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# Metal-free hydrosulfonylation of $\alpha,\beta$ -unsaturated ketones: synthesis and application of $\gamma$ -keto sulfones†

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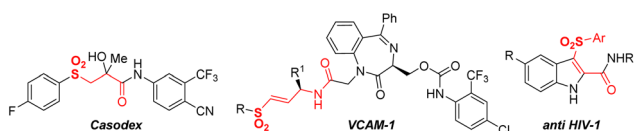
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As a useful common structural fragment in a broad number of pharmaceuticals<sup>1</sup> and functional materials,<sup>2</sup> keto sulfones are usually present in promising biologically active molecules such as *Casodex*,<sup>3</sup> *VCAM-1* (ref. 4) and *anti-HIV-1* (ref. 5) (Fig. 1). Furthermore, a valuable synthetic impression is associated with the role of reactive intermediates in various high-demand synthetic transformations,<sup>6</sup> including total synthesis.<sup>7</sup> Owing to their excellent properties, and efficient and practical synthesis methods keto sulfones are in high demand.

In the past decades, a variety of protocols have been developed to construct  $\beta$ -keto sulfones.<sup>8</sup> Whereas succinct synthetic routes toward structurally related  $\gamma$ -keto sulfones are scarce,<sup>9</sup> traditionally,  $\gamma$ -keto sulfones were synthesized *via* the nucleophilic substitution of sodium sulfinates by 2-chlorovinyl ketones,<sup>10</sup> the elimination of the bromo derivatives of saturated keto sulfones<sup>11</sup> and the oxidation of the corresponding sulfides

or sulfoxides.<sup>12</sup> However, the principal drawback is that these procedures were strongly limited by multiple steps, narrow substrate scope, or poor stereoselectivity.

Indeed, several streamlined strategies for the preparation of  $\gamma$ -keto sulfones involves addition reaction of alkenes or alkynes have been developed.<sup>13</sup> Li's group<sup>14</sup> reported the synthesis of (*E*)-vinyl sulfones through Pd-catalyzed conjugate additions of alkynes with 1,2-bis(phenylsulfonyl)ethane. In 2013 Jiang and co-workers<sup>15</sup> showed that a Pd-catalyzed sulfonylation of alkyne with sodium sulfinates affords  $\gamma$ -keto sulfones (Scheme 1a). Li and coworkers<sup>16</sup> reported that BPO triggered the hydro-sulfonylation of chalcones with arylsulfonyl hydrazides producing  $\gamma$ -keto sulfones. Subsequently, Bi's group<sup>17</sup>


 Fig. 1 Representative biologically active  $\gamma$ -keto sulfones.

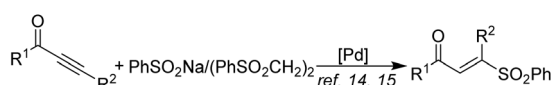
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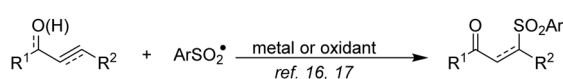
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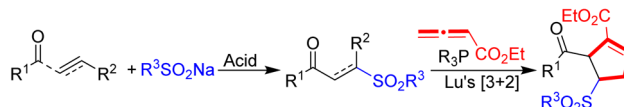
### a) Palladium-Catalyzed Cross-Coupling Reaction



### b) Metal-catalyzed or Metal-free Radical Cascade Reaction



### c) This work: Acid-Promoted Sulfonylation of $\alpha,\beta$ -Unsaturated Ketones



- Metal-free, no oxidant
- High functional group tolerance
- Mild, efficient and high yield
- Broad substrate scope
- Lu's [3+2] cycloaddition of  $\gamma$ -Keto Sulfones

 Scheme 1 Methods for the synthesis of  $\gamma$ -keto sulfones.


developed a  $\text{Ag}_2\text{CO}_3$ -promoted sulfonylation of allyl/propargyl alcohols with sodium sulfinates for the preparation of  $\gamma$ -keto sulfones (Scheme 1b). Nevertheless, most cases still have to use large excess oxidants, noble metal catalysts, or require high temperatures. Accordingly, an efficient, mild and practical method to furnish  $\gamma$ -keto sulfones is worthwhile studying.

With growing demand for sustainable chemistry, an “ideal” reaction system for such transformations would be “metal-free” due to cost efficiency and possible advantages regarding toxicity, as well as selectivity. With this intent, we herein describe a simple and efficient acid-mediated sulfonylation of sodium sulfinates and  $\alpha,\beta$ -unsaturated ketones for the selective synthesis of  $\gamma$ -keto sulfones (Scheme 1c). The significant advantages of this method are high efficiency, metal-free and mild reaction conditions, thus providing a potential application in natural product synthesis and medicinal chemistry.

