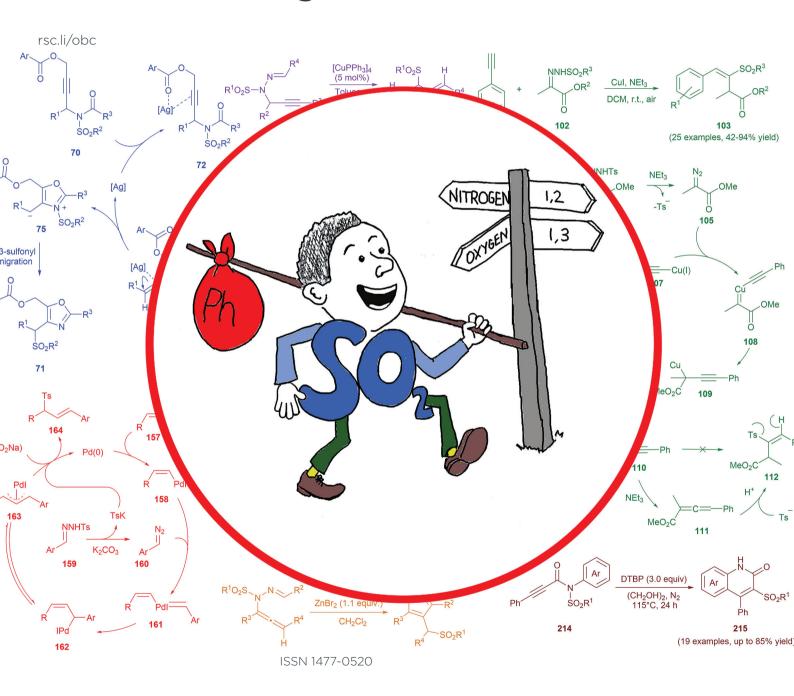
Volume 18 Number 14 14 April 2020 Pages 2541-2770

Organic & Biomolecular Chemistry





Organic & Biomolecular Chemistry



REVIEW

View Article Online



Cite this: *Org. Biomol. Chem.*, 2020, **18**, 2549

Synthetic and mechanistic aspects of sulfonyl migrations

Aaran J. Flynn, 📵 a Alan Ford 📵 b and Anita R. Maguire 📵 *c

Over the past 20 years reports of sulfonyl migrations have appeared, frequently described as 'unusual' and 'unexpected'. This comprehensive review compiles, for the first time, sulfonyl migrations reported over the last 20 years including formal 1,2-, 1,3-, 1,4-, 1,5-, 1,6- and 1,7-sulfonyl shifts, occurring through either radical or polar processes, either inter- or intramolecularly. Discussion of the sulfonyl migrations is structured according to reaction type, *i.e.* nitrogen-carbon, nitrogen-oxygen, nitrogen-nitrogen, oxygen-carbon (including anionic and non-anionic thia-Fries rearrangements), oxygen-oxygen and carbon-carbon migrations. Discussion of the underlying mechanisms for the migrations is included, with particular attention afforded to the principal techniques utilised for their elucidation, namely isotopic-labelling, crossover experiments, density functional theory calculations and electron paramagnetic resonance spectroscopy amongst others.

Received 4th December 2019, Accepted 3rd February 2020 DOI: 10.1039/c9ob02587a

rsc.li/obc

^aSchool of Chemistry, Analytical and Biological Research Facility, Synthesis and Solid State Pharmaceutical Centre, University College Cork, Cork, Ireland ^bSchool of Chemistry, Analytical and Biological Research Facility, University College

^cSchool of Chemistry and School of Pharmacy, Analytical and Biological Research Facility, Synthesis and Solid State Pharmaceutical Centre, University College Cork, Cork, Ireland. E-mail: a.maguire@ucc.ie

1. Introduction

Retrosynthetic analysis, formalised by E. J. Corey in the 1989 book *The Logic of Chemical Synthesis* revolutionised the art of total synthesis of complex organic molecules,¹ and coupled with an ever increasing number of efficient and selective synthetic methodologies with predictable outcomes across a diverse substrate range, has delivered elegant total syntheses. Critical to success is the ability to accurately anticipate the



Aaran J. Flynn

Aaran J. Flynn was born in London, England, in 1992. He obtained his B.Sc. in Chemistry of Pharmaceutical Compounds from University College Cork in 2015. He was awarded a Ph.D scholarship from the Synthesis and Solid State Pharmaceutical Centre and commenced his studies under the direction of Prof. Anita Maguire later that year. Under her guidance he has conducted research in a variety of areas, including copper-cata-

lysed asymmetric sulfur oxidation, [3 + 2]-dipolar cycloadditions of electron deficient diazo compounds, and the synthesis of acyclic α -carboxynucleoside phosphonates.



Alan Ford

Dr Alan Ford was born in Gateshead, England, in 1972. He studied at the University of Hull, England, and received a B.Sc. in chemistry in 1993 and a Ph.D. in 1996. He has held postdoctoral positions in the Selective Synthesis Group, University of Hull, from 1997 to 1998, in the Department of Metal-Mediated Organic Synthesis, Institute, University of Utrecht, The Netherlands, from 1998 to 2000, and in the Organic and

Pharmaceutical Synthesis Research Team, Department of Chemistry, University College Cork, Ireland, from 2000 to the present. His main research interests include development of novel rhodium catalysts for asymmetric carbene chemistry and the synthesis of nucleoside analogues as potential antiviral agents.

reactivity of molecules under different conditions, which requires an excellent understanding of functional group chemistry including identification of trends in reactivity that are both predictable and readily rationalisable.

Numerous reports observing 'unusual', 'unprecedented', 'unexpected' and 'novel' sulfonyl migrations attracted our attention, following observation of an unanticipated sulfonyl migration in our work.2 What became clear from a survey of the literature is that sulfonyl migrations remain only partially understood despite their potential synthetic utility. Sulfones³⁻¹⁴ and related species¹⁵⁻¹⁷ are widely used as activating groups and/or protecting groups and offer substantial synthetic versatility. Accordingly, sulfonyl migrations are potentially valuable from a synthetic perspective, provided they are sufficiently understood to enable their use in a predictive manner.

While most sulfonyl migrations prior to the beginning of the 21st century were originally discovered as side reactions, and regularly as isolated cases, the last 20 years has seen a significant increase in the number of reports focusing on the utility of incorporating a sulfonyl molecular handle capable of migration. As such, attempts to understand the mechanisms of these often 'unexpected' reactions have garnered significant recent attention; however, the ability to observe formal 1,2-, 1,3-, 1,4-, 1,5-, 1,6- or 1,7-sulfonyl migrations, in an inter- or



Anita R. Maguire

Professor Anita R. Maguire was born in 1964 in Cork. She undertook undergraduate and postgraduate studies at University College Cork (B. Sc., 1985; Ph.D., 1989), focusing during her studies on asymmetric catalysis in reactions of α -diazoketones. Following postdoctoral research in the Facultes Universitaires, Namur, Belgium, and sequently at the University of Exeter, she returned to UCC in 1991 initially as a Lecturer in

Organic Chemistry, then as Associate Professor of Organic Chemistry in 2002, and then as the first Professor of Pharmaceutical Chemistry in 2004. In 2011 she was appointed as Vice President for Research and Innovation at University College Cork. She was an Adjunct Professor at the University of Bergen from 2011-2016. Her research interests include asymmetric synthesis, including biocatalysis and transition-metal catalysis, the development of novel synthetic methodology employing α -diazocarbonyl compounds, organosulfur chemistry, and continuous flow chemistry, and the design and synthesis of bioactive compounds with potential pharmaceutical applications and she is a Co-PI in the SSPC. She is the inaugural Chair of the National Forum on Research Integrity and was elected a Member of the Royal Irish Academy in 2014.

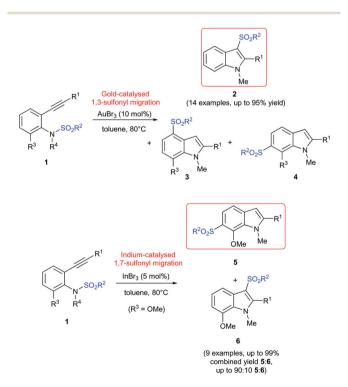
intramolecular fashion, occurring through either radical or polar processes, highlights the difficulty in accurately predicting the outcome of such reactions. Bearing this complexity in mind, it is not surprising that the current knowledge in this field is not sufficiently developed to enable incorporation of sulfonyl migration into a retrosynthetic plan.

In this review, sulfonyl migrations reported over the last two decades (up to early 2019) are compiled, and their synthetic and mechanistic development is described; the sulfonyl migrations are classified based on the migration type, namely nitrogen-carbon, nitrogen-oxygen, nitrogen-nitrogen, oxygencarbon (including anionic and non-anionic thia-Fries rearrangements), oxygen-oxygen and carbon-carbon. Particular emphasis is afforded to the efforts made to elucidate the mechanistic pathway for the migrations.

Nitrogen to carbon sulfonyl migration

2.1. Transition-metal catalysed reactions

2.1.1. Gold-catalysed sulfonyl migration. Nakamura et al. reported the gold- and indium-catalysed synthesis of 3- and 6-sulfonylindoles from ortho-alkynyl-N-sulfonylanilines 1 (Scheme 1). 18,19 In the presence of catalytic AuBr₃, a 1,3-sulfonyl migration was observed, to afford 3-sulfonylindoles 2 in good to high yields (up to 95%), with minor amounts of the regioisomers 3 and 4 also observed. Interestingly, using InBr₃ as catalyst the major products are 6-sulfonylindoles 5 which



Scheme 1 Gold- and indium-catalysed synthesis of 3- and 6-sulfonylindoles from ortho-alkynyl-N-sulfonylanilines, via 1,3- and 1,7-sulfonyl migration.

were isolated in up to 99% yield, indicating that an unprecedented 1,7-sulfonyl migration has occurred. The presence of a methoxy group at the 6-position of the *ortho*-alkynyl-*N*-sulfonylanilines proved crucial in yielding the 1,7-sulfonyl migration products.

In order to probe the mechanism of the sulfonyl migration, crossover experiments were performed which determined that both the gold- and indium-catalysed reactions were intramolecular processes. Interconversion of the reaction products was eliminated as a possibility by stirring a mixture of the 3-,4- and 6-sulfonylindole products in the presence of catalyst for a further two hours – no change in product distribution was observed.

The following mechanism was postulated in accordance with the observed results (Scheme 2). Coordination of the Lewis-acidic transition metal to the alkyne of 1 forms the intermediate π -complex 7. Nucleophilic addition of the nitrogen to the electron-deficient alkynyl moiety leads to the cyclised intermediate 8, which can undergo two diverging pathways depending on the metal catalyst employed. For the gold-catalysed process, intramolecular 1,3-sulfonyl migration occurs followed by elimination of AuBr $_3$ to afford the 3-sulfonylindole products 2. Alternatively, for the indium-catalysed process, a consecutive 1,7-sulfonyl migration and 1,5-proton shift occurs. Elimination of InBr $_3$ yields the 6-sulfonylindole products 5. Notably, the formation of indole 2 is the first example of sulfodemetalation, in which the vinyl–Au intermediate is captured intramolecularly by the sulfonyl group (Scheme 2, 8 to 2).

In an earlier communication the authors described the reaction of *N*-methoxymethyl-2-(1-pentynyl)-*N*-tosylaniline **12** in the presence of catalytic PdBr₂, to give the indole **13** in 33% yield, with only trace amounts of the tosyl migration product **14** observed (Scheme 3).²⁰ Interestingly, repeating this reaction using the optimised AuBr₃ catalyst afforded exclusively **13**

$$R^{2}O_{2}S \xrightarrow{N} Me$$

$$R^{1}$$

$$R^{2}O_{2}S \xrightarrow{N} Me$$

$$R^{3} Me$$

$$R^{4} \xrightarrow{N} SO_{2}R^{2}$$

$$R^{4} \xrightarrow{N} SO_{2}R^{2}$$

$$R^{5} \xrightarrow{N} Me$$

$$R^{5} \xrightarrow{N} SO_{2}R^{2}$$

$$R^{5} \xrightarrow{N} SO_{2}R^{2}$$

$$R^{5} \xrightarrow{N} Me$$

$$R^{5} \xrightarrow{N} SO_{2}R^{2}$$

$$R$$

Scheme 2 Proposed mechanistic cycle for the gold- and indium-catalysed synthesis of 3-and 6-sulfonylindoles.

