂CO₃ successfully enabled radical cleavage of the "NHTs" unit (entries 1 and 2), which was strongly supported by the detection of adducts **A**, **B** and **B′**, deriving from the diazo precursor and the tosyl radical, respectively. Interestingly, a catalytic amount of potassium carbonate afforded the same result of fragment abundance in the HRMS spectrum, even for the case with high purity reagents (entries 3 and 4). A parallel experiment without 1,10-phen gave only the cyclopropanation product (**A**, entry 5). The observations in entries 3 and 4 deserve to be highlighted since the tosyl anion could be generated in the presence of excess base, and a single-electron oxidation of the tosyl anion by metal catalysts has been reported to afford the tosyl radical;[14] however, the

Table 1 Studies on cleavage of *N*-tosylhydrazones: evidence of tosyl radical and molecular hydrogen evolution[a]
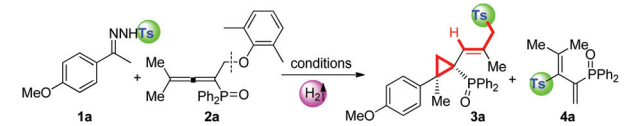

Entry	Radical initiator	HR-MS result	H₂ evolution
1	20 mol% 1,10-phen/1.5 equiv. *t*-BuOK	**A + B + B′**	Yes
2	20 mol% 1,10-phen/1.5 equiv. K₂CO₃	**A + B + B′**	Yes
3	20 mol% 1,10-phen/15 mol% K₂CO₃	**A + B + B′**	Yes
4[b]	20 mol% 1,10-phen/15 mol% K₂CO₃	**A + B + B′**	Yes
5	1.5 equiv. K₂CO₃	Only **A**	No
6[c]	20 mol% 1,10-phen/15 mol% K₂CO₃	—	No
7	0.2 equiv. TBAI/2 equiv. TBHP	**B + B′**	No
8	5 mol% Pd(OAc)₂/20 mol% 1,10-phen/15 mol% K₂CO₃	**A + B + B′**	Yes
9	5 mol% Pd(PPh₃)₂Cl₂/15 mol% K₂CO₃	Only **A**	No

[a] *N*-Tosylhydrazone (**1a**, 0.1 mmol), *N*,*N*-diallylbenzamide (0.12 mmol), catalyst or oxidant in 3 mL refluxing 1,4-dioxane for 2 hours. [b] High purity reagents: 1,10-phen (anhydrous, purity > 99 + %), K₂CO₃ (purity: 99.997%). [c] TsNa was used instead of **1a**.

negative result of sodium 4-methylbenzene-sulfinate and *N*,*N*-diallyl-benzamide entirely ruled out the possibility of forming the tosyl radical from the tosyl anion under the current conditions (entry 6). Although TBAI/TBHP evidenced a positive result in producing the trapping products (**B** and **B′**) from the tosyl radical as monitored by HR-MS, it was found that the diazo precursor decomposed rapidly (entry 7). The results in entries 8 and 9 showed that a palladium catalyst would not inhibit the radical process but did not deliver the tosyl radical without the participation of 1,10-phen. Intriguingly, molecular hydrogen evolution was detected by gas chromatography in entries 1–4 and 8, indicating that the hydrogen radical or hydrogen anion might be produced in the system (in ESI†).

Subsequently, we applied this strategy in the coupling of *N*-tosylhydrazones and phosphinyl allenes (Scheme 1b-2). This choice was based on our previous report of a transition-metal-catalyzed coupling of *N*-tosylhydrazones with phosphinyl allenes to form phosphinyl [3]dendralenes,[11a] which we believe would be a model reaction suitable for providing an expeditious platform for investigating the reactivity of the tosyl radical and diazo compound *in situ* generated from *N*-tosylhydrazones and differentiating the 1,10-phen/K₂CO₃ system from metal contamination.[1a,15] The study was initiated by examining the coupling of **1a** with phosphinyl allene (**2a**). As shown in Table 2, for a preliminary experiment with a catalytic amount of 1,10-phen and *t*-BuOK, 6% yield of (*E*)-(2-(4-methoxy phenyl)-2-methyl-1-(2-methyl-3-tosylprop-1-en-1-yl) cyclopropyl)diphenyl-phosphine oxide (**3a**) was obtained with high diastereoselectivity, along with 50% yield of tosylated 1,3-diene (**4a**) (entry 2). The ratios of **3a**/**4a** changed in proportion to the amount of base used (entries 3–5), in which 2.5 equiva-