Further studies were commenced with the optimization of the conditions for the hydrosulfonylation of the ynone **1f** with sodium benzenesulfonate **2a** (Table 1). Acetate buffer solution (pH = 3.5)<sup>13e</sup> and acetyl chloride/ $\text{H}_2\text{O}$ ,<sup>19</sup> as used in the previous

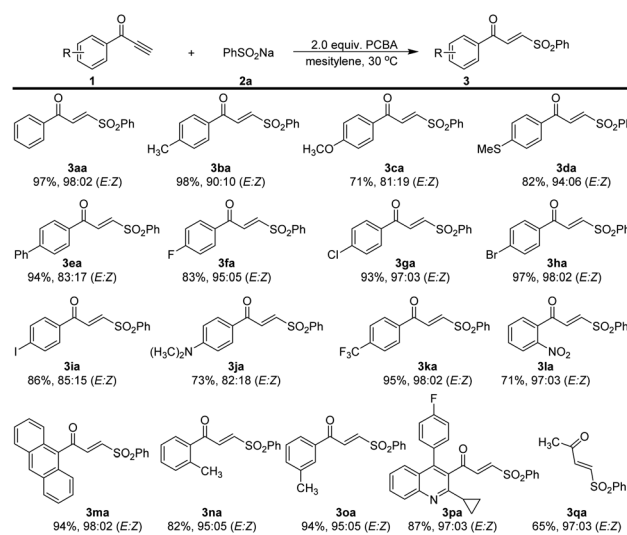
study, were completely ineffective due to several unknown complex products being formed (entry 1). Gratifyingly, the desired  $\gamma$ -keto sulfone **3fa** was isolated in a 49% yield ( $E/Z = 90 : 10$ ) as the major product for the reaction mediated by AcOH (entry 3). Encouraged by this initial result, we screened an array of acids. The results showed that 4-chlorobenzoic acid (PCBA) gave the best result, leading to the isolation of  $\gamma$ -keto sulfone **3fa** in a yield of 80% ( $E/Z = 98 : 02$ ) (entries 4–15). Solvent screening indicated that mesitylene could improve the yield to 85% ( $E/Z = 95 : 05$ ) (entry 21). Further investigations on the reduced usage of PCBA to 2.0 equivalents, the yield of **3fa** was slightly reduced (entry 22, 83% yield,  $E/Z = 95 : 05$ ). The amounts of sodium benzenesulfonate **2a** and the reaction temperature have deleterious effects on the reaction yields (entries 23–27). Thus, the optimized reaction conditions were successfully established as **1f** (1.0 equiv.), **2a** (2.5 equiv.), PCBA (2.0 equiv.), and mesitylene (2.0 mL) at 30 °C in this process.

We then sought to explore the generality of the method for the synthesis of  $\alpha,\beta$ -unsaturated  $\gamma$ -keto sulfones, using various ynones in reactions with **2a** under the optimized conditions (Scheme 2). The reaction of the 1-phenylprop-2-yn-1-one **1a** with **2a** proceeded reasonably to provide an excellent yield of the corresponding  $\gamma$ -keto sulfone **3aa** (97% yield,  $E/Z = 98 : 02$ ). To our delight, the reaction worked successfully with a range of ynones **1** bearing various substituents on the aromatic ring. Substituents such as methyl, thiomethylmethoxy, phenyl, halogen and dimethylamino atoms could be tolerated and gave the corresponding products **3ba–3ja** with high to excellent yields (71–98% yield) and stereoselectivity ( $E/Z = 82 : 18$  to  $98 : 02$ ). Trifluoromethyl and nitro substituents on the aromatic ring were also compatible and products **3ka** and **3la** were afforded 95% and 71% yields, respectively. 9-Anthracene-derived ynone successfully afforded **3ma** in a 94% yield ( $E/Z = 98 : 02$ ). The methyl group in the *ortho* or *meta* positions of the aromatic ring

Table 1 Optimization of the reaction conditions<sup>a</sup>

Entry	Acid (x equiv.)	Solvent	Yield <sup>b</sup> (%)	$E/Z$ <sup>c</sup>
1	Buffer (pH = 3.5)	DMF	NR	—
2	Acetyl chloride/ $\text{H}_2\text{O}$	$\text{CHCl}_3$	NR	—
3	AcOH (3.0)	Toluene	49	90 : 10
4	$\text{HCO}_2\text{H}$ (3.0)	Toluene	23	85 : 15
5	HCl (3.0)	Toluene	36	80 : 20
6	$\text{HNO}_3$ (3.0)	Toluene	36	87 : 13
7	Benzoic acid (3.0)	Toluene	66	96 : 04
8	<i>p</i> -Toluic acid (3.0)	Toluene	52	96 : 04
9	4-Acetylbenzoic acid (3.0)	Toluene	57	96 : 04
10	4-Fluorobenzoic acid (3.0)	Toluene	73	98 : 02
11	PCBA (3.0)	Toluene	80	98 : 02
12	4-Bromobenzoic acid (3.0)	Toluene	72	95 : 05
13	PNBA (3.0)	Toluene	57	88 : 12
14	2-Naphthoic acid (3.0)	Toluene	48	94 : 06
15	2-Nitrobenzoic acid (3.0)	Toluene	29	94 : 06
16	PCBA (3.0)	<i>o</i> -Xylene	73	92 : 08
17	PCBA (3.0)	<i>p</i> -Xylene	70	90 : 10
18	PCBA (3.0)	<i>m</i> -Xylene	72	96 : 04
19	PCBA (3.0)	DMF	NR	—
20	PCBA (3.0)	MeOH	68	89 : 11
21	PCBA (3.0)	Mesitylene	85	95 : 05
22	PCBA (2.0)	Mesitylene	83	95 : 05
23	PCBA (1.2)	Mesitylene	76	91 : 09
24	PCBA (0.5)	Mesitylene	44	73 : 27
25 <sup>d</sup>	PCBA (2.0)	Mesitylene	79	90 : 10
26 <sup>e</sup>	PCBA (2.0)	Mesitylene	80	95 : 05
27 <sup>f</sup>	PCBA (2.0)	Mesitylene	53	97 : 03