Scheme 3 Migratory aptitude of tosyl and mesyl groups relative to methoxymethyl and allyl groups respectively.

albeit in 10% yield.¹⁹ Therefore, regardless of the catalyst species, the migratory aptitude of the migrating group appears to be crucial to the outcome. Specifically, in this instance, the methoxymethyl group has a greater ability to migrate than the tosyl group. Similarly, in a separate report, Fürstner and Davies observed that an allyl group preferentially migrated in the presence of a mesyl group for the platinum-catalysed transformation of 15 to 16 (Scheme 3).²¹

In 2011, the Chan group described the gold-catalysed tandem 1,3-migration/[2 + 2]-cycloaddition of 1,7-enyne benzoates **19** to azabicyclo[4.2.0]oct-5-enes **20** (Scheme 4, catalyst **17**). Interestingly, during optimisation studies, the gold(I)

Scheme 4 Gold-catalysed tandem 1,3-migration/[2 + 2]-cycloaddition of 1,7-enyne benzoates to azabicyclo[4.2.0]oct-5-enes; observation of a potential deaurative 1,3-sulfonyl migration.

carbene complex 18 catalysed the cycloisomerisation of 1,7enyne ester 19 to afford the 3-sulfonyl-1H-pyrrole 22 in 20% yield (Scheme 3, catalyst 14). Inspired by this fortuitous result, and recognising that the reaction pathway may have involved a deaurative 1,3-sulfonyl migration, the authors set out to investigate the rearrangement process.

In their continuation of these studies, the authors reasoned that the chemical yield of the process could be enhanced by use of the corresponding 1,7-enyne alcohols 23 as substrates (Scheme 5), presumably due to ease of water elimination. The NHC-gold(1) complex 18 was determined to be the optimal catalyst, with moderate to excellent yields of the rearranged pyrroles 24 obtained.²³ An intramolecular 1,3-sulfonyl migration was postulated based on the results of crossover experiments, and the fact that pyrrole 25 was recovered unchanged after exposure to p-toluenesulfonyl chloride under the optimised reaction conditions. The reaction mechanism was postulated to proceed via activation of the propargylic alcohol 23 through coordination of the gold catalyst with the alkyne moiety to give the Au(1)-intermediate 26. An intramolecular aminocyclisation is triggered involving anti addition of the N,N-disubstituted amino moiety to the triple bond affording the vinyl gold complex 27. Dehydration of this species leads to the formation of the cationic pyrrole-gold

aminocyclisation/1,3-sulfonyl Scheme 5 Gold-catalysed domino migration of N-substituted N-sulfonyl-aminobut-3-yn-2-ols to 1-substituted 3-sulfonyl-1H-pyrroles.

adduct 28, which subsequently undergoes an intramolecular 1,3-sulfonyl migration resulting in deauration and generation of the pyrrole product 24 (Scheme 5, path A). Alternatively, the vinyl gold complex 27 undergoes the deaurative 1,3-sulfonyl migration first to afford the 2,3-dihydro-1H-pyrrol-3-ol adduct 29 that upon dehydrative aromatisation affords the pyrrole 24 (Scheme 5, path B).

The Shin group reported the gold-catalysed synthesis of 3-pyrrolidinones 31 and nitrones 32 from N-sulfonyl hydroxylamines 30 via oxygen-transfer redox and 1,3-sulfonyl migration (Scheme 6).24 In the case of terminal alkynes, a gold-catalysed 5-exo-dig addition of the hydroxylamine moiety to the alkyne occurs through the oxygen (Scheme 7). Cleavage of the N-O bond is rate limiting, and the presence of the electron-withdrawing sulfonyl moiety facilitates the overall reaction process to afford 3-pyrolidinones 31 in moderate to good yields.

However, to the surprise of the authors, when internal alkynes are utilised a different mechanistic pathway occurs, resulting in the formation of 3-sulfonylnitrones 32. In this instance, the nitrogen of the hydroxylamine moiety is the preferred nucleophile, which allows for a 5-endo-dig cyclisation to occur giving 36 (Scheme 7). Subsequent 1,3-sulfonyl migration leads to 37. Loss of the gold catalyst and tautomerisation of the resulting vinyl hydroxylamine leads to the nitrone 32. The identity of the nitrone products 32 were confirmed by trapping with dipolarophiles via [3 + 2]-dipolar cycloaddition (Scheme 6).

Terminal alkyne substrates
$$\begin{bmatrix} \text{Au(IPr)} \end{bmatrix} \begin{bmatrix} \text{BF}_4 \end{bmatrix} \\ \text{(5 mol\%)} \end{bmatrix}$$

$$\begin{bmatrix} \text{(5 mol\%)} \end{bmatrix}$$

$$\begin{bmatrix} \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{SO}_2 \\ \text{R}^3 \end{bmatrix}$$

$$\begin{bmatrix} \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^4 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^4 \\ \text{END}_2 \\ \text{(9 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{(10 examples, 49-74\% yield)} \end{bmatrix}$$

$$\begin{bmatrix} \text{R}^3 \\ \text{END}_2 \\ \text{$$

Scheme 6 Gold-catalysed synthesis of 3-pyrrolidinones and nitrones from N-sulfonyl hydroxylamines via oxygen-transfer redox and 1,3-sulfonyl migration.

Scheme 7 Access to 3-pyrrolidinones and nitrones via Λ sulfonylhydroxylamines.

Liu et al. recently developed a gold-catalysed cascade reaction of diynamides 38 to generate a series of sulfone containing pyrrolo[2,l-a]isoquinolines 39 featuring the core structural motif of the lemellarin alkaloids (Scheme 8).25 Notably, all three functional moieties on the nitrogen of the ynamide participate in the cascade transformation, with a formal 1,4-sulfonyl migration a key mechanistic step. A crossover experiment, with two different sulfonyl diynamides, did not lead to crossover products, indicating that the migration of the sulfonyl group occurs in an intramolecular fashion. DFT studies suggested that the formal 1,4-sulfonyl migration is in fact two sequential 1,2-sulfonyl shifts (Scheme 8). The alternative 1,3sulfonyl shift was considered to be an unlikely mechanistic route as the transition states for both the suprafacial and antarafacial 1,3-sulfonyl shifts are 24.0 and 22.6 kcal mol⁻¹ higher in energy than that for TS6 (Scheme 8).

The Sahoo group recently developed a regioselective sulfonyl/sulfinyl migration cycloisomerisation cascade of alkynetethered ynamides **40** in the presence of XPhosgold catalyst to afford a series of novel 4-sulfinylated pyrroles **41** in yields up to 85% (Scheme 10). Notably, this reaction process is the first example of a general [1,3]-sulfonyl migration from the nitrogen centre to the β -carbon of ynamides, followed by umpolung 5-endo-dig cyclisation of the ynamide α -carbon atom to the gold-activated alkyne, and final deaurative [1,5]-sulfinylation. Control experiments in conjunction with DFT calculations were used to deduce an operative reaction pathway.

The de-sulfinylated pyrroles **45** and **46** were generated from *N*-mesyl protected yne-ynamides **42** and **43** respectively under the optimised conditions (Scheme 9a), highlighting the role of adventitious water in the protodeauration of the organo-Au intermediate **44**. Furthermore, the transformation of **43** in the

Scheme 8 Cascade reaction of diynamides and relevant section of the DFT reaction coordinate for sulfonyl migration.

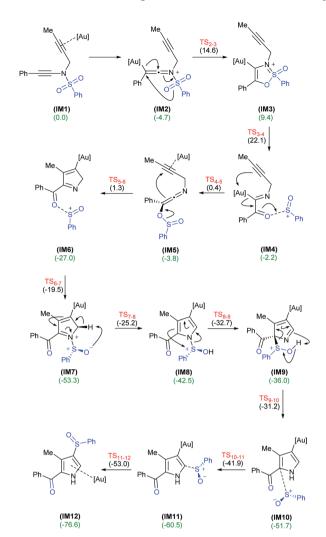
presence of D₂O afforded [D]47 indicating that a deuterium quench of 44 is preferred to the consecutive migration of the methyl sulfinyl cation motif in the pyrrole ring. A crossover experiment between 42 and 48 (1:1) generated 49 and 50 exclusively, indicating that both the [1,3]-sulfonyl and [1,5]-sulfinyl migration are intramolecular processes (Scheme 9b). No sulfinylated pyrrole 53 was observed when the pyrrole 45 was reacted in the presence of 51, highlighting that intermolecular deaurative sulfinylation is unlikely (Scheme 9c). The reaction of 54 in the presence of [¹⁸O]-labelled H₂O under the optimised conditions did not yield the [¹⁸O]-labelled 56, with 55 instead exclusively formed, indicating that an intramolecular oxygen transfer could be utilised in the mechanistic pathway (Scheme 9d).

DFT calculations proved useful in further understanding the mechanistic features of the cascade process (Scheme 10). The gold complex (**IM1**) was chosen as reference for the free energy, while coordination of the gold catalyst to the ynamide affords the isomerised allene-type complex (**IM2**). Attack of the sulfonyl oxygen onto the ynamide β -carbon yields the cyclic sulfoniminium (**IM3**), while extrusion of the sulfinylium ion PhSO⁺ affords the heterodiene complex (**IM4**). Migration of AuL⁺ to the propargyl triple bond generates a 1,2-azadiene (ketinimine) core (**IM5**), while subsequent 5-*endo-dig* cyclisation generates the 2*H*-pyrrole complex (**IM6**), which is strongly exergonic by 27.0 kcal mol⁻¹. Migration of the PhSO⁺ to the nitrogen atom of the pyyrole ring affords **IM7**, which lies very

Scheme 9 Control experiments for mechanism elucidation.

low on the potential energy surface $(-53.3 \text{ kcal mol}^{-1})$. The sulfoxide oxygen is utilised as a base to shuttle one of the hydrogen atoms of the CH2 group to the nitrogen atom of the pyrrole ring to afford IM10, despite being energetically unfavourable. The sulfonimidate-oxygen assisted 1,4-H shift via TS₇₋₈ at -25.2 kcal mol⁻¹ was found to be feasible affording **IM8.** Subsequent [1,2]-migration of the [PhSOH]⁺ moiety, followed by [1,5]-H shift generates **IM10**, while antarafacial [1,4]-S shift of the PhSO+ to afford IM11 was observed to be favourable requiring 9.8 kcal mol⁻¹ of free energy. To complete the

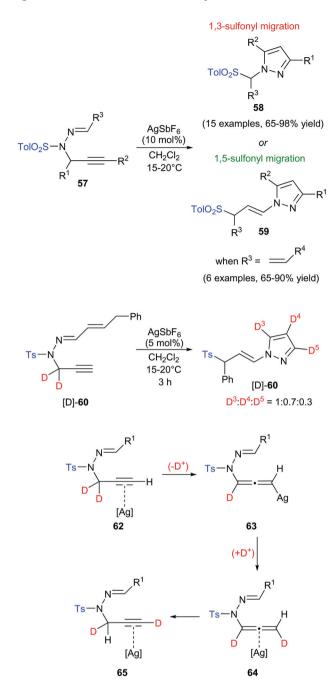
[18O]56 (not observed)



Scheme 10 Calculated energy profile of the umpolung cycloisomerisation migration cascade process (ΔG_{298} , kcal mol⁻¹).

transformation, a suprafacial [1,2]-S shift affords the IM12 located at -76.6 kcal mol⁻¹ on the PES.

2.1.2 Silver-catalysed sulfonyl migration. The synthesis of pyrazoles 58/59 via the silver(1)-catalysed rearrangement of propargyl N-sulfonylhydrazones 57, involving a 1,3- or 1,5-sulfonyl migration, was described by the Chung group.27 Using this methodology efficient and regioselective synthesis of 1,3- and 1,5-disubstituted, and 1,3,5-trisubstituted pyrazoles can be achieved in moderate to excellent yields (Scheme 11). Notably, in the absence of a sulfonyl moiety no pyrazole formation is observed. An intermolecular sulfonyl migration was elucidated by means of crossover experiments. Interestingly, deuterium incorporation studies highlighted an unexpected scrambling of deuterium at the C(4) and C(5) positions in the pyrazole product 61; this was rationalised through the silver(i) allene intermediate 63 (Scheme 11). Loss of a deuterium ion causes the π -intermediate 62 to rearrange to a silver-substituted allene intermediate 63. Subsequently, recombination with 63 affords intermediate 64, which can isomerise to regenerate the π -intermediate 65, which when cyclised gives pyrazole deriva-



Scheme 11 Silver(ı)-catalysed synthesis of pyrazoles from propargyl N-sulfonylhydrazones via 1,3- or 1,5-sulfonyl migration; proposition of a silver(ı)-substituted allene intermediate.

tives with deuterium incorporated at both the C(4) and C(5) positions.