Table 2 Metal-free coupling of *N*-tosylhydrazone (**1a**) with phosphinyl allenes (**2a**): screening of conditions[a]
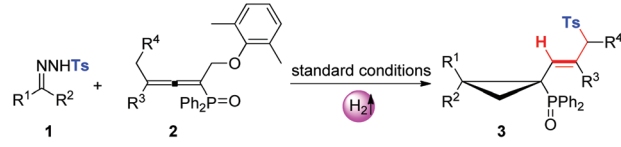

Entry	Catalyst (20 mol%)	Base	Yield (%) (3a/4a)[b]
1	1,10-Phen	*t*-BuOK (15 mol%)	0/14
2	1,10-Phen	*t*-BuOK (40 mol%)	6/50
3	1,10-Phen	K_2CO_3 (15 mol%)	<5/85
4	1,10-Phen	K_2CO_3 (1.5 equiv.)	35/30
5	**1,10-Phen**	**K_2CO_3 (2.5 equiv.)**	**74/0**
6	1,10-Phen	NaHCO$_3$ (2.5 equiv.)	56/0
7	1,10-Phen	CsF (2.5 equiv.)	53/0
8	1,10-Phen	Cs$_2$CO$_3$ (2.5 equiv.)	17/0
9	1,10-Phen	DBU (2.5 equiv.)	0/0
10	2,2′-Bipyridine	K_2CO_3 (2.5 equiv.)	38/13
11	2,9-Dimethyl-1, 10-phenanthroline	K_2CO_3 (2.5 equiv.)	36/11
12	2,2′:6′,2″-Terpyridine	K_2CO_3 (2.5 equiv.)	42/9
13	4,7-Dimethoxy-1, 10-phenanthroline	K_2CO_3 (2.5 equiv.)	50/0
14[c,d]	Pd(PPh$_3$)$_2$Cl$_2$	K_2CO_3 (2.5 equiv.)	0/0
15[c]	Pd(OAc)$_2$/1,10-phen	K_2CO_3 (2.5 equiv.)	40/0
16[c]	Cu(OAc)$_2$/1,10-phen	K_2CO_3 (2.5 equiv.)	0/0
17[c]	CoCl$_2$/1,10-phen	K_2CO_3 (2.5 equiv.)	21/0
18[e]	1,10-Phen	K_2CO_3 (2.5 equiv.)	75/0

[a] Reaction conditions: *N*-Tosylhydrazone (**1a**, 0.9 mmol), phosphinyl allene (**2a**, 0.3 mmol), catalyst (20 mol%) and base in 3 mL refluxing 1,4-dioxane for 8 hours. [b] Isolated yield by column chromatography (dr > 20 : 1, only *E*-isomer for all cases). [c] 5 mol% palladium catalyst. [d] The major product was phosphinyl[3]dendralenes, see our previous work in ref. 11*a*. [e] High purity reagents: 1,10-phen (anhydrous, purity > 99 + %), K_2CO_3 (purity: 99.997%).

lents of K_2CO_3 improved the isolated yield of **3a** up to 74% (Note: this observation does not conclude that stoichiometric base is necessary to generate the tosyl radical, instead, excess base plays a vital role in converting **4a** into **3a** in a sulfonyl rearrangement step). A series of bases, including inorganic and organic bases, were then screened. Weaker inorganic bases, such as Na$_2$CO$_3$, NaHCO$_3$ and CsF, enabled the cascade reactions with yields ranging from 26 to 56%, whereas organic bases entirely inhibited the reaction (see the ESI†). Other catalysts of pyridine or phenanthroline derivatives were tested, which exhibited considerable activities as well (entries 10–13). The cascade reaction was also susceptible to solvents and catalyst loadings (in ESI†). Control experiments under transition-metal catalysis were conducted as a comparison. Transition metals, including palladium, cobalt, nickel, rhodium, copper, zinc, manganese, iron and iridium, were investigated; however, all of the results were not comparable (entries 14–17, also in the ESI†). Most importantly, a high-impurity of 1,10-phenanthroline and potassium carbonate delivered the final product **3a** in a slightly better yield of 75% (entry 18), excluding the possibility of a metal-catalytic pathway and keeping in line with the HR-MS evaluations given in Table 1. The above

observations indicated that the tosyl radical produced by 1,10-phenanthroline and an alkali metal cation plays a key role in cleavage of the C(sp^3)–OAr bond, probably *via* a radical pathway, achieving a multistep cascade reaction with high efficiency.