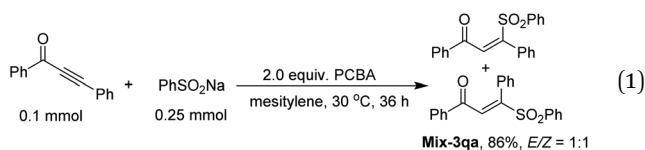
<sup>a</sup> Reaction conditions: **1f** (0.1 mmol), **2a** (0.25 mmol), acid (x equiv.), solvent (1.0 mL), 30 °C, 48 h. <sup>b</sup> Isolated yields. <sup>c</sup> Determined by RP-HPLC. <sup>d</sup> With 2.0 equiv. **2a**. <sup>e</sup> 50 °C. <sup>f</sup> 80 °C. PCBA = 4-chlorobenzoic acid. PNBA = *p*-nitrobenzoic acid.



Scheme 2 Sulfonylation reaction of various terminal alkynes with **2a**. All reactions were carried on 0.2 mmol scale in mesitylene (2.0 mL) and used 2.5 equiv. of **2a**, 2.0 equiv. PCBA, at 30 °C. Yields of isolated products are reported.  $E/Z$  ratios were determined by RP-HPLC.

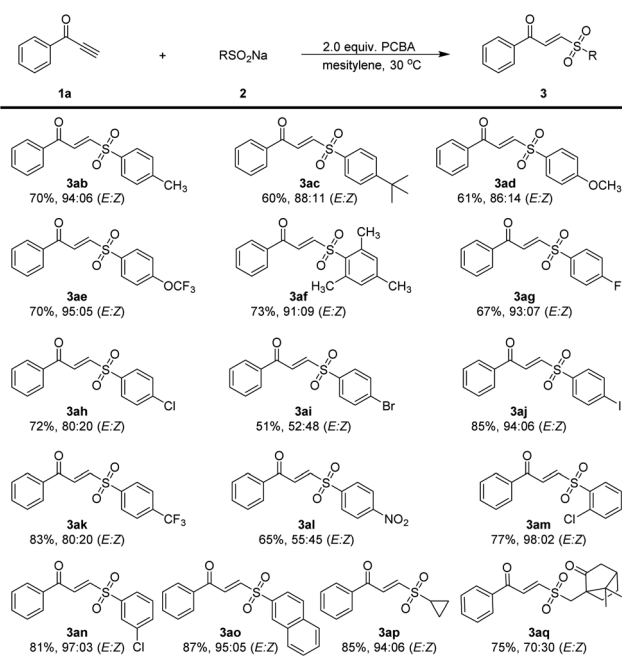


gave the desired  $\gamma$ -keto sulfones in 82% and 94% yield, respectively. The desired product **3pa** bearing a pitavastatin unit could be readily prepared in a yield of 87%. When alkyl terminal alkyne **1q** was subjected to the reaction, affording the desired product **3qa** in 65% yield ( $E/Z = 97 : 03$ ).

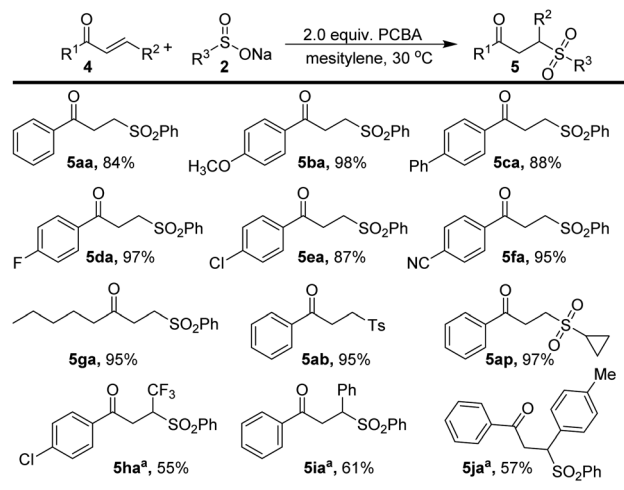


Inspired by the above results, the nonterminal alkyne was used as the substrate to react with  $\text{PhSO}_2\text{Na}$  at 30 °C for 36 h. The reaction provided *E* and *Z*- $\beta$ -sulfonyl- $\alpha,\beta$ -unsaturated carbonyl mixed compounds **3qa**<sup>13c</sup> (86% yield,  $E/Z = 1 : 1$ ).