Taking the above into account the following mechanism was postulated (Scheme 12). Upon coordination of the electrophilic silver source to the alkyne moiety of 57, nucleophilic cyclisation occurs yielding the silver(1) intermediate 67. Deprotonation leads to elimination of the sulfonyl moiety affording the ion pairs 68. The sulfinate anion attacks the electrophilic iminium carbon completing the 1,3-sulfonyl

$$R^3$$
 SO_2Tol
 R^3 SO_2Tol

Scheme 12 Postulated mechanism for the silver(i)-catalysed synthesis of pyrazoles from propargyl N-sulfonylhydrazones via 1,3- or 1,5-sulfonvl migration.

migration. In instances in which the imine substituent is extended by conjugation, the sulfonate anion attacks the β-carbon leading to 1,5-sulfonyl migration being preferred. Finally, protodemetallation of 69 regenerates the catalytic silver species and gives the pyrazole products 58.

The Wan group subsequently reported the silver(1)-catalysed cyclisation of N-sulfonyl propargylamides 70 for the synthesis of 4-(sulfonylmethyl)oxazoles 71 in moderate to good yields (Scheme 13).²⁸ The introduction of an aryl acyloxy directing group proved critical in realising the key silver-mediated [3,3]rearrangement. Crossover experiments indicated that the sulfonyl migration may occur in both an intra- and intermolecular manner. The following plausible mechanism was presented (Scheme 13). Coordination of the silver(1) cation to the alkyne moiety of the propargylamide 70 as well as the acyloxy directing group generates the π -complex 72. Due to the increased electrophilicity of the alkyne moiety an intramolecular nucleophilic attack of the amide oxygen occurs via a 6-endo-dig cyclisation giving the intermediate 73. Subsequent collapse of the cyclic intermediate 73 affords the allene intermediate 74. Nucleophilic attack of the nitrogen atom on the allene affords the 5-membered cyclic zwitterionic intermediate 75. It is envisaged that the 1,3-sulfonyl migration occurs at this point in both an intra- and intermolecular manner, to give the rearranged 4-(sulfonylmethyl)oxazole 71.

The Wan group further demonstrated that silver catalysis can be used in conjunction with trifluoromethyl-substituted

Ar O O R1 N R3 SO₂R³

70
$$R_1$$
 N R3 SO₂R²

71 (21 examples, up to 90% yield)

Ar O O R1 N R3 SO₂R²

70 R_1 N R3 SO₂R²

71 (21 examples, up to 90% yield)

Ar O O O R1 N R3 SO₂R²

72 R_1 N R3 SO₂R²

75 R_1 N R3 SO₂R²

76 R_1 N R3 SO₂R²

77 R_1 N R3 SO₂R²

78 R_1 N R3 SO₂R²

79 R_1 N R3 SO₂R²

70 R_1 N R3 SO₂R²

71 R_1 N R3 SO₂R²

72 R_1 N R3 SO₂R²

74 R_1 N R3 SO₂R²

Scheme 13 Silver-catalysed cyclisation of propargylamides in the generation of functionalised oxazoles via 1,3-sulfonyl migration.

3-aza-1,5-enynes 76 to generate highly functionalised pyrroles 77 containing a trifluoromethyl group at the 2-position in a selective manner (Scheme 14).²⁹ Analogous to the group's previously mentioned report, a 1,3-sulfonyl migration again occurs. Both electron-rich and electron-deficient aryl moieties were well tolerated at R¹, however, the reaction does not work with alkyl substituents at this position. The alkynyl substituent could be readily diversified, with both alkyl and aryl groups tolerated. Crossover experiments indicated an intermolecular process for the sulfonyl migration, while a deuterium incorporation experiment was consistent with the absence of C-H bond cleavage at the C-4 position. As a result, the following mechanism was proposed (Scheme 14). Initial aza-Claisen rearrangement of 76 affords the intermediate 78, which upon isomerisation gives the allene 79. Coordination of the silver(1) catalyst with the allene intermediate 79 leads to cyclisation of the silver complex 80, affording the cationic pyrrole 81. Cleavage of the N-S bond ensues affording the intermediate 82 and the sulfinate anion. Regioselective recombination displaces the silver(1) cation in an intermolecular manner and in doing so generates the rearranged pyrrole 77.

2.1.3. Transition metal-catalysed sulfonyl migration using N-sulfonylhydrazones. N-Sulfonylhydrazones undergo a range of transition-metal-catalysed and transition-metal-free transformations. The breadth of reactivity and synthetic application

Scheme 14 Generation of 2-trifluoromethyl-5-(arylsulfonyl)methyl pyrroles via silver-catalysed 1,3-sulfonyl migration.

of this family of compounds has been reviewed extensively in recent years, 30-32 however, the overwhelming majority of reports involve either retention of the sulfonyl moiety at nitrogen or decomposition with elimination of the sulfonyl moiety. Notwithstanding, N-sulfonylhydrazones have recently been observed to be synthetically useful precursors to both allyl and vinyl sulfones, utilising sulfonyl migration in atom-economical syntheses. In this section, recent advances in the reactivity of these compounds utilising transition-metal catalysis, incorporating sulfonyl migration, will be considered.

2.1.3.1. Copper-catalysed sulfonyl migration N-sulfonylhydrazones. Mao et al. developed a high-yielding stereoselective synthesis of terminal and α,β -unsaturated (E)vinyl sulfones 84 from N-sulfonylhydrazones 83 via a radical pathway (Scheme 15).33 The radical pathway was confirmed by the addition of TEMPO to the standard reaction conditions, which completely inhibited the formation of the sulfonyl migration product. The role of the sulfonyl free radical was further confirmed by the addition of 1,1-diphenylethylene (DPE), an alternative radical scavenger, with 85 isolated as the major product in 72% yield completely replacing formation of 84. A small amount of water was required for an efficient transformation to occur; when anhydrous Cu(OAc)₂ was used a 35% reduction in yield was observed for 84 ($R^1 = R^2 = Ph$) when compared to when one drop of water was added. The mechanism is postulated to proceed via isomerisation of the N-tosylhydrazone 83 to 86. Coordination of the copper catalyst to the alkene promotes the decomposition of 87, with concomitant extrusion of diazene and the free tosyl radical affording the complex 88. Recombination of 88 and the tosyl radical affords the carbenoid 89, which undergoes O-H insertion with

(30 examples, 56-95% yield)

NNHTs
$$R^2$$
 R^2 R^2

Scheme 15 Copper-catalysed stereoselective synthesis of (*E*)-vinyl sulfones *via* the radical reaction of *N*-tosylhydrazones.

water to afford the alcohol **90**. *trans*-Elimination of water stereoselectively affords the desired (*E*)-vinyl sulfone.

The Zhang group reported the one-pot generation of 2-sulfonylmethyl 1H-indenes 93 in moderate yields via a coppermediated sulfonyl radical-enabled cyclisation of N-arylsulfonyl hydrazones (Scheme 16).³⁴ A radical process was confirmed through the suppression of the reaction pathway on the addition of the radical scavengers TEMPO or 1,4-benzoquinone (BQ). Starting with the benzaldehyde 94, in the absence of either CuBr or DTBP, the major product isolated was the N-sulfonylhydrazone 95, highlighting the key role of the copper salt and oxidant in the reaction process. Stopping the reaction after 5 minutes afforded exclusively 95, with complete consumption of starting material. The N-tosylhydrazone 95 was demonstrated to afford the indene 100 on treatment with TsNHNH₂ under the standard conditions. In the absence of a second equivalent of TsNHNH2 the desired product was afforded in 10% yield, highlighting that efficient sulfonyl radical attack at the terminal vinyl carbon requires the second equivalent of TsNHNH₂.

Considering this the following mechanism was proposed. Condensation of TsNHNH₂ with the aldehyde 94 affords the *N*-tosylhydrazone 95. A tosyl radical is generated *in situ via* the DTBP and copper-mediated oxidative decomposition of the second equivalent of TsNHNH₂. Subsequent addition of the sulfonyl radical to the terminal alkenyl carbon of 95 affords the intermediate radical 96. Intramolecular 5-exo-trig cyclisation and hydrogen abstraction affords 98, which loses dinitro-

Scheme 16 Access to sulfonylmethyl 1*H*-indenes *via* copper-mediated sulfonyl radical-enabled 5-exo-trig cyclisation of alkenyl aldehydes.

gen and a tosyl radical to give **99**. Finally, a copper-mediated single electron transfer oxidation, and subsequent elimination via β -H abstraction by tert-butoxide affords the indene product **100**.

The Wang group described the copper(1)-catalysed one-step cross-coupling of terminal alkynes N-sulfonylhydrazones 102 to afford α,β-disubstituted vinyl sulfones 103 in moderate to excellent yields (Scheme 17).35 the reaction proceeds readily for various N-tosylhydrazones with both electron-donating and electronwithdrawing groups tolerated on the aryl ring, albeit in lower yield when electron-withdrawing groups are present. Both naphthyl- and alkysulfonyl derivatives are also well tolerated, while both the ester substituent and the electronics of the aryl ring of the terminal alkyne can readily be altered with no deleterious effect. A radical-mediated transformation was excluded based on the absence of inhibition of the reaction on addition of TEMPO or BHT to the optimised reaction medium. Both the alkyne 110 and allene 111 afforded the desired product 112 when treated with p-toluenesulfinate in the presence of triethylamine. Notably, the alkyne 110 did not furnish any product in the absence of base, confirming the role of the allene intermediate 111 in the reaction cascade.

In light of these findings and previous reports the authors postulated the following mechanism (Scheme 17). Base-mediated decomposition of the N-tosylhydrazone 104 affords the tosylate anion and diazo compound 105. Subsequent reaction of 105 with the copper acetylide 107 affords the carbenoid 108 which undergoes migratory insertion of the alkynyl moiety to the α -carbon to give the intermediate 109. Protonation of 109 releases the copper cation which becomes available for the next catalytic cycle and generates the internal alkyne 110. Deprotonation with triethylamine affords the allene intermedi-

Scheme 17 One-step copper(i)-catalysed cross-coupling of terminal alkynes with N-sulfonylhydrazones affording α,β -disubstituted vinyl sulfones.

ate **111** which reacts with the tosyl anion in a regioselective manner, completing the sulfonyl migration, and affording the product **112**. The stereoselectivity of the reaction can be explained by the steric hindrance between the tosyl and phenyl moieties that inhibits the formation of the *Z*-isomer **113**.

The Ji group described a copper(II)/silver(I)-catalysed domino reaction of anthranils 114 with *N*-sulfonylhydrazones 115 to afford a series of 2-aryl-3-sulfonyl disubstituted quinoline derivatives 116 in moderate yields (Scheme 18).³⁶ To elucidate a mechanism the authors carried out a series of control experiments. The presence of TEMPO suppressed the reaction of 114 and 117 affording the desired product 118 in only 16% yield, while also forming the decomposition product 119 and the quinoline 120. Additionally, in the presence of the alternative radical scavenger DPE, the trapped vinyl sulfone product 85 was observed by LC-MS confirming the presence of a sulfonyl radical in the mechanistic pathway. When 114 and 122 were reacted in the presence of the quinoline 123 no formation of 118 was observed highlighting that the sulfonyl migration occurs prior to the formation of the quinoline skeleton.

In light of the above the authors proposed that the zwitterion **114** reacts with the *N*-tosylhydrazone **126** under thermal conditions to afford the diazo intermediate **127** with expulsion

Scheme 18 Copper(||)/silver(|)-catalysed formation of 2-aryl 3-sulfonyl disubstituted quinoline derivatives via the reaction of N-sulfonylhydrazones and anthranils.

of a tosyl radical (Scheme 19). Loss of nitrogen from the diazo compound 127 effected by the copper catalyst gives the carbenoid 128, which subsequently coordinates with the anthranil 114 to give 129. Carbene migratory insertion ensues to form 130, while the following N–O bond cleavage affords the tautomer pair 131 and 132. Addition of the tosyl radical to the terminal alkenyl carbon of 132 leads to the intermediate 133, which cyclises in the presence of the AgOTf catalyst to yield the rearranged quinoline 125.

Xu and co-workers recently reported the synthesis of 4-methyl 2H-chromene derivatives 135 from alkyne tethered N-sulfonvl hydrazones 134 using copper (Scheme 20).³⁷ Notably, in the absence of copper spiro-4*H*-pyrazoles (e.g. 139) are instead the major products. Monitoring of the reaction progress by ¹H NMR allowed the identification of the 3H-pyrazole 137, which was isolable. Furthermore, reacting 137 with one equivalent of CuI under thermal conditions gave 138 and 139 in 44% and 55% conversion respectively, highlighting that the 3H-pyrazole 137 is a key intermediate in both potential transformations. The formation of 138 in this instance, which does not require a catalyst, suggested that dintrogen extrusion could be preceded by anion exchange (Ts⁻/I⁻) and/or coordination of the copper catalyst with 137. As such, using CuOTf as catalyst, both the copper complex 140 and the triflyl addition product 141 were observed by ESI-MS. Crossover experiments indicated not only that the sulfonyl

Scheme 19 Proposed mechanism for the copper(II)/silver(I)-catalysed formation of 2-aryl-3-sulfonyl quinolines.