With the optimal conditions in hand, we then evaluated the substrate scopes of various *N*-tosylhydrazones (**1**) with phosphinyl allenes (**2**). As summarized in Table 3, the cascade reactions gave adducts (**3**) in yields ranging from acceptable to medium with excellent diastereoselectivities and *E*-selectivities, relying on the structure and electronic properties of substituents. For instance, electron-neutral *N*-tosylhydrazones and *para*-electron-rich ones afforded the products **3a**–**3c** with medium yields. Otherwise, electron-deficient substituents, including *p*-F, *p*-Cl, and *p*-Br, impaired the efficiency to some extent, with yields dropping to below 50%. *N*-Tosylhydrazones bearing strong electron-deficient substituents of *p*-CF$_3$ and *p*-NO$_2$ performed very sluggishly without formation of the corresponding products. 56% yield of **3h** was obtained for β-naphthyl substituted substrates. Notably, the X-ray crystal structure of **3h** unambiguously displayed the location of the tosyl group and the dimensional orientations of anchored moieties,[16] with methyl and diphenylphosphine oxide groups at *syn*-positions. Ethyl, *n*-butyl, and benzyl derived *N*-tosylhydrazones were also applicable to the system with acceptable to medium yields (**3i**–**3m**). Nevertheless, diphenyl derived *N*-tosyl-hydrazone performed

Table 3 1,10-Phen/K_2CO_3 catalyzed coupling of *N*-tosyl-hydrazones (**1**) with phosphinyl allenes (**2**): formation of H-*endo*-isomers[a]
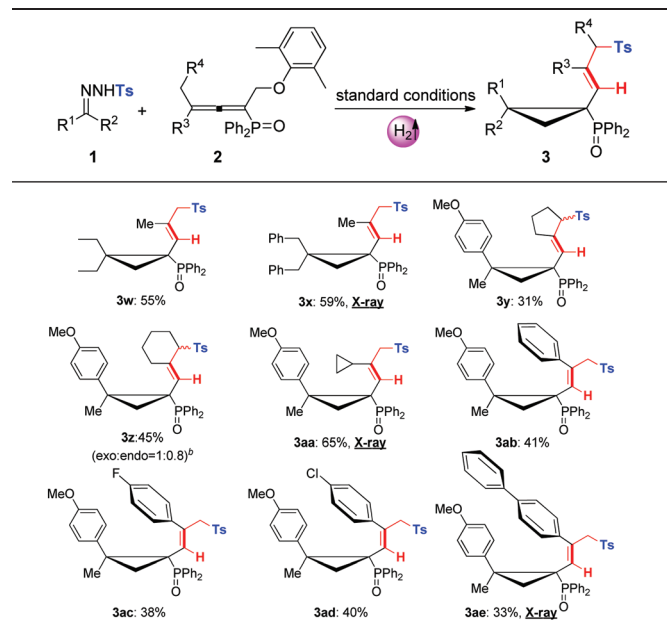

[a] Isolated yield by column chromatography, dr > 20 : 1, only *E*-isomer.