The results of ynone **1a** reacting with a number of sodium sulfonates under the optimized condition are depicted in Scheme 3. Gratifyingly, no matter whether the phenyl ring of sodium sulfinate was substituted with either a sterically hindered, electron-donating, or electron-withdrawing group, all of them smoothly furnished the corresponding products in moderate to excellent yields with a high range of  $E/Z$  ratios from 52 : 48 to 97 : 03 (**3ab–3an**). Likewise, 2-naphthyl and cyclopropyl substituted sodium sulfonates were both effective in this reaction with a yield of 87% and 85%, respectively (**3ao** and **3ap**). Additionally, *L*-10-camphorsulfonyl sulfinate **2q** was also suitable for this reaction.



**Scheme 3** Sulfonylation reaction of terminal alkyne (**1a**) with sodium Sulfonates. All reactions were carried on 0.2 mmol scale in mesitylene (2.0 mL) and used 2.5 equiv. of **2**, 2.0 equiv. PCBA, at 30 °C. Yields of isolated products are reported.  $E/Z$  ratios were determined by RP-HPLC.



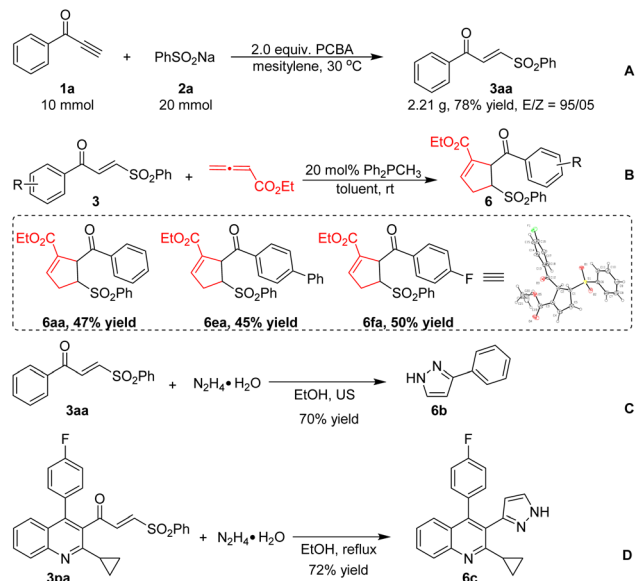
**Scheme 4** Sulfonylation reaction of vinyl ketone with sodium sulfonates. All reactions were carried on 0.2 mmol scale in mesitylene (2.0 mL) and used 2.0 equiv. of **2a**, 2.0 equiv. PCBA, at 30 °C. Yields of isolated products are reported. <sup>a</sup>At 80 °C for 72 h.

Interestingly, the treatment of the vinyl ketone **4a** with  $\text{PhSO}_2\text{Na}$  (**2a**) under the standard conditions furnished sulfone **5aa** (Scheme 4). The substrate scope was also explored in Scheme 4. Delightfully, it was perfectly tolerable to introduce both electron-donating ( $\text{OCH}_3$  and  $\text{Ph}$ ) and electron-withdrawing ( $\text{F}$ ,  $\text{Cl}$ , and  $\text{CN}$ ) groups at the *para* position of the phenyl ring, affording the corresponding products (**5ba–5fa**) in excellent yields. 4-Toluene sulfonate and cyclopropane sulfonate also reacted well with substrate **2a** to form  $\gamma$ -keto sulfone in excellent yields. We were pleased to find that the  $\beta$ -trifluoromethylated enone **4h** and *trans*-chalcone (**4i–4j**) could be successfully employed to give desired products (**5ha–5ja**, 55–61% yields). Unfortunately, no reaction occurred for 2-cyclopentenone.

Additionally, the synthetic utility of the  $\gamma$ -keto sulfones obtained by the present method was explored (Scheme 5). Gram-scale ynone **1a** was reacted with sodium benzenesulfonate **2a** to form product **3aa** with an excellent  $E/Z$  ratio (**A**). Lu's [3 + 2] cycloaddition of 2,3-butadienoate with  $\alpha,\beta$ -unsaturated  $\gamma$ -keto sulfones **3** mediated by phosphine produced cycloadducts **6** (ref. 18) in good yields (**B**). Moreover, pyrazole derivative **6b** could be efficiently obtained from **3aa** under ultrasound (US) irradiation conditions (**C**). Next,  $\gamma$ -keto sulfone **3pa** derived from the biologically active pitavastatin could also react with hydrazine to give a high yield of **6c** (**D**).