Scheme 20 Copper-catalysed synthesis of 4-methyl 2*H*-chromenes alkyne tethered *N*-sulfonyl hydrazones.

Scheme 21 Proposed mechanism for the copper-catalysed transformation of alkyne tethered *N*-sulfonyl hydrazones to 4-methyl 2*H*-chromene derivatives.

migration is an intermolecular process but also that it is likely that the counter ion is either in close proximity or associated to the intermediate during the transformation, and that the catalytic rate of reaction is faster than the counter ion exchange; this is as a result of observing that the less nucleophilic nosyl anion afforded a significantly higher combined yield than that of the tosyl anion (Scheme 20). Isolation of the deuterated product [D]-138 rationalised the protonation after recombination with the tosyl anion. Further evidence for the reaction pathway was obtained *via* the identification of the intermediates 145 and 146 by ¹H NMR and HRMS (see Scheme 21).

Considering this the following mechanism was proposed (Scheme 21). K_2CO_3 -mediated deprotonation of the N-sulfonyl hydrazone **144** affords the potassium salt **145**. Subsequent ion exchange affords the copper complex **146**, which undergoes a [3 + 2] cycloaddition/dinitrogen extrusion/sulfonyl anion recombination to give the desired product **148** via **147**. Alternatively, dissociation of the copper catalyst could occur leading to the rearranged spiro-product **150** via van Alphen-Hüttel rearrangement of **149**.

2.1.3.2. Palladium-catalysed sulfonyl migration using N-sulfonylhydrazones. Allylic sulfones are accessible via palladium-catalysed cross-coupling of aryl and vinyl iodides 151 and 154 with N-sulfonylhydrazones 152 and 155, involving carbene migratory insertion and regioselective addition of the released sulfonyl anion (Scheme 22). 38,39 For example, using Pd(OAc)₂ and triphenylphosphine as catalyst, and BTAC as phase-transfer additive, a series of allylic sulfones 156 were generated in moderate to high yields, with electron-deficient and electron-rich aryl rings all well tolerated, as well as a range of sulfonyl moieties. The reactions are believed to proceed via initial base-mediated decomposition of the N-tosylhydrazone 159 to afford the diazo 160 with concomitant release of the tosylate salt. The diazo 160 reacts with the vinylpalladium iodide complex 158 to form the carbenoid 161, which under-

Scheme 22 Generation of allylic sulfones via palladium-catalysed cross-coupling of aryl iodides and N-tosylhydrazones.

goes migratory insertion to afford the η^{1} -allylpalladium intermediate 162. Isomerisation to the η^3 -allylpalladium complex 163 is followed by selective nucleophilic addition of the tosylate anion to give 164 as the exclusive product.

2.1.4. Miscellaneous metal-catalysed sulfonyl migration. The introduction of a sulfonyl group to the C-7 position of indoles can be achieved in moderate to good yields through the aluminium trichloride-mediated regioselective 1,3-sulfonyl migration of N-sulfonyl indoles 165 (Scheme 23).40 The sulfonyl migration was found to proceed smoothly when an electron-donating group was present at the C-5 position of 165, however the regioselectivity of the transformation was attenuated by the presence of electron-withdrawing groups with some formation of the 3-sulfonyl indole observed. The presence of the bulky tert-butyl group at the C2 position appears to assist the cleavage of the N-S bond allowing the sulfonyl migration to occur; when a *n*-butyl substituent was present at

Scheme 23 AlCl₃-mediated 1,3-sulfonyl migration of N-sulfonyl indoles; access to 7-sulfonyl indoles.

C2 no migration was observed, despite the acylation readily occurring. In the absence of acyl chloride the sulfonyl migration still readily occurred, highlighting the key role of AlCl₃ in the reaction. The mechanism was proposed to involve a non-concerted, intermolecular sulfonyl migration based on the outcome of crossover experiments. Thus, the reaction seems to proceed via AlCl3-assisted activation of the indolyl double bond followed by cleavage of the N-S bond to give 168 which subsequently undergoes sulfonylation at the C7 position to give 171 via 170, completing the sulfonyl migration.

The Zhan group reported the copper(1)-catalysed stereoselective synthesis of (1E,3E)-2-sulfonyl-1,3-dienes 173 from N-propargylic sulfonylhydrazones 172 involving a stereoselective sulfonyl migration (Scheme 24).41 When employing catalytic [Cu(PPh₃)I]₄ in refluxing toluene yields of 51-92% were achieved, with electron-poor sulfonylhydrazones leading to higher yields than electron-rich analogues. Aryl groups at both R² and R⁴ bearing electron-withdrawing and electrondonating substituents were also well tolerated.

Crossover experiments indicated that the migration of the sulfonyl group is an intermolecular process. Based on these observations the authors hypothesised that the mechanism involves initial 6-endo-dig addition of the sulfonylhydrazone onto the copper(1)-alkyne complex 174 to generate the intermediate 175 which collapses to the allenic intermediate 176, completing the initial [3,3]-rearrangement. Intermediate 176 is unstable and readily loses dinitrogen, leaving ion pair 177. Finally, the tosyl anion regioselectively and stereoselectively attacks the central sp carbon atom of the allenic moiety, with subsequent electron transfer affording the (1E,3E)-2-sulfonyl-1,3-diene 173 (Scheme 24). The release of nitrogen is most likely the trigger for the sulfonyl migration.

Zhan and co-workers reported the zinc chloride mediated synthesis of 4-(sulfonyl)-methyl-1*H*-pyrazoles **179** in excellent

R¹O₂S - N R³
$$\begin{bmatrix} Cu(PPh_3)I]_4 \\ (5 \text{ mol/%}) \\ Toluene \\ Reflux \end{bmatrix}$$
 $\begin{bmatrix} 173 \\ (21 \text{ examples, up to } 92\% \text{ yield}) \end{bmatrix}$ $\begin{bmatrix} R^1 O_2 S \\ R^2 \end{bmatrix}$ $\begin{bmatrix} Cul \end{bmatrix}$ $\begin{bmatrix} Cul$

Scheme 24 Copper(i)-catalysed stereoselective synthesis of (1E,3E)-2sulfonyl-1,3-dienes utilising migration of the sulfonyl group.

yields from N-allenic sulfonylhydrazones 178 via a formal 1,4nitrogen to carbon sulfonyl migration (Scheme 25).42 Crossover experiments utilising two different N-allenic sulfonylhydrazones highlighted an intermolecular process for the sulfonyl migration. Mesyl, tosyl and benzenesulfonyl substituents were tolerated. The authors postulated that coordination of ZnBr₂ to the azomethine nitrogen atom of 178 induces a nucleophilic addition of the central allenyl carbon to the azomethine carbon to give exclusively (E)-182. Formation of (Z)-**181** is inhibited due to steric hindrance between the R³ and R⁴ substituents. Bromide assists the N-S bond scission to generate the intermediate 183 and tosyl bromide, which then reacts with the endocyclic alkene moiety to complete the formal 1,4migration, and in doing so generates Tautomerisation affords the rearranged aromatic pyrazole 179.

2.2. Single electron-mediated sulfonyl migration

2.2.1. Radical-mediated sulfonyl migration. The Maulide group observed an unexpected nitrogen to carbon 1,3-sulfonyl migration of a tosyl group when attempting to expand the scope of electrophilic Claisen rearrangements to aza-derivatives. While alkyl and alkenyl oxygen-based substrates under-

Scheme 25 Selective synthesis of 4-(sulfonyl)-methyl-1H-pyrazoles from N-allenic sulfonylhydrazones via 1,4-nitrogen to carbon sulfonyl migration (see also Scheme 66).

R¹O₂S

went straightforward Claisen rearrangement to afford a series of hydrocoumarins, aza-derivatives 185-187 did not afford the expected α-substituted lactams 191, but instead the amidinium derivatives 188-190 (Scheme 26).43 Both the allyl and benzyl derivatives 185 and 186 underwent tosyl migration, while the propargyl derivative 187 underwent an additional cyclisation with concurrent tosyl migration. It was postulated that the tosyl migration occurs as a result of a radical pathway, with homolytic cleavage of N-S bond in the intermediate 193. It was suggested that recombination of the radical pair 194 to afford 188 may be faster than diffusion, and that this process is more favourable energetically than migration of the allyl group.

The thermal 1,3- and 1,5-sulfonyl migrations N-arenesulfonylphenothiazines 195 N-arenesulfonylphenoxazines 196 were realised by the Xu group (Scheme 27).44 Under neutral, thermal conditions a series of sulfonyl substituted phenothiazine 197/199 or phenoxazine derivatives 198/200 are afforded with moderate yields and regioselectivities. Crossover experiments indicated that the sulfonyl migration was an intermolecular process while a

188

Scheme 26 Generation of amidinium derivatives *via* 1,3-tosyl migration.

radical-radical coupling reaction mechanism was proposed based on competitive trapping experiments using electron-rich 1,4-dimethoxybenzene, which ultimately allowed the ruling out of a possible ion-pair mechanism. As such, homolytic cleavage of the N-S bond affords the free radical 203 and a sulfonyl radical. The radical intermediate 203 can readily interconvert between the resonance structures 204 and 205 through electron delocalisation. Recombination of the sulfonyl radical with 204 or 205, leads to formal 1,3- and 1,5-sulfonyl migrations to give intermediates 206 and 207. Finally, isomerisation of these intermediates affords the rearranged phenothiazine or phenoxazine products 197-200. The formation of the dissociation products 201/202, via abstraction of a hydrogen atom from a neighbouring molecule, such as solvent, provides further supportive evidence for the radical mechanism.

The She group developed a sequential catalysed cyclo-addition of N-heterocyclic carbene (NHC) activated 1,3-dioxo-isoindolin-2-yl 2-phenyl acetate **210** and α,β -unsaturated imines **209** in which the *N*-hydroxyphthalimide (NHPI) by-product **212** of the first reaction catalysed a further nitrogen to carbon 1,3-sulfonyl migration of the tosyl group (Scheme 28). ⁴⁵ Notably,

Scheme 27 Radical–radical coupling reaction mechanism for the 1,3- and 1,5-sulfonyl migrations of N-arenesulfonyl-phenothiazines and phenoxazines.

the enantiomeric composition of the major product **211** from the cycloaddition step was retained through the subsequent sulfonyl migration to afford the desired product **213** in moderate yields and high enantioselectivities. The efficiency of the NHC/NHPI catalytic cascade process was found to be strongly dependant on the electronic nature of the R² substituent, with electron donating groups on the aromatic ring affording final products in significantly higher yields after 2 steps. While the mechanism of the sulfonyl migration is not fully understood, a radical mechanism was deemed most likely, as the addition of the radical scavenger TEMPO completely inhibited the migration.

Wang *et al.* reported the di-*tert*-butyl peroxide-mediated radical rearrangement of *N*-sulfonyl-*N*-aryl propynamides **214** to afford 3-sulfonyl-2-(1*H*)-quinolinones **215** in moderate to good yields with good functional group compatibilities, with a 1,3-sulfonyl migration from nitrogen to carbon a key step (Scheme 29). ⁴⁶ Crossover experiments indicated the involvement of an intermolecular process, while a radical pathway was postulated based on the inhibition of the reaction cycle upon the addition of the radical scavengers TEMPO, BHT or galvinoxyl. The intramolecular and intermolecular kinetic isotope effect (KIE) was determined to be 1.08 and 1.04 respectively, indicating that the rate determining step was un-

Scheme 28 Application of upstream by-product NHPI as catalyst for sequential 1,3-sulfonyl migration.

Scheme 29 Di-tert-butyl peroxide mediated radical rearrangement of N-sulfonyl-N-aryl propynamides; observation of a formal 1,3-sulfonyl migration.

likely to involve the cleavage of the aromatic C-H bond, while also suggesting that either a radical or electrophilic aromatic substitution pathway was involved. Considering this the authors proposed that homolytic scission of the N-SO₂ bond

leads to the radical 216 and a sulfonyl radical. Addition of the sulfonyl radical to the alkyne group of radical 216 generates the diradical 217, which abstracts a hydrogen atom from the solvent, to give the radical 218. A 6-endo-dig cyclisation affords the cyclised radical 219, which on abstraction of a hydrogen by a tert-butoxyl radical affords the 3-sulfonyl-2-(1H)-quinolinone 215.

2.2.2. Photoinduced sulfonyl migration. Photochemical irradiation of N-sulfonyl anilines 220 was found to promote thia-Fries-type rearrangements to afford mixtures of regioisomeric ortho- and para-aminophenyl sulfone derivatives 221 and 222 in moderate yields, via nitrogen to carbon 1,3- or 1,5sulfonyl migration (Scheme 30).47 N-Alkylation of the sulfonanilides 220 increased the yield of the rearranged products, while the presence of electron-withdrawing groups on the aromatic ring did not greatly lower the yields.