sluggishly under current conditions. The phosphinyl allenes could be expanded to other aliphatic substitutions. For instance, the allenes with distal *n*-propyl, *n*-hexyl substituents furnished the target products (**3o**, **3p**) in yields of 40% and 31%, respectively. Other *N*-sulfonylhydrazone derivatives, including *p*-methoxyphenyl, *m*-methylphenyl, *p*-bromophenyl, polyaromatic and aliphatic ones, maintained certain reactivities in the radical cleavage and sulfonyl rearrangement step, giving exclusively *E*-isomers (**3r–3v**) with slightly lower yields. Moreover, it is worth mentioning that most of the proton chemical shifts of products (**3a–3p**, **3r–3v**) locate in a range of 5.20–5.46 ppm, with alkenyl-H pointing to the top side of the three-membered ring (denoted as the H-*endo*-isomer). An exceptional case was found in the reaction of allenes bearing cycloheptyl substitution with **1a**. Interestingly, 42% yield of H-*endo*-isomer **3q** and 9% yield of H-*exo*-isomer **3′q** were both isolated, and ¹H-NMR spectra of **3′q** showed a significant downfield shift to 6.04 ppm. No reciprocal transformation was detected for these two isomers under thermal conditions, indicating that the cyclopropanation step should be decisive to obtain either atropisomer. Besides, this spatial configuration could be attributed to the congestion of moieties on a three-membered ring, in which aryl and diphenylphosphine oxide substituents strongly restricted the single bond rotation of the alkenyl moiety. DFT calculations showed that **3′q** possesses higher energy than **3q** with an energy gap of 20 kJ mol⁻¹, and the torsion energy associated with the dihedral angle between **3q** and **3′q** is as high as 59 kJ mol⁻¹ (see details in the ESI†).

To our delight, dominant H-*exo*-isomers appeared while altering the substitutions on *N*-tosylhydrazones and phosphinyl allenes (Table 4). In the case of diethyl and dibenzyl derived *N*-tosyl-hydrazones, products **3w** and **3x** were characterized as H-*exo*-configurations, evidenced by distinct alkene-H chemical shifts (5.62, 5.86 ppm) and an X-ray crystal structure of **3x**.[16] The ORTEP drawing of **3x** unambiguously manifested the spatial proximity of the alkene-H atom to the P=O moiety, thus the deshielding effect resulted in an apparent downfield chemical shift. The scope of phosphinyl allenes was subsequently investigated. In general, the allenes bearing distal cyclopropyl, cyclopentyl and various aryl substituents furnished the corresponding H-*exo*-isomers exclusively in yields of 31–65% (**3y–3ae**), except for the cyclohexyl one (**3z**, *exo* : *endo* = 1 : 0.8). Meanwhile, the DFT calculation results were also well consistent with the ratio of product configurations (in the ESI†). X-ray crystal structures of **3aa** and **3ae** supported the formation of single atropisomers as well. Distinct from the substituents on hydrazones, electron effects were not apparent for allenes with terminal aromatics. Electron-deficient groups of *para*-fluoro and *para*-chloro gave indistinctive results compared to that of the electron-neutral substrate. Note that the development of atropisomers is currently a central task and hot research topic in organic chemistry.[17] However, as far as we know, atropisomeric cyclopropanation has never been reported and this cascade reaction provides highly efficient construction of multi-substituted atropisomers in one pot.

Table 4 1,10-Phen/K₂CO₃ catalyzed coupling of *N*-tosyl-hydrazones (**1**) with phosphinyl allenes (**2**): formation of H-*exo*-isomers[a,b]

[a] Isolated yield by column chromatography, dr > 20 : 1, H-*exo* : H-*endo* > 20 : 1 with an exception of **3z**. [b] The ratio of H-*exo*- and H-*endo*-isomers was determined by ¹H NMR, which cannot be separated even by preparative HPLC.