To understand the reaction mechanism, control reactions of **1a** with **2a** were examined (Scheme 6a). When **1a** and **2a** was subjected to the standard reaction conditions except using deuterated 4-chlorobenzoic acid system, the **3a** were detected with 80% yield. An attempt to run the reaction of **1a** and **2a** in a anhydrous solvent system under an  $\text{N}_2$  atmosphere also successfully delivered **3a** in 97% yield.<sup>20</sup> The results unambiguously disclosed that the incorporated hydrogen atoms in **3a** originated from acid rather than water. The reaction using 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) and 2,4-di-*tert*-





Scheme 5 Gram-scale preparation and further synthetic utilization.

butyl-4-methylphenol (BHT) as the radical scavengers showed no observable radical intermediates and unaffected desired products formation, which suggests that the radical process could be ruled out.<sup>20</sup> On the basis of the results presented above and previous reports, we propose the following mechanism in Scheme 6b. The 4-chlorobenzoic acid activates the carbonyl group in  $\alpha,\beta$ -unsaturated ketones **1** (**4**) to afford intermediate **I** or tautomerize to intermediate **II**. Finally, sulfonyl anion can

add to the unsaturated bond of intermediate **II** to afford the products **3** (**5**).

## Conclusions

In summary, we developed a simple and efficient acid-mediated approach for the formation of  $\gamma$ -keto sulfones from sodium sulfonates and  $\alpha,\beta$ -unsaturated ketones. This environmentally friendly methodology features a convenient, mild, efficient, C-S sulfonylation approach without the use of any metal catalysts and stoichiometric oxidants. The procedure results in good to excellent yields with various substituted ynones or vinyl ketones, as well as good functional group tolerance. The sulfonylation was easily scaled up and successfully integrated into Lu's [3 + 2] cycloaddition based on transformations of  $\alpha,\beta$ -unsaturated  $\gamma$ -ketosulfones (**3**). All these advantages make the new method highly attractive to the organic chemist in both academia and industry.

## Conflicts of interest

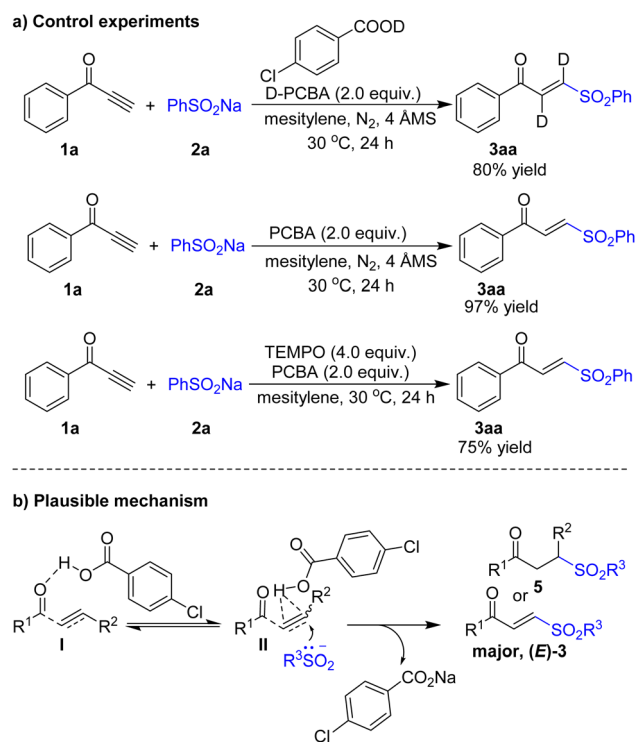
There are no conflicts to declare.

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## Notes and references

- (a) R. Ahmadi and S. Emami, Recent applications of vinyl sulfone motif in drug design and discovery, *Eur. J. Med. Chem.*, 2022, 114255; (b) P. Pakavathkumar, A. Noël, C. Lecrux, A. Tubeleviciute-Aydin, E. Hamel, J. E. Ahlfors and A. C. LeBlanc, Caspase vinyl sulfone small molecule inhibitors prevent axonal degeneration in human neurons and reverse cognitive impairment in Caspase-6-overexpressing mice, *Mol. Neurodegener.*, 2017, 12, 22; (c) J. Xiang, M. Ipek, V. Suri, M. Tam, Y. Xing, N. Huang, Y. Zhang, J. Tobin, T. S. Mansour and J. McKew,  $\beta$ -Keto sulfones as inhibitors of 11 $\beta$ -hydroxysteroid dehydrogenase type I and the mechanism of action, *Bioorg. Med. Chem.*, 2007, 15, 4396; (d) C. Curti, M. Laget, A. O. Carle, A. Gellis and P. Vanelle, Rapid synthesis of sulfone derivatives as potential anti-infectious agents, *Eur. J. Med. Chem.*, 2007, 42, 880; (e) W. M. Wolf, The fungicidal activity of  $\beta$ -keto sulfones. Molecular conformation of  $\alpha$ -phenylhydrazono- $\beta$ -ketosulfones as determined by an X-ray analysis, *J. Mol. Struct.*, 1999, 474, 113.
- (a) S. Patai, C. Z. Rappoport and J. M. Stirling, *The Chemistry of Sulfones and Sulfoxides*, Wiley, New York, 1988; (b) N. S. Simpkins, *Radical cyclisation of dienes and enynes using TolSO<sub>2</sub>SePh*, Pergamon Press, Oxford, 1993.