In their efforts to establish a total synthesis of the kopsifoline alkaloid framework 225, Padwa and co-workers observed an unanticipated desulfonvlation of 223, while attempting to carry out a photochemical rearrangement. The desulfonylation proceeded efficiently, affording 224 90% vield (Scheme 31).48,49

Scheme 30 Photochemical rearrangement thia-Fries-type of N-sulfonyl anilines.

Scheme 31 Photoinduced desulfonylation strategy toward the synthesis of the kopsifoline alkaloid framework.

Scheme 32 Mechanism for the photoinduced thia-Fries type rearrangement of indoles.

Due to the efficiency of this reaction, and the mild conditions required, the authors sought to extend the scope of the reaction to a series of related indoles 226, however a significant reduction in yield was observed for this class of compound due to the competing formation of both ortho- and para-photo Fries rearrangement products 228 and 229 (Scheme 32). In most instances the para-rearrangement byproduct 228, the result of a formal 1,5-sulfonyl migration, was the major isomer formed. The reaction is likely initiated by single electron transfer from triethylamine to the electronically excited indole 226* leading to the triethylamine radical cation and the indole radical anion 231 (via the indole radical 230). Proton transfer from the radical cation of triethylamine affords the desired desulfonylated indole 227. In competing processes, the phenylsulfonyl radical can also add to the aromatic framework of the radical anion 231 to afford the transient intermediates 232 or 233. Subsequent electron transfer from 232 and 233 to the triethylamine radical cation affords the ortho- and para-sulfonylated indoles 228 and 229. The competing thia-Fries pathway can be suppressed by addition of n-Bu₃SnH, which allows capture of the sulfonyl radical via hydrogen atom transfer.

Smith and coworkers reported the first selective example of a nitrogen to carbon 1,3-sulfonyl migration of dihydropyridones 234 *via* prolonged storage and heating, however, most notable was the quantitative isomerisation observed under photochemical conditions (Scheme 33).^{50,51} Highlights of the

methodology include a high degree of tolerance for both Nand C-substituent diversification around the dihydropyridinone ring, to afford the corresponding rearranged C-sulfonyl products 235 in moderate to high yields with no erosion of stereochemical integrity. Significant efforts to rationalise the mechanism of the sulfonyl migration were made by the authors. Crossover experiments elucidated an intermolecular event, while adding TEMPO under the standard conditions led to complete suppression of the sulfonyl transfer, indicating a radical mechanism. Rather than a straightforward homolytic N-S bond cleavage to give a sulfonyl radical and radical 236 followed by recombination at carbon to give the rearranged product 235, electron paramagnetic resonance (EPR) spectroscopy indicated the presence of a larger radical that was assigned as the intermediate benzylic radical 237. Therefore the authors proposed that after the homolytic cleavage, the sulfonyl radical adds to the dihydropyridinone 234 generating the benzylic radical 237 which can extrude a sulfone radical to generate the neutral imine 238. Tautomerisation of 238 affords the rearranged dihydropyridinone 235.

227

The Rutjes group discovered the first example of a photo-induced rearrangement of 1,2-benzothiazole-1,1-diones **240** to form 3-amino-1-benzothiophene-1,1-dione derivatives **241** in excellent yields *via* a nitrogen to carbon 1,3-sulfonyl migration (Scheme 34).⁵² Based on literature precedent for the photo-induced cleavage of sulfonamides the authors postulated the following radical mechanism.^{53–56} Irradiation of **240** induces

235

Scheme 33 Photoisomerisation of *N*-sulfonyldihydropyridinones; observation of a visible light induced 1,3-sulfonyl migration.

238

Scheme 34 Photochemical rearrangement of 1,2-benzothiazole-1,1-diones to 3-amino-1-benzothiophene-1,1-diones; observation of a nitrogen to carbon 1,3-sulfonyl migration.

homolytic cleavage of the N–S bond which generates the diradical 242. Recombination of the sulfinate radical with the C-terminus of the enaminyl radical generates the imine 243, which subsequently tautomerises to generate the rearranged 3-amino-1-benzothiophene-1,1-dione 241. The requisite substrates 240 for the photoinduced sulfonyl migration were

Scheme 35 Irradiation of N-aryl sulfonimides; observation of single and double photo thia-Fries rearrangement.

demonstrated to be accessible through a palladium-catalysed regioselective and highly stereoselective intramolecular hydroarylation of sulfonyl ynamines 239.

Torti *et al.* described the use of *N*-arylsulfonimides **244** as potential nonionic photoacid generators able to photorelease up to two equivalents of sulfonic acids for each mole of substrate under deaerated conditions in acetonitrile. ^{57,58} The product distribution of the reaction under deaerated conditions proved to be complex with all compounds formed arising from the cleavage of the S–N bond to afford both photo thia-Fries rearrangement products **246**, **247**, **249** or **250** and desulfonylated products **245** or **248** (Scheme 35).

In order to further understand the photoreactivity of the N-arylsulfonamides 244, and to investigate secondary photochemical pathways, laser flash photolysis (LFP) and electron paramagnetic resonance (EPR) spectroscopy experiments were performed. Considering the supporting evidence of these studies the authors tentatively proposed the following mechanism (Scheme 36). Initial irradiation of 244 causes excitation to the singlet state ¹244, which undergoes homolytic cleavage of the N-S bond to generate the sulfamido 251 and sulfonyl 252 radicals, the presence of which were confirmed by both time-resolved absorption and EPR spectroscopy (path A). Once formed, the radicals 251 and 252 can undergo either thia-Fries rearrangement as a result of recombination (path D) to afford 246 via intermediate 253, or escape from the solvent cage to release sulfonic acids. The photoreactive sulfonamide 246 can undergo a second thia-Fries rearrangement to generate the rearranged aniline 249 (path D"), however desulfonylation appears to have no role (path D'). In contrast, hydrogen abstraction by the sulfamido radical 251 from the reaction medium affords the sulfonamide 245 (path C). The favoured pathway, between path C and D, is dependent on both the functional groups present on the aryl ring and the reaction medium. The single thia-Fries rearrangement product 246 is preferred in less polar solvents and in the presence of electrondonating groups (NMe2, OMe) on the aromatic ring.

The *N*-arylsulfonamide **245** is also photoactive and can undergo both thia-Fries rearrangement to afford the rearranged aniline **247** (path C"), or desulfonylation to give **248** (path C'). The thia-Fries rearrangement is favoured for electron-rich sulfonamides, while for unsubstituted

Scheme 36 Mechanism for the photochemical reactivity of N-arylsulfonimides under inert and aerated conditions.

N-arylsulfonamides **245** (FG = H) both desulfonylation to generate aniline **248** or thia-Fries rearrangement to give the *para*-substituted aniline **250** can occur.

2.2.3. Non-metal-catalysed radical-mediated migration of N-sulfonylhydrazones. In 2014, the Prabhu group reported the generation of (E)-vinyl sulfones 255 from the reaction of N-tosylhydrazones 254 with cyanogen bromide and TBAB; involving 1,2-tosyl migration for derivatives bearing a methyl or aryl substituent at R1 (Scheme 37).59 The reaction is thought to proceed via generation of a bromine radical from the reaction of CNBr-TBAB, which adds to 254 affording the bromo-azo-sulfone 256, which releases dinitrogen and a tosyl radical to afford 257. Recombination of the tosyl radical and 257 affords the isolable intermediate 258, which undergoes either dehydrohalogenation to give the vinyl sulfone 259 when R^1 = H, or a 1,2-sulfone migration in addition to elimination of HBr to afford 255. Crossover experiments were used to confirm an intermolecular tosyl migration.

Luo *et al.* described a $PhI(OAc)_2$ -mediated stereoselective synthesis of (*E*)-vinyl sulfones **261** from aliphatic and aryl *N*-sulfonyl hydrazones **260** in moderate to high yields (Scheme 38). Both electron-withdrawing and electron-donating aryl moieties at R^1 were well tolerated, while the methodology was further applied to a range of aromatic heterocyclic

254

$$R^{1}$$
 R^{1}
 R^{1}
 R^{1}
 $R^{2}CO_{3}$
 R^{1}
 R^{1}

CNBr, TBAB

NNHTs

Scheme 37 Generation of vinyl sulfones via the reaction of N-tosylhydrazones with CNBr and aliphatic quaternary ammonium salts; observation of an intermolecular tosyl migration.

Scheme 38 $Phl(OAc)_2$ -mediated synthesis of (E)-vinyl sulfones from aliphatic and aromatic N-sulfonyl hydrazones.

derivatives. A radical mechanism was envisaged based on the inhibition of the reaction on the addition of the radical scavenger TEMPO. As such, the authors postulated that the hypervalent iodine intermediate 263 forms in the presence of PhI(OAc)₂, which undergoes homolytic N–S bond cleavage to afford a sulfonyl radical and 264. Subsequent elimination of dinitrogen from 264 affords the radical intermediate 265, which on recombination with the sulfonyl radical affords 268 (or 266 when $\rm R^2=H$). Base-mediated reductive elimination of 266/268 affords either the α - or β -substituted vinyl sulfones 267 or 269.

Deagostino and co-workers described the first visible-lightmediated transformation of α,β-unsaturated-N-sulfonylhydrazones 270 to allylic sulfones 271 with optimal results achieved using [Ru(bpy)₃]Cl₂6H₂O as photocatalyst (Scheme 39).⁶¹ Tosyl, mesyl, and triflyl moieties were well tolerated. Interestingly, on addition of TEMPO, to the standard reaction conditions, 272 was isolated confirming that the process involves a vinyl radical intermediate. A radical chain mechanism was excluded based on observation that no reaction occurs in the presence of AIBN, while the use of the more reactive benzoyl peroxide produced a complex mixture of products. In light of these results the authors postulated the following mechanism. Treatment of the N-tosylhydrazone 272 with base affords the anion 273. Visible-light promotes the excitation of the photocatalyst, and it is the excited state *[Ru(bpy)₃]²⁺ that induces the single electron oxidation of 273 to give the N-centered radical 274. A formal 1,5-sulfonyl migration, suggested to occur via a 6-membered transition state, leads to the expulsion of dinitrogen and the formation of the vinyl tosylate radical 275. Abstraction of a hydrogen atom from the solvent, as confirmed via deuterium incorporation studies using CDCl₃, generates the final product 276 and a CCl₃ radical that promotes the regeneration of the photocatalyst $[Ru(bpy)_3]^{2+}$.

Scheme 39 Visible-light-mediated photocatalytic transformation of α,β -unsaturated *N*-sulfonylhydrazones to allylic sulfones.

2.3. Non-metal-catalysed sulfonyl migration

In 1997, the Tamaru group reported the thermal [2 + 2] cycloaddition of allenesulfonamides with electron deficient alkenes and alkynes to yield substituted cyclobutene derivatives, for example the reaction of 277 with methyl acrylate afforded the cyclobutane 279 in 73% yield (Scheme 40, X = H).62 In an extension of this study, the authors were surprised to find that when the alkene substrate was an enol ether, such as methyl β-methoxyacrylate 278 (R = OMe), that a completely different pathway was operational, with the tetrahydropyridine 280 isolated as the major product and no evidence for the expected cyclobutane product (Scheme 40, R = OMe). 63 Notably, this pathway involved an unexpected 1,3-nitrogen to carbon sulfonyl migration, while enol ethers including acyclic and cyclic aldehyde enol ethers and acyclic and cyclic ketone-enol ethers all reacted similarly. Using this methodology highly functionalised tetrahydropyridines could be accessed in moderate to excellent yields (Scheme 41).64

Scheme 40 Novel addition–cyclisation reaction of 4-vinylidene-1,3-oxazolidin-2-ones and enol ethers; observation of a 1,3-sulfonyl migration.

Scheme 41 Possible mechanistic pathways for the selective formation of tetrahydropyridines.

The reaction mechanism is believed to proceed through the transition state 284 in which the cumulative effect of the electron density of the C1'-C2' alkene bond being pushed into the sulfonamide moiety and the electron density being drawn away from the carbamate through conjugation with the C4'-C1' alkene bond significantly weakens the N-S bond, allowing for the 1,3-sulfonyl migration and the generation of s-trans-1azabutadiene 285. Subsequent isomerisation of the terminal double bond to s-cis 285, allows for a facile hetero-Diels-Alder reaction with the enol ether 282 to afford the tetrahydropyridine product 283 (Scheme 41, path A). In certain instances the enol ether was observed to isomerise during the reaction with the allenesulfonamides 281 with both E- and Z-isomers recoverable; however, no isomerisation was observed in the absence of 281. In contrast, the allenesulfonamide 281 readily isomerised to 3-tosyl-4-vinyl-4-oxazolin-2-one under thermal conditions via a 1,3-H shift in the absence of enol ether highlighting that allenesulfonamide 281 promotes the isomerisation of the enol ether, while the enol ether is crucial in promoting the 1,3-sulfonyl migration. For enol ethers that are highly electron-donating (e.g., ketone enol ethers and furans) it is possible that pathway B could be operational to some extent due to being more able to stabilise the zwitterionic species 286.