Next, in order to understand the reaction mechanism, control experiments were performed. Delightfully, while shortening the reaction time to 1 hour, we isolated the key intermediate, tosylated 1,3-dienes (**4a**), in a good yield of 85% (eqn (a), Scheme 2). Kinetic studies on this step verified that it proceeds through a radical pathway, and the aromatic ether moiety left in the radical form is trapped by BHT (in ESI†). The parallel reaction of tosyl sodium and allene **2a** left all substrates intact (eqn (b)), implying that the tosyl anion cannot cleave the C–O bond to initiate the cascade reaction. Eqn (c) presented that the intermediate **4a** could be converted into a sulfonyl rearrangement product **5a**,[18] but stoichiometric K₂CO₃ turned out to be necessary, otherwise, this step severely retarded the cascade process. A crossover experiment with sodium 4-methoxybenzenesulfinate in eqn (d) indicated that the sulfonyl rearrangement step occurs inter-molecularly. After that, **5a** underwent atropisomeric cyclopropanation rapidly to afford final product **3a** in 60% yield. Besides, deuterium labelling experiments were conducted to investigate the kinetic isotope effects (KIE) (eqn (e)). The reaction of **1a** and **2a-D⁶** afforded deuterated product **4a-D⁶** in 84% yield, which transformed into **5a-D** in 60% yield with deuterium atoms distributed over all of the alkenyl positions. The KIE value from two parallel reactions between **4a** and **4a-D⁶** was found to be k_H/k_D = 1.5, suggesting that the rate-determining step probably involves in the sulfonyl rearrangement step, but does not contain a C(sp³)–H bond cleavage. Therefore, the mechanism studies and results in Table 1 collectively pointed out that the
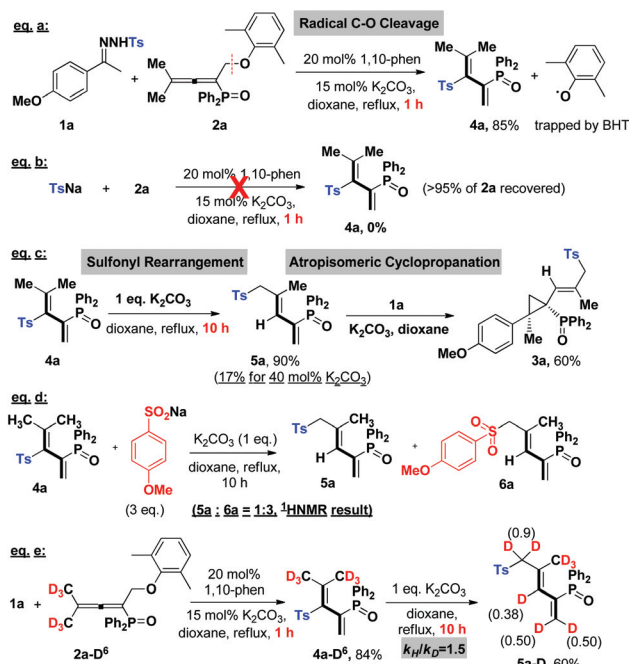
Scheme 2 Mechanism studies.

Scheme 3 Proposed mechanism and rationalization of atropisomer formation.

cascade reaction consists of four steps: 1,10-phen/K$_2$CO$_3$ catalysed cleavage of the NH-Ts bond to generate the tosyl radical, radical cleavage of the C(sp^3)–OAr bond, base-promoted sulfonyl rearrangement, and atropisomeric cyclopropanation.