Scheme 6 Mechanistic studies.





- 3 P. Iversen, C. J. Tyrrell, A. V. Kaisary, J. B. Anderson, H. E. I. N. Van Poppel, T. L. Tammela and I. Melezinek, Bicalutamide monotherapy compared with castration in patients with nonmetastatic locally advanced prostate cancer: 6.3 years of followup, *J. Urol.*, 2000, **164**, 1579.
- 4 R. Ettari, E. Nizi, M. E. D. Francesco, M. A. Dude, G. Pradel, R. Vicik, T. Schirmeister, N. Micale, S. Grasso and M. Zappala, Development of Peptidomimetics with a Vinyl Sulfone Warhead as Irreversible Falcipain-2 Inhibitors, *J. Med. Chem.*, 2008, **51**, 988.
- 5 (a) G. La Regina, A. Coluccia, A. Brancale, F. Piscitelli, V. Gatti, G. Maga, A. Samuele, C. Pannecouque, D. Schols, J. Balzarini, E. Novellino and R. Silvestri, New Nitrogen Containing Substituents at the Indole-2-carboxamide Yield High Potent and Broad Spectrum Indolylarylsulfone HIV-1 Non-Nucleoside Reverse Transcriptase Inhibitors, *J. Med. Chem.*, 2012, **55**, 6634; (b) V. Famigliini and R. Silvestri, Indolylarylsulfones, a fascinating story of highly potent human immunodeficiency virus type 1 non-nucleoside reverse transcriptase inhibitors, *Antiviral Chem. Chemother.*, 2018, **26**, 2040206617753443.
- 6 (a) A.-N. R. Alna, X. Companyó and R. Rios, Sulfones: new reagents in organocatalysis, *Chem. Soc. Rev.*, 2010, **39**, 2018; (b) K. Inanaga, T. Fukuyama, M. Kubota, Y. Komatsu, H. Chiba, A. Kayano and K. Tagami, Novel and Efficient Chromium(II)-Mediated Desulfonylation of  $\alpha$ -Sulfonyl Ketone, *Org. Lett.*, 2015, **17**, 3158; (c) M.-Y. Chang, H.-Y. Chen and Y.-L. Tsai, Temperature-Controlled Desulfonylative Condensation of  $\alpha$ -Sulfonyl *o*-Hydroxyacetophenones and 2-Formyl Azaarenes: Synthesis of Azaaryl Aurones and Flavones, *J. Org. Chem.*, 2018, **84**, 326; (d) Y.-D. Shao and D.-J. Cheng, Catalytic Asymmetric 1,2-Difunctionalization of Indolenines with  $\alpha$ -(Benzothiazol-2-ylsulfonyl) Carbonyl Compounds, *Adv. Synth. Catal.*, 2017, **359**, 2549; (e) R. E. Swenson, T. J. Sowin and H. Q. Zhang, Synthesis of Substituted Quinolines Using the Dianion Addition of N-Boc-anilines and  $\alpha$ -Tolylsulfonyl- $\alpha,\beta$ -unsaturated Ketones, *J. Org. Chem.*, 2002, **67**, 9182; (f) W.-M. He, Y.-W. Lin and D.-H. Yu, Uranyl photocatalysis: precisely controlled oxidation of sulfides with ground-state oxygen, *Sci. China: Chem.*, 2020, **63**, 291.
- 7 H. Yang, R. G. Carter and L. N. Zakharov, Enantioselective Total Synthesis of Lycopodine, *J. Am. Chem. Soc.*, 2008, **130**, 9238.
- 8 For examples, see: (a) Q. Tian, P. He and C. Kuang, Copper-catalyzed arylsulfonylation of N-arylsulfonyl-acrylamides with arylsulfonylhydrazides: synthesis of sulfonated oxindoles, *Org. Biomol. Chem.*, 2014, **12**, 6349; (b) S. Handa, J. Fennewald and B. Lipshutz, Aerobic Oxidation in Nanomicelles of Aryl Alkynes, in Water at Room Temperature, *Angew. Chem., Int. Ed.*, 2014, **53**, 3432; (c) Y.-L. Zhu, B. Jiang, W.-J. Hao, A.-F. Wang, J.-K. Qiu, P. Wei, D.-C. Wang, G. Li and S.-J. Tu, A new cascade halosulfonylation of 1,7-enynes toward 3,4-dihydroquinolin-2(1H)-ones via sulfonyl radical-triggered addition/6-exo-dig cyclization, *Chem. Commun.*, 2016, **52**, 1907; (d) W. Yu, P. Hu, Y. Fan, C. Yu, X. Yan, X. Li and X. Xu, Metal-free TBAI-catalyzed arylsulfonylation of activated alkenes with sulfonylhydrazides, *Org. Biomol. Chem.*, 2015, **13**, 3308; (e) X. Li, X. Xu, P. Hu, X. Xiao and C. Zhou, Synthesis of Sulfonated Oxindoles by Potassium Iodide Catalyzed Arylsulfonylation of Activated Alkenes with Sulfonylhydrazides in Water, *J. Org. Chem.*, 2013, **78**, 7343; (f) M.-Z. Zhang, P.-Y. Ji, Y.-F. Liu, J.-W. Xu and C.-C. Guo, Disulfides as Sulfonylating Precursors for the Synthesis of Sulfone-Containing Oxindoles, *Adv. Synth. Catal.*, 2016, **358**, 2976; (g) W. Wei, J. Wen, D. Yang, J. Du, J. You and H. Wang, Catalyst-free direct arylsulfonylation of N-arylacrylamides with sulfinic acids: a convenient and efficient route to sulfonated oxindoles, *Green Chem.*, 2014, **16**, 2988; (h) L. Liu, H. Xiao, F. H. Xiao, Y. J. Xie, H. W. Huang and G.-J. Deng, Synthesis of  $\beta$ -Ketosulfone from Sodium Sulfinite and Aryl Ethyl Ketone/Indanone, *Chin. J. Org. Chem.*, 2021, **41**, 4749; (i) I. Chikunova, Y. Kukushkin and Y. Dubovtsev, Atom-economic synthesis of  $\beta$ -ketosulfones based on gold-catalyzed highly regioselective hydration of alkynylsulfones, *Green Chem.*, 2022, **24**, 3314; (j) F. Xiao, C. Liu, D. Wang, H. Huang and G.-J. Deng, Concise synthesis of ketoallyl sulfones through an iron-catalyzed sequential four-component assembly, *Green Chem.*, 2018, **20**, 973–977; (k) S. Zhong, Z. Zhou, F. Zhao, G. Mao, G.-J. Deng and H. Huang, Deoxygenative C-S Bond Coupling with Sulfinates via Nickel/Photoredox Dual Catalysis, *Org. Lett.*, 2022, **24**, 1865–1870.
- 9 (a) S. Liang, K. Hofman, M. Friedrich, J. Keller and G. Manolikakes, Recent Progress and Emerging Technologies towards a Sustainable Synthesis of Sulfones, *ChemSusChem*, 2021, **14**, 4878; (b) P. Li, L. Wang and X. Wang, Recent advances on the pesticidal activity evaluations of sulfone derivatives: A 2010 to 2020 decade in mini-review, *J. Heterocycl. Chem.*, 2021, **58**, 28; (c) D. Yadav and R. S. Menon, Recent developments in the chemistry of allenyl sulfones, *Org. Biomol. Chem.*, 2020, **18**, 365; (d) W. Guo, K. Tao, W. Tan, M. Zhao, L. Zheng and X. Fan, Recent advances in photocatalytic C-S/P-S bond formation via the generation of sulfur centered radicals and functionalization, *Org. Chem. Front.*, 2019, **6**, 2048; (e) G. Qiu, K. Zhou, L. Gao and J. Wu, Insertion of sulfur dioxide via a radical process: an efficient route to sulfonyl compounds, *Org. Chem. Front.*, 2018, **5**, 691; (f) B. Qin, S. Huang, J.-Q. Chen, W. Xiao and J. Wu, Metal-free synthesis of sulfonylated indolo[2,1-a]isoquinolines from sulfur dioxide, *Org. Chem. Front.*, 2022, **9**, 3521; (g) X.-L. Chen, C.-Y. Wu, J.-T. Ma, S.-Y. Zhuang, Z.-C. Yu, Y.-D. Wu and A.-X. Wu, Rongalite as C1 Synthone and Sulfone Source: A Practical Sulfonylmethylation Based on the Separate-Embedding Strategy, *Org. Lett.*, 2022, **24**, 223.
- 10 (a) D. B. Reddy, N. C. Babu, V. Padmavathi and R. P. Sumathi, A Novel Route for the Synthesis of Unsaturated Oxo Sulfones and Bissulfones, *Synthesis*, 1999, **3**, 491; (b) B. Cavalchi, D. Landini and F. Montanari, Stereospecific synthesis of cis- and trans-2-halogenovinyl ketones. Stereochemistry of nucleophilic substitutions at vinylic carbon, *J. Chem. Soc. C*, 1969, 1204.



- 11 E. P. Kohler and G. R. Larsen, The Properties of Unsaturated Sulfur Compounds. II. Alpha, Beta-Unsaturated Ketosulfones, *J. Am. Chem. Soc.*, 1935, **57**, 1448.
- 12 (a) B. K. Peters, T. Zhou, J. Rujirawanich, A. Cadu, T. Singh, W. Rabten, S. Kerdphon and P. G. Andersson, An Enantioselective Approach to the Preparation of Chiral Sulfones by Ir-Catalyzed Asymmetric Hydrogenation, *J. Am. Chem. Soc.*, 2014, **136**, 16557; (b) V. Padmavathi, B. J. M. Reddy and A. Padmaja, A novel and simple route for the synthesis of 3,4-disubstituted pyrroles, *J. Heterocycl. Chem.*, 2005, **42**, 333; (c) S. Hinterbergera, O. Hofer and H. Greger, Synthesis of amides from Glycosmis species: Methylthiopropenoic acid, methylsulfonylpropenoic acid, thiocarbamic acid S-methyl ester, and senecioic acid amides, *Tetrahedron*, 1998, **54**, 487; (d) E. P. Kohler and G. R. Larsen, The Properties of Unsaturated Sulfur Compounds. I. Alpha Beta Unsaturated Sulfones, *J. Am. Chem. Soc.*, 1935, **57**, 1316.
- 13 (a) E. P. Kohler and G. R. Barrett, Some addition reactions of phenyl benzoyl acetylene, *J. Am. Chem. Soc.*, 1924, **46**, 747; (b) W. Shi, B. Zhang, B. Liu, F. Xu, F. Xiao, J. Zhang, S. Zhang and J. Wang, Unusual reaction of  $\beta$ -hydroxy  $\alpha$ -diazo carbonyl compounds with TsNHNHCOCl/Et<sub>3</sub>N, *Tetrahedron Lett.*, 2004, **45**, 4563; (c) Y. L. Zhu, B. Jiang, W. J. Hao, A. F. Wang, J. K. Qiu, P. Wei, D. C. Wang, G. Li and S. J. Tu, A new cascade halosulfonylation of 1,7-enynes toward 3,4-dihydroquinolin-2(1H)-ones via sulfonyl radical-triggered addition/6-exo-dig cyclization, *Chem. Commun.*, 2016, **52**, 1907; (d) J.-K. Qiu, C. Shan, D.-C. Wang, P. Wei, B. Jiang, S.-J. Tu, G. Li and K. Guo, Metal-Free Radical-Triggered Selenosulfonylation of 1,7-Enynes for the Rapid Synthesis of 3,4-Dihydroquinolin-2(1H)-ones in Batch and Flow, *Adv. Synth. Catal.*, 2017, **359**, 4332; (e) W. Zhang, G. Johnsonb, Z. Guan and Y.-H. He, Regio- and Stereoselective Hydrosulfonylation of Electron-Deficient Alkynes: Access to Both E- and Z- $\beta$ -Sulfonyl- $\alpha,\beta$ -Unsaturated Carbonyl Compounds, *Adv. Synth. Catal.*, 2018, **360**, 4562; (f) J. Jiang, Z. Wang and W.-M. He, Electrosynthesis of 1-indanones, *Chin. Chem. Lett.*, 2021, **32**, 1591; (g) X.-X. Meng, Q.-Q. Kang, J.-Y. Zhang, Q. Li, W.-T. Wei and W.-M. He, Visible-light-initiated regioselective sulfonylation/cyclization of 1,6-enynes under photocatalyst- and additive-free conditions, *Green Chem.*, 2020, **22**, 1388; (h) Y. Gu, L. Dai, J. Zhang, X. Lu, X. Liu, C. Wang, J. Zhang and L. Rong, Silver-Catalyzed Radical Cascade Sulfonylation/Cycloaddition for the Construction of Multifunctional Succimides Containing Separable Z/E-Isomers, *J. Org. Chem.*, 2021, **86**, 2173.
- 14 R.-J. Song, Y. Liu, Y.-Y. Liu and J.-H. Li, Palladium-Catalyzed Conjugate Addition to Electron-Deficient Alkynes with Benzenesulfinic Acid Derived from 1,2-Bis(phenylsulfonyl) ethane: Selective Synthesis of (E)-Vinyl Sulfones, *J. Org. Chem.*, 2011, **76**, 1001.
- 15 Y. Xu, J. Zhao, X. Tang, W. Wu and H. Jiang, Chemoselective Synthesis of Unsymmetrical Internal Alkynes or Vinyl Sulfones via Palladium-Catalyzed Cross-Coupling Reaction of Sodium Sulfinates with Alkynes, *Adv. Synth. Catal.*, 2014, **356**, 2029.
- 16 Z.-Z. Chen, S. Liu, W.-J. Hao, G. Xu, S. Wu, J.-N. Miao, B. Jiang, S.-L. Wang, S.-J. Tu and G. Li, Catalytic arylsulfonyl radical-triggered 1, 5-enyne-bicyclizations and hydrosulfonylation of  $\alpha$ ,  $\beta$ -conjugates, *Chem. Sci.*, 2015, **6**, 6654.
- 17 G. Fang, J. Liu, W. Shang, Q. Liu and X. Bi, Silver(I)-Promoted Radical Sulfonylation of Allyl/Propargyl Alcohols: Efficient Synthesis of  $\gamma$ -Keto Sulfones, *Chem.-Asian J.*, 2016, **11**, 3334.
- 18 The structure of **6fa** (CCDC 2181007<sup>†</sup>) was clearly determined by X-ray crystallographic analysis.
- 19 Z. Fang, Y. Zhang, Z. Zhang, Q. Song, Y. Wu, Z. Liu and Y. Ning, Synthesis of gem-Disulfonyl Enamines via an Iminyl-Radical-Mediated Formal 1,3-HAT/Radical Coupling Cascade, *Org. Lett.*, 2022, **24**, 6374.
- 20 More detail information for control experiments in ESI.<sup>†</sup>