Subsequent studies by the group highlighted that allyl silanes and hydrosilanes react in an analogous manner, albeit with reduced efficiency, despite being much poorer nucleophiles than enol ethers. ⁶⁵ Further extension to hetero-nucleophiles including alcohols and thiols afforded both 1,3-sulfonyl

migration products in addition to significant amounts of nonsulfonyl migration products as a result of simple addition to the $C\alpha$ = $C\beta$ bond. Indoles were observed to undergo a similar reaction profile, however the addition occurs through the alkenyl carbon, rather than the nitrogen atom, akin to an electrophilic aromatic substitution.⁶⁴

Wudl reported the first example of an uncatalysed 1,3-sulfonyl migration from a sulfonamide 287 to a keteneimine 288 under thermal conditions. 66 Notably, the rearrangement of the ynamide 287, which proceeds cleanly either in the melt or in solution at 100-120 °C, involves the migration of both the tosyl group and the p-methoxybenzyl (PMB) group from the nitrogen atom to the same β-carbon, to afford the nitrile 291 in an isolated yield of 92%. Variable temperature ¹H NMR was readily used to follow the progress of the rearrangement in the nonaromatic solvent decalin. This demonstrated that the rearrangement occurs via the observable intermediate 289, which also demonstrates that the 1,3-sulfonyl migration occurs first. The identity of the keteneimine intermediate 288 was further inferred as it hydrolysed readily on contact with water to afford the amide 292, which was characterised by X-ray crystallography. Quantum mechanical calculations suggest that strong resonance stabilisation of the transition state facilitates the sulfonyl migration (Scheme 42). Both rearrangement processes were calculated to be thermodynamically favoured.

The Zhang group described the thermal aza-Claisen rearrangements of N-allyl ynamides **293** to allyl-keteneimine intermediate **295** via the aza-Claisen transition state **294**, with subsequent spontaneous 1,3-sulfonyl migrations affording quaternary nitriles **296** in moderate yields (7 examples, 45–64%) (Scheme 43).⁶⁷ The sulfonyl migration was not observed when R^2 = TIPS, with the generated silyl keteneimine **298** sufficiently stable to not undergo subsequent sulfonyl migration. Monitoring of the reaction progress by ¹H NMR did not reveal any of the allyl-keteneimine intermediate **295**, suggesting rapid sulfonyl migration at 110 °C.

The authors attempted to extend this methodology to ynamides of type **299** possessing a propargylic stereocenter, with the possibility to undergo a stereoselective **1**,3-sulfonyl migration leading to either **302** or **302**′ (Scheme 44). They

Scheme 42 1,3-Sulfonyl migration of a sulfonyl group from sulfonamide to keteneimine.

Scheme 43 Thermal aza-Claisen rearrangement of *N*-allyl ynamides and subsequent 1,3-sulfonyl migration.

Scheme 44 Attempted diastereoselective *N*-to-*C* 1,3-sulfonyl migration.

reasoned that the conformational preference of the allyl-keteneimine intermediate 301 or 301' would dictate the level of selectivity, with the $A^{1,2}$ -strain present in 301 potentially meaning that the conformer 301' would be preferred. If so, this preference could result in facially selective 1,3-sulfonyl migration to give 302'. They further hypothesised that suitable modification of the protecting group (P) could lead to the conformational preference shown for 303' in which anchimeric assistance could also result in facially selective 1,3-sulfonyl migration. In the event, however, the highest diastereomer ratio achieved was 2:1.

The Wan group reported the highly regioselective sulfonyl group migration in the synthesis of functionalised pyrroles. A significant feature of the work is that the regioselectivity of the sulfonyl migration can be tuned with high selectivity for

Scheme 45 1,3- and 1,4-sulfonyl migration in the generation of both α - and β -(arylsulfonyl)methyl pyrroles under thermal and basic conditions respectively.

314

the formation of both α - and β -(arylsulfonyl)methyl pyrroles **306** and **305** in excellent yields (Scheme 45). Under thermal conditions, the azaenyne derivative **304** is transformed into **307** *via* an aza-Claisen rearrangement. Due to the electron-withdrawing character of both the double bond and the sulfonyl group the nitrogen atom is rendered electrophilic, leading to ring closure to afford the zwitterionic intermediate **308** through nucleophilic attack of the allene moiety. Cleavage of the N-S bond leads to the ion pair **309**, which recombines to complete the 1,3-sulfonyl migration. The presence of the ionpair **309**, and the intermolecular nature of the migration was confirmed by crossover experiments. Finally, isomerisation of **310** affords the α -(arylsulfonyl)-methyl pyrrole **306**.

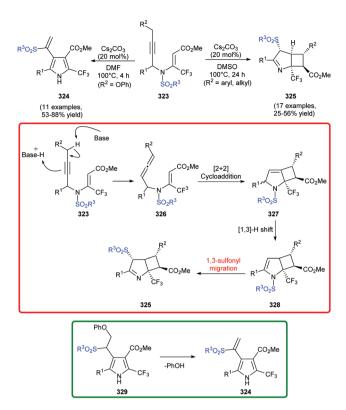
In the presence of base, namely CsCO₃, β -(arylsulfonyl) methyl pyrroles **305** were the favoured rearrangement products indicative of an alternate mechanism for the transformation (Scheme 45). Under basic conditions the propargyl group of **304** is converted to the allene intermediate **312** *via* protonation of **311**. Subsequent ring closing affords the zwitterionic intermediate **313**, with the electrophilic carbocation instead γ - to the nitrogen atom. Akin to the thermal reaction an intermolecular sulfonyl migration was elucidated, hence elimin-

ation of the sulfonyl moiety gives the ion-pair **314**, which on recombination completes the 1,4-sulfonyl migration. Isomerisation of **315** affords the β -(arylsulfonyl)methyl pyrrole **305**. The group subsequently reported that this methodology could be extended to the synthesis of 2-trifluoromethyl-4-(arylsulfonyl)methyl pyrroles **305** (R^4 = CF_3), with crossover and competition experiments indicating the likelihood of the same mechanism, however, in this instance CsOPiv was the optimal base (Scheme 45).²⁹

Using this precedent, the authors reasoned that the replacement of the alkenyl group with an acyl group could provide a route towards base-catalysed cycloisomerisation to access sulfonylmethyl-substituted oxazoles. With this in mind the authors reacted a series of N-sulfonyl propargylamides 316 in the presence of catalytic DBU affording various 5-(sulfonylmethyl)oxazoles 317 in up to 98% yield.69 The allene intermediate 318 was determined to be a key intermediate in the mechanistic cycle, while monitoring of the conversion process by HPLC highlighted the presence of a further intermediate, that despite not being isolable, the authors reasoned was the zwitterionic species 319. Key to the mechanistic cycle is a formal 1,4-sulfonyl migration which by means of crossover experiments was determined to be an intermolecular process. While not fully understood, the DBU is likely pertinent to facilitating the dissociation of the sulfonyl group (Scheme 46).

In a further extension to this methodology the group rationalised that incorporating an additional methylene group at the C-7 position of 3-aza-1,5-enynes could be utilised in complex heterocycle synthesis. Accordingly, a series of 2-azabicyclo [3.2.0]hept-2-enes 325 were synthesised *via* base-catalysed cycloisomerisation of the requisite substrates 323 in moderate yields (Scheme 47).⁷⁰ Similar to their previous studies, a 1,3-

Scheme 46 DBU-catalysed cycloisomerisation of *N*-sulfonyl propylargylamides *via* 1,4-sulfonyl migration.



Scheme 47 Base-catalysed selective synthesis of 2-azabicyclo[3.2.0] hept-2-enes and sulfonyl vinyl-substituted pyrroles from 3-aza-1,5-enynes *via* 1,3- and 1,4-sulfonyl migrations respectively.

sulfonyl migration was observed. Consistent with the results of deuterium labelling experiments the following mechanism was formulated. Deprotonation of the less sterically hindered C-7 position (compared to the more acidic C-4 proton) generates the allene intermediate 326. [2 + 2] Cycloaddition affords the bicyclic intermediate 327, which undergoes sequential [1,3]-H shift and 1,3-sulfonyl migration to afford the desired 2-azabicyclo[3.2.0]hept-2-ene 325. Interestingly, when the R^2 substituent in 323 is a phenoxy group the product formed is the vinyl-substituted pyrrole 324, with 1,4-sulfonyl migration a crucial step (Scheme 47). The mechanism for this transformation is thought to be the same as the one presented for the synthesis of β -(arylsulfonyl)-methyl pyrroles 305 in Scheme 45. Once the pyrrole 329 is formed elimination of phenol affords the vinyl group in the product 324.

The synthesis of tetrasubstituted imidazoles 333 via a twostep one-pot approach from the three-component reaction of propargyl amines 330, sulfonyl azides 332 and alkynes 441 utilising 1,3-sulfonyl migration has been described (Scheme 48).⁷¹ Initially, the keteneimine 334 is generated $in \ situ$ by means of a copper catalysed azide-alkyne cycloaddition between the alkyne and tosyl azide. Nucleophilic addition of the propargyl amine 335 to the ketenimine 334 affords the intermediate 336. In the second step, the allene 337 is generated through the deprotonation of the propargyl moiety, which subsequently undergoes a 6π -electron electrocyclic ring closure (6π -ECR) to give the zwitterionic structure

Scheme 48 One-pot synthesis of tetrasubstituted imidazoles utilising intramolecular 1,3-sulfonyl migration.

338. Finally, an intramolecular 1,3-sulfonyl migration completes the process affording the imidazole product **339.** Crossover experiments supported the intramolecular nature of the sulfonyl migration.

Following the Zhan group's seminal report regarding the reactivity of N-propargylic sulfonylhydrazones in the presence of copper catalysts, they further demonstrated that compounds of this type could undergo Lewis base catalysed reaction to give 4-sulfonyl-1H-pyrazoles 341 in moderate to good yields, with allenic sulfonamide formation and 1,3-sulfonyl migration key steps in the transformation (Scheme 49).⁷² DMAP in a mixed solvent system of tetrahydrofuran and triethylamine at 80 °C proved to be the optimal conditions for the transformation with yields up to 92% achieved. As per their initial optimisation study, the allenic sulfonamide 342 was formed exclusively at room temperature in 0.5 h indicating that it is likely a key intermediate in the cascade process. This was confirmed by reacting the allenic sulfonamide 342 under the optimised conditions with the pyrazole 341 formed in 97% yield. Notably, in the absence of DMAP no reaction occurred at room temperature indicating that both the allenamide formation and cyclisation reactions are catalysed by DMAP.

Considering this the authors proposed the following mechanism (Scheme 49). The propargylic amide moiety of **340** is transformed into the allenic sulfonamide intermediate **342** in the presence of DMAP. Nucleophilic addition of the Lewis

Scheme 49 Lewis base catalysed synthesis of 4-sulfonyl-1*H*-pyrazoles involving 1,3-sulfonyl migration.

base to the sp^2 terminus of the allene moves electron density towards the sulfonamide moiety to give the transition state 343, leading to the breakage of the N–S bond forming 344, completing an intramolecular 1,3-sufonyl migration as supported by crossover experiments. Elimination of the Lewis base affords the α,β -unsaturated imine 345 which undergoes intramolecular 1,4-addition to form the zwitterionic species 346. Finally, 1,3-hydride shift and electron transfer occur to give the rearranged pyrazole 341.

The base-mediated decomposition of a series of bicyclic amide-substituted furfuryl tosylhydrazones 347 was observed to lead to formal nitrogen to carbon 1,5-sulfonyl migration affording sulfone derivatives 348 with the furan ring remaining intact (Scheme 50).⁷³ Competition experiments suggested that the sulfonyl migration most likely proceeds in an intermolecular manner. The authors postulated that the mechanism proceeds via the base-mediated generation of the anion 349 which decomposes to the diazo compound 350 with concomitant extrusion of the tosyl group. Loss of nitrogen from the diazo moiety affords the electrophilic carbene 351, which mediates ring opening of the furan ring to generate the enynyl-ketoamide 352. Regioselective nucleophilic addition of the tosyl group to the α,β-unsaturated system of 352 regenerates the furan ring giving 353 which is converted to the final rearranged product 348 following protonation aromatisation.

Scheme 50 Observation of a 1,5-nitrogen to carbon tosyl migration to afford sulfone derivatives from furfuryl tosylhydrazones.

Li reported the diamination of the domino aryne precursor 354 74,75 with sulfonamides, affording 1,3-diaminobenzenes 356 in moderate to good yields (Scheme 51).76 Interestingly, in their investigation to ascertain the origin of the proton at the 2-position, a deuterium-labeling experiment in MeCN-d₆ indicated that the proton comes from both the solvent and the N-H bond of the amine starting material (25% deuterium incorporation, compound 358). The authors therefore rationalised that this methodology could be further applied to the synthesis of 1,2,3-trisubstituted benzenes 357 by capturing an electrophile rather than a proton. Indeed, by carrying out the reaction in the inert solvent toluene, and in the presence of K₂CO₃ and 18-crown-6 as activating agents, a formal 1,3 nitrogen to carbon sulfonyl migration of the triflyl group readily occurred in good yields. Extension of the methodology to the migration of a tosyl group proved unsuccessful.

Kakiuchi's team developed a synthesis of α-functionalised enoximes 360 via nitrosoallenes 363,77 a group of compounds pioneered by the group, 78,79 through a fluoride-mediated deprotection of the silyl moiety and tandem elimination of sulfinate from N-sulfonyl hydroxylamines 359 (Scheme 52).

Scheme 51 1,3-Sulfonyl migration via aryne precursors.

Scheme 52 Synthesis of α-substituted enoximes via fluoride mediated deprotection of nitrosoallenes.

Recombination of the sulfinate with the electrophilic moiety of the allene 363, completes a formal intermolecular 1,3-sulfonyl migration, with subsequent O-protonation affording α-sulfonyl enoximes 360 in high yields. In some instances, where all substituents on the allenylamides 359 were aryl groups,

2-isoxazolines 361 were afforded as major products derived from the cyclocondensation of the initially fomed vinylsulfones 360. The group further established that by adding an azodicarboxylate as a sulfinate scavenger that the protocol could be extended to allow functionalisation of the α -position by various nucleophiles in moderate to excellent yields (compounds 362).

The utility of triflic anhydride-mediated amide activation of a series of α -aminoamides **364** to generate tetrasubstituted imidazoles **365** in moderate yields was demonstrated to proceed *via* a mechanistically intriguing [2,3]-sigmatropic rearrangement of a sulfinate intermediate, promoting a formal 1,2-sulfonyl migration from nitrogen to carbon (Scheme 53). Quantum-chemical calculations were used to rationalise the overall mechanistic transformation. Initially, triflic anhydride

Scheme 53 Generation of tetrasubstituted 5-aminoimidazoles *via* formal 1,2-sulfonyl migration.

activation of the α-aminoamide 364 and subsequent nucleophilic addition of acetonitrile to the keteneiminium ion 366 affords intermediate 367. A 7-endo-dig cyclisation of 367 via nucleophilic attack of the sulfonamide oxygen onto the nitrilium moiety gives the intermediate 368. Cleavage of the N-S bond ensues giving the sulfinate 369 which subsequently cyclises to 370 which then undergoes a [2,3]-sigmatropic rearrangement, reminiscent of a retro-Mislow-Evans-type rearrangement, 81 to complete the formal 1,2-sulfonyl migration to give 371. Deprotonation of intermediate 371 affords the final rearranged imidazole 365 through aromatisation. While the computational analysis indicated that the 7endo-dig cyclisation is endergonic ($\Delta G_{A-B} = +14 \text{ kcal mol}^{-1}$), the subsequent cleavage of the N-S bond ($\Delta G_{B-C} = -25.8$ kcal mol^{-1}) and the [2,3]-sigmatropic rearrangement (ΔG_{D-E} = -21.4 kcal mol⁻¹) provides significant thermodynamic stabilisation.

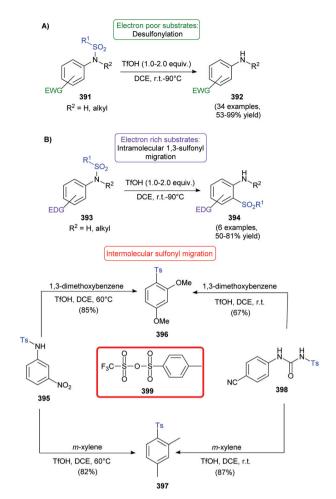
The Bharatam group reported a mechanistically interesting 1,3-sulfonyl migration from nitrogen to carbon within the pyrrole framework, the first example of such a rearrangement for this heterocycle class. They demonstrated that *N*-sulfonyl-2-arylpyrroles 373 undergo a 1,3-sulfonyl migration in pivalic acid to afford 2-aryl-3-sulfonylpyrroles 374 in moderate to excellent yields. They further realised that this sulfonyl migration could be incorporated into a one-pot tandem palladium-catalysed oxidative arylation of the 2-position of *N*-sulfonylpyrroles 372, followed by regioselective sulfonyl migration (Scheme 54).

While further clarity is required, the authors tentatively proposed an operative intramolecular nucleophilic displacement pathway based on a series of experimental observations and computational results. An intermolecular process was deemed unlikely based on crossover experiments. The addition of CsF, benzylsulfonate or benzenesulfonyl chloride to the N-sulfonylpyrroles 375, 376 and 377 afforded neither 381 or 382, which would be expected if an intimate ion-pair mechanism were operational. The sulfonyl migration occurs readily in the presence of TEMPO, suggesting that the reaction does not involve the formation of a free-radical. Interestingly, when N-tosylpyrroles 383-385 (i.e. unsubstituted, 2-substituted or 2,5-disubstituted without an aryl substituent) were heated under the optimised conditions no reaction was observed. Notably, the reaction was found to be completely inhibited in the absence of an aryl group at the 2-position, while blockage of the ortho-position of the aryl ring, as seen for the reaction of N-tosyl-2-pentafluorophenylpyrrole 389, had the same effect. Deuterium incorporation studies indicated that C-H bond breaking was unlikely to be involved in the sulfonyl migration, but that an aryl group at the 2-position is crucial for the migration to occur, which suggests an intramolecular C-2 aryl group assisted sulfonyl migration is operational for this transformation.

Javorskis and Orentas described the chemoselective deprotection of neutral and electron-deficient sulfonamides **391** under acidic conditions using trifluoromethanesulfonic acid (Scheme 55A).⁸³ Interestingly, when this deprotection strategy

Scheme 54 One-pot tandem oxidative arylation and sulfonyl migration of pyrroles; mechanistic studies supporting an intramolecular nucleophilic displacement mechanism.

was applied to electron-rich *N*-arylsulfonamides **393** a completely different reaction profile was observed, with a 1,3-sulfonyl migration preferred (Scheme 55B). Notably, mesyl, tosyl and nosyl substituents were well tolerated. An independent crossover experiment confirmed that this sulfonyl migration is most likely an intramolecular process. On the basis of the mechanism proposed for the hydrolysis of neutral and electron-deficient *N*-arylsulfonamides, which involves the formation of



Scheme 55 Chemoselective deprotection of sulfonamides under acidic conditions; observation of a 1,3-sulfonyl migration.

the mixed anhydride **399** as a side-product, the authors hypothesised that the high reactivity of the mixed anhydride **399** may facilitate an intermolecular sulfonyl group migration. Verification of this assumption was achieved *via* deprotection of the electron-deficient aniline **395** in the presence of electron-rich arenes, **1,3-dimethoxybenzene** and *m-xylene*, which afforded the sulfones **396** and **397** respectively through a Friedel–Crafts sulfonylation. In subsequent optimisation studies the *N*-sulfonylated urea **398** was determined to undergo desulfonylation much more readily, allowing access to the mixed anhydride **399** under more facile conditions.

The Hoye group reported the generation of tetrahydroquinolines **402** from hexadehydro-Diels-Alder substrates **400** through a cascade cyclisation and sulfonyl migration. For substrates **400** bearing a trimethylene linker between the alkyne and sulfonamide a newly fused piperidine ring is generated, with a formal 1,3-sulfonyl migration of a tosyl group also observed (6 examples, 83–92% yield) (Scheme 56). Variation of the sulfonyl group in certain instances led to suppression of the sulfonyl migration (Scheme 57). For mesyl substituted substrates **400**, the desulfonylated tetrahydroquinolines **406** were generated, through elimination of sulfene from the zwitter-

Scheme 56 Synthesis of tetrahydroquinolines and indolines accompanied by 1,3-sulfonyl migration or desulfonylation *via* sulfonamide-trapping reactions of thermally generated benzynes.

For p-nitrobenzenesulfonyl (Ns) groups

For strain inhibition of sulfonyl migration

Scheme 57 Mechanistic rationales for desulfonylation of mesyl groups, migration of p-nitrobenzene from nosyl group and inhibition of sulfonyl migration for indoline derivatives.

ionic intermediate **405**. Substitution with a nosyl group afforded the expected rearrangement product **410** as the major product, but its formation was accompanied by the generation of the *p*-nitrophenyl-substituted biaryl compound **409** in which sulfur dioxide has been eliminated. This variant of the Truce–Smiles rearrangement⁸⁵ is thought to take place *via ipso*-attack *para* to the nitro group in **407**. The zwitterionic intermediate **408** loses SO₂ to form **409**. Interestingly, incorporation of the shorter dimethylene tether between the diyne moiety and the sulfonamide of **403** afforded exclusively desulfonylated indolines **404** regardless of the sulfonyl moiety (mesyl and tosyl both studied) (Scheme 55). This was attributed to the increased strain in the transition state that would lead to the 5-membered zwitterion **411**, and hence the product **412** was not formed (Scheme 57).

Selvaraj and Swamy reported the generation of 6-sulfonyl substituted α-carbolines 416 via a Brønsted acid-mediated reaction of 2-sulfonamidoindolines 414 and propargylic alcohols 413, via a formal 1,6-tosyl migration (Scheme 58).86 Despite the moderate yields achieved (21-40%), and the selective formation of α -carbolines 417 via competing 1,2-aryl migration, this was the first example of the direct introduction of a sulfonyl moiety to the C-6 position of the indole framework in the absence of a metal catalyst. A crossover experiment between the conjugated sulfonamidoindoline 415 (R^1 , R^2 = Tol; $R^3 = Ph$, $R^4 = H$) and sodium benzenesulfinate did not lead to the incorporation of the sulfonyl moiety at the C-6 position of the indole system, while the migration product was acquired when 415 was heated to reflux in the presence of p-toluenesulfonic acid. Considering this, the authors suggested that the incorporated tosyl moiety has exclusively migrated from the indole framework.

In light of these observations the authors proposed the following mechanism to account for the observed tosyl migration (Scheme 59). The allenic carbocation 418 is formed *via* Brønsted acid-mediated Meyer–Schuster rearrangement of 413, which undergoes a Friedel–Crafts reaction with the indoline

Scheme 58 Regioselective tosyl group migration from indole 2- to 6-position.

Scheme 59 Formation of α -carbolines from the reaction of propargyl alcohols and sulfonamido-indoles; observation of an unexpected 1,6-tosyl migration.

414 to afford the conjugated intermediate 419. Subsequent [1,5]-hydride shift affords the tosylimine 415, which was isolable. A 6π -electrocyclic ring closure, followed by elimination of the tosylate anion gives the carbocation 421 which can undergo two divergent pathways. Firstly, and preferentially, a [1,2]-aryl shift affords 422 which upon aromatisation gives the major α -carboline product 417. Alternatively, regioselective addition of the tosylate to the C-6 position of the indole affords 423, with subsequent elimination of an aryl group affording the aromatised product 416.

Shen *et al.* reported the coupling of carboxylic acids **424** and ynamides **425** to form α -acyloxyenamides **428**, with subsequent 1,3-sulfonyl migration and Mumm rearrangement observed at high temperatures leading to imides **426** in moderate to excellent yields (Scheme 60A). In the presence of base, the functionalised imides undergo additional rearrangement to give β -keto amides **427** in moderate to good yields in a one-pot process (Scheme 60B). Crossover experiments demonstrated that the thermally induced 1,3-sulfonyl migration of the α -acyloxyenamide **428** involves cleavage of the N–S bond, generating an ion pair **429** that undergoes intermolecular rearrangement to afford the intermediate **430** (Scheme 60).

Sulfonyl-substituted trifluoroalanine derivatives 434 can be accessed in almost quantitative yields via nitrogen to carbon 1,2-sulfonyl migration from the reaction of vicinal sulfonyliminocarboxylates 432 and phosphites 433 (Scheme 61).

Scheme 60 Coupling of carboxylic acids with ynamides to afford imides and amides *via* sulfonyl migration and subsequent rearrangement.

Scheme 61 Access to sulfonyl-substituted trifluroalanine derivatives *via* 1,4-cycloaddition and 1,2-sulfonyl migration.

Monitoring the progress of the reaction by ³¹P and ¹⁹F NMR spectroscopy revealed the presence of two pentacoordinate phosphorus intermediates which were transformed over time to the iminophosphorane 434. Based on the NMR data the authors assigned the intermediate stereoisomeric phosphorane 435, generated through the 1,4-cycloaddition of 432 and 433. Accordingly, it was proposed that the transformation from the intermediate 435 to 434 involves intramolecular nucleophilic attack of the sp²-hybridised carbon on the sulfonyl moiety, which is favoured by the cumulative effect of the alkoxy and phosphoryloxy substituents, which on subsequent breakdown completes a formal 1,2-sulfonyl migration. Replacement of the ester moiety by a trifluoromethyl group completely inhibits the reaction, supporting the likelihood of intermediate 435 being generated *via* cycloaddition.