Based on our experimental facts and previous reports,[2a,10g,19] a proposed mechanism is outlined in Scheme 3. Initially, single electron transfer (SET) from the 1,10-phen/K$_2$CO$_3$ complex to N-tosylhydrazone (**1**) gives a radical anion (**I**), which undergoes N–S bond cleavage to result in a tosyl radical and an N-anion intermediate (**II**) ((**II**) could be trapped by the CF$_3$ cation source and detected by HR-MS, see details in the ESI†). The N-anion intermediate (**II**) will leave the hydrogen anion rapidly to give a diazo compound [**C**]. Molecular hydrogen evolution comes from the deprotonation of **1** by the *in situ* generated hydrogen anion. Meanwhile, the accompanying tosyl anion helps to quench the associated radical cation (**IV**) to end the catalytic cycle and releases another portion of the tosyl radical. This proposed catalytic cycle keeps in line with the result of catalytic amounts of 1,10-phen and K$_2$CO$_3$ in eqn (a), Scheme 2. Afterwards, the tosyl radical attacks allene **2** to yield tosylated 1,3-butadienes (**4**). Base-promoted sulfonyl rearrangement of **4** leads to the formation of thermally reversible (*E*)-*S*-trans or (*E*)-*S*-cis isomers (**5/5′**), depending on the nature of substituents on the olefin double bond. Eventually, these two isomers undertake 1,3-dipolar cycloaddition with diazo intermediate [**C**] to give atropisomers **3** in the H-*exo* or H-*endo* configuration, along with the extrusion of nitrogen. Above all, the equilibrium ratios of **5** and **5′** are associated directly with the dominant stereo-configuration of atropisomers. For instance, when the R^3
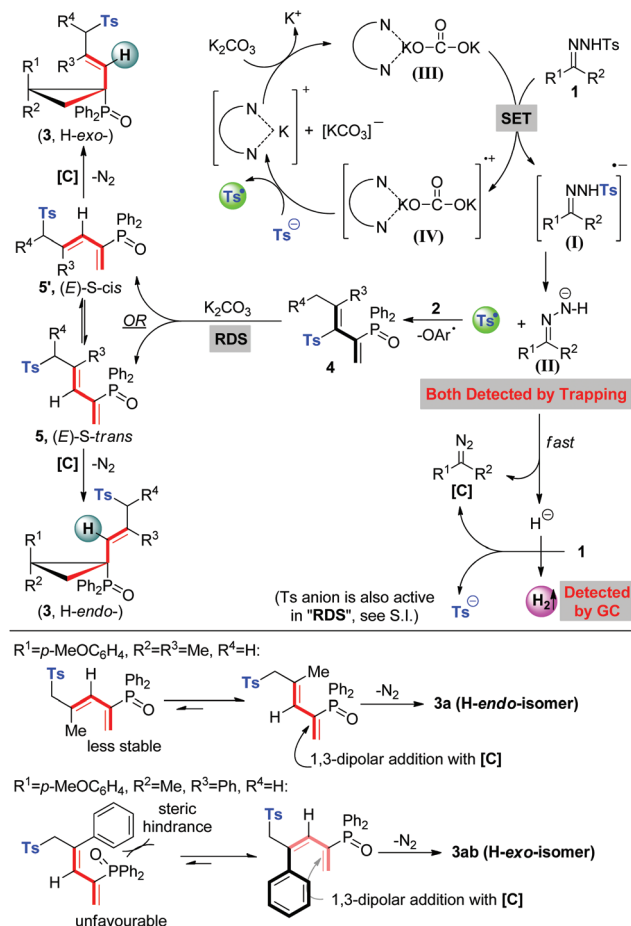
group is a bulky phenyl group, an (*E*)-*S*-cis isomer is favourably formed and rapidly transforms into an H-*exo*-isomer (**3ab**).

Experimental

General procedure

To a 15 mL sealed reaction tube were added N-tosylhydrazones (**1a**, 286 mg, 0.9 mmol), phosphinyl allenes (**2a**, 120 mg, 0.3 mmol), 1,10-phen (12 mg, 20 mol%), K$_2$CO$_3$ (103.5 mg, 0.75 mmol), and 3 mL degassed 1,4-dioxane. The reaction mixture was then heated to reflux for 8 hours until the complete consumption of **2a** monitored by TLC. After all of the volatiles were removed under vacuum, the crude product was purified by flash chromatography (eluent: 1 : 2 : 1 (v/v) of ethyl acetate/petroleum ether) to afford product **3a** as a white solid.

Conclusions

In conclusion, we disclosed, for the first time, a transition-metal-free radical cleavage of a hydrazonyl "NH-Ts" unit with a catalytic amount of 1,10-phenanthroline and potassium car-

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bonate. The cleavage of N-tosylhydrazone through a radical anion pathway toward a tosyl radical, diazo compound and molecular hydrogen was rationalized by DFT calculations and verified by radical trapping, EPR experiment and gas chromatography. Further application of this novel strategy into metal-free coupling of N-tosylhydrazones and phosphinyl allenes provides expeditious synthesis of unprecedented atropisomeric 3-tosyl-1-enyl-cyclopropyldiphenyl-phosphine oxide derivatives with excellent diastereoselectivity and E-selectivity. A variety of atropisomeric products, confirmed by ^{1}H NMR, DFT calculations, and X-ray crystallography, were controllably formed depending on the substitutions of N-tosyl-hydrazone and phosphinyl allenes. Mechanistic studies indicate that the cascade reaction proceeds through a tosyl radical initiated successive C(sp^3)–OAr cleavage, sulfonyl rearrangement and atropisomeric cyclopropanation. We expect that this strategy will enrich the blooming radical chemistry and offer new scaffolds for the development of potential chiral molecules.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Notes and references

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