Published on 14 1398. Downloaded on 11/08/1404 09:52:44

Nitrogen to nitrogen sulfonyl migration

Michaelidou and Koutentis observed a surprising 1,4-nitrogen to nitrogen tosyl migration in their attempts to detosylate the indoles 437 under basic conditions; 3-(N-tosylamino)indoles 438 were isolated in moderate to good yields (Scheme 62).89 While several mechanistic pathways can be considered to explain the transformation, the authors favoured path B, in which base-catalysed elimination of tosylate affords the imine 440 (Scheme 62). Their preference was for the ambidentate tosylate to directly add to the indolimine at the C-2 position through the oxygen atom to afford the sulfinate ester 442. Subsequent isomerisation via either a concerted 2,3-sigmatropic rearrangement or a stepwise ion pair process affords the desired product, completing the formal 1,4-nitrogen to nitrogen tosyl migration. This proposed pathway was preferred as path C would involve a less favourable four-membered transition state to complete the 1,3-sulfonyl migration, compared to the five-membered analogue required for path B, while intermediate 442 would also be less sterically crowded than 443 at the C-2 indole position (Scheme 62). The direct addition of tosylate to the indolimine 440 (path A) was disfavoured due to electrophilicity of the nitrogen atom being offset by the conflicting local dipole and lone pair repulsion centered at that atom.

Scheme 62 Base-mediated 1,4-nitrogen to nitrogen tosyl migration of 3-amino-1-tosylindole-2-carbonitriles.

The Lewis acid mediated tandem reaction of propargyl alcohols 444 and N-sulfonylhydrazones 445 to afford dihydropyrazoles 446 in moderate to good yields via a nitrogen to nitrogen 1,2-sulfonyl migration was reported by Wang and co-workers (Scheme 63).90 Lewis acid mediated conversion of the tertiary alcohol 444 to the allenic carbocation 448 occurs by Meyer-Schuster rearrangement.91 The allenic carbocation 448 is trapped by N-sulfonylhydrazone 445 to afford the N-sulfonylallenamide 449. Cyclisation via nucleophilic addition of the internal carbon of the allene to the electrondeficient carbon of the hydrazone can be envisaged to construct the cyclised intermediate 450. The sequence is completed by intramolecular 1,2-sulfonyl migration to afford the dihydropyrazole 446 via 451. The intramolecular nature of the sulfonyl migration was confirmed by the addition of sodium p-toluene sulfinate to the standard reaction conditions, with

In 2013, the Dong group reported the regioselective synthesis of polysubstituted 4-amino- and 6-amino-2-iminopyridines 452 via copper-catalysed three-component reaction of sulfonyl azides, alkynes, and 2-[(amino)methylene]malono-

no incorporation of the tosyl group observed.

Scheme 63 Formation of dihydropyrazoles from the Lewis acid-catalysed tandem reaction of N-sulfonyl hydrazones and propargyl alcohols via intramolecular 1,2-nitrogen to nitrogen sulfonyl migration.

NC
$$\frac{NH_2}{Ar^2}$$
 $\frac{KOH}{t\text{-BuOH}}$ $\frac{NH_2}{OHN}$ $\frac{NH_2}{Ar^1}$ $\frac{NH_2}{Ts}$ $\frac{Ar^2}{Ar^2}$ $\frac{Ar^2}{Toluene}$ $\frac{Ar^2}{reflux}$ $\frac{Ar^2}{Ts}$ $\frac{Ar^2}{Ts}$ $\frac{Ar^2}{Ts}$ $\frac{Ar^2}{Ar^2}$ $\frac{Ar^2}{HO}$ $\frac{NH_2}{Ar^1}$ $\frac{NH_2}{Ts}$ $\frac{Ar^2}{Ar^2}$ $\frac{NH_2}{Ar^1}$ $\frac{NH_2}{Ts}$ $\frac{NH_2}{Ar^1}$ $\frac{NH_2}{Ts}$ $\frac{Ar^2}{Ar^2}$ $\frac{Ar^2}{Ts}$ $\frac{Ar^$

Scheme 64 Thermal rearrangement of 5-oxo-pent-3-enimidamides to 4-aminopyridines *via* 1,3-nitrogen-to-nitrogen sulfonyl migration.

nitriles. Subsequently, during examination of the synthetic potential of these substrates, the same group observed that that these pyridine derivatives readily undergo base-mediated regioselective ring opening to afford 5-oxo-pent-3-enimidamides **453** in high yields. Under thermal conditions, rearrangement involving a rare nitrogen-to-nitrogen **1**,3-sulfonyl migration affords 4-aminopyridines **454** in excellent yields (Scheme 64). It is thought that **455**′, the enol tautomer of **453**, being a polysubstituted azatriene, undergoes a 6π -azaelectrocyclisation $^{94-96}$ at high temperatures to give the **1**,2-dihydropyridine intermediate **456**. Subsequently, a **1**,3-nitrogen-to-nitrogen tosyl migration generates the aromatic 4-aminopyridine **454**, after loss of water (Scheme 64).

The thermal ring expansion of 2-sulfonylimidoyl-1-phthalimidoaziridines 457 to generate N-sulfonylimidazoles 458, involving a 1,3-nitrogen to nitrogen sulfonyl migration, in moderate to good yields has been described (Scheme 65).97 To confirm the nitrogen to nitrogen sulfonyl migration the ¹⁵Nlabelled aziridine 462 was prepared, which when heated afforded the ¹⁵N-labelled imidazole 463 with the tosyl group on the unlabelled nitrogen. By virtue of crossover experiments the sulfonyl migration was determined to be an intramolecular process. The mechanism is postulated to involve ring opening of the aziridine ring of 457, which affords the azomethine ylide 459. A 1,5-electrocyclisation to imidazoline 460 precedes elimination of the phthalimide moiety to give the sterically hindered imidazole 461. Isomerisation via an in intramolecular 1,3-sulfonyl migration affords the less sterically hindered rearranged imidazole 458.

Interestingly, while the Zhan group observed a 1,4-nitrogen to carbon sulfonyl migration for the $ZnCl_2$ -mediated reaction

Scheme 65 Thermal ring expansion of 2-sulfonylimidoyl-1-phthalimidoaziridines into *N*-sulfonylimidazoles involving 1,3-nitrogen to nitrogen sulfonyl migration.

of *N*-allenic sulfonylhydrazones **178** (see Scheme 25), ⁴² a 1,2-nitrogen to nitrogen sulfonyl migration was observed in the presence of FeCl₃ as a catalyst with the same substrate class (Scheme 66). ⁴² As with the zinc-catalysed reaction, intermolecular sulfonyl migration was supported by crossover experiments. Analogous to the ZnCl₂ catalysed reaction, the intermediate **469** is generated in the same manner from **465**, however, under this set of conditions elimination of FeCl₂ facilitates direct nucleophilic addition of the nitrogen atom to tosyl chloride completing a formal 1,2-nitrogen to nitrogen sulfonyl migration to give the rearranged pyrazole **470**.

The Beak group reported the application of the endocyclic restriction test in the evaluation of the geometries of nucleophilic substitutions at the sulfonyl moiety of aryl sulfonamides 471/472 to afford alkyl sulfonamides 473/474 *via* base-catalysed nitrogen to nitrogen migration (Scheme 67). By incorporating a short molecular tether (X = CH₂, 472) linking the nucleophilic amine and the sulfonyl leaving group, the geometry is restrained. Therefore, the simultaneous apical entering of the nucleophile and leaving of the sulfonyl moiety affording a trigonal biypyramidal transition state structure is disfavoured; hence an intermolecular migration is most likely. In contrast a long tether [X = O(CH₂)₁₁, 471] which is much more flexible would make such a transition state more likely, and as

Scheme 66 Selective synthesis of (*E*)-4,5-dihydro-1*H*-pyrazoles from *N*-allenic sulfonylhydrazones *via* 1,2-nitrogen to nitrogen sulfonyl migration.

Scheme 67 Evaluation of the geometries of nucleophilic substitutions at the sulfonyl moiety of aryl sulfonamides using the endocyclic restriction test.

Trigonal bipyramidal transition state for intramolecular sulfonyl migration

a result an intramolecular migration may become the operative pathway.

To test this assumption a double-labelled crossover experiment was performed between an equimolar mixture of unlabelled 471 and labelled 471- d_{10} at 0.1 and 0.01 M. Following isolation and analysis of the isotopic composition of the products by FABMS it was determined that at a concentration of 0.1 M the sulfonyl migration occurs in both an intra- and intermolecular manner. However, at a dilution of 0.01 M a significant increase in intramolecular substitution is observed (Scheme 67). This increase at higher dilution is consistent with a first-order (intramolecular) reaction which becomes competitive with a second-order (intermolecular) reaction which occurs more readily at higher concentrations. Repeating the double-labelled crossover experiment with the less flexible arylsulfonamides 472 and 472- d_{10} at 0.01 M determined that the sulfonyl migration is instead an intermolecular process. These results are consistent with the requirement of an almost linear arrangement of the nucleophile and leaving group at sulfur in the transition state, with a trigonal bipyramidal structure 475 with a large bond angle between the incoming and leaving groups a reasonable candidate for the transition state for such reactions.

4. Nitrogen to oxygen sulfonyl migration

4.1. Transition metal-catalysed sulfonyl migration

Boominathan et al. described the iron-catalysed cascade generation of 5H-benzo[b]carbazole derivatives 477 utilising an intramolecular 1,4-nitrogen to oxygen sulfonyl migration (Scheme 68). 99 The following mechanism was tentatively suggested by the authors. Keto-enol tautomerisation of the ketone 476 occurs, with subsequent coordination of the iron catalyst to the alkyne 478 facilitating a 5-exo-dig cyclisation and protodemetallation to afford the vinylidene intermediate 479. Keto-enol tautomerisation of this intermediate generates the enol 480, which, after 6π-electrocyclisation gives the ringclosed intermediate 481. Aerial oxidative aromatisation 100-103 gives the hydroxy 5H-benzo[b]carbazole intermediate 482, which was isolable. Coordination of the iron catalyst with the sulfonyl group of intermediate 482 gives the intermediate 483, which due to the increased electrophilicity at sulfur undergoes an intramolecular nucleophilic attack of the phenolic OH giving the 5-membered intermediate 484. Finally, the irondriven scission of the N-S bond completes the 1,4-sulfonyl migration from nitrogen to oxygen. The intramolecular nature of the sulfonyl migration was supported by the results of crossover experiments. Notably, no sulfonyl migration was observed for the reaction of the intermediate 482 in the absence of the iron catalyst, highlighting that the catalyst is required for both the cascade process and the sulfonyl migration.

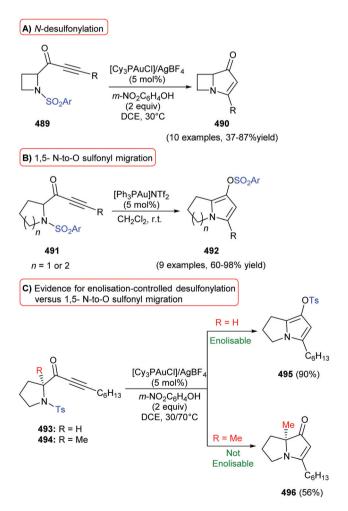
The Blanc group reported the synthesis of 1-azabicycloalkane derivatives **487** *via* a gold-catalysed desulfonylative cyclisation. Notably, *N*-sulfonyl azacyclic ynone derivatives **485** can

Scheme 68 Iron-catalysed cascade generation of benzo[b]carbazoles followed by 1,4-nitrogen to oxygen sulfonyl migration.

readily undergo two divergent reaction pathways; the pathway followed is strongly dependant on whether a suitable protic oxygen-nucleophile is added, and the ability of the substrate to enolise (Scheme 69).

In the presence of [Cy₃PAuCl]/AgBF₄ as catalyst and an excess of m-nitrophenol, the azabicyclic products 490 were generated in moderate to good yields via N-desulfonylation of the ammonium intermediate 486 (Scheme 69/70A). Expanding the scope of the reaction to more flexible substrates, which are more readily enolisable, an alternative 1,5-nitrogen to oxygen sulfonyl migration occurred in the presence of triphenylphosphine gold(I) triflimidate and in the absence of external nucleophile. Using this approach pyrrolizine or indolizine derivatives 492 were accessible in moderate to high yields (Scheme 70B). Crossover experiments unambiguously confirmed that the 1,5-sulfonyl migrations proceeds intramolecu-

Scheme 69 Overview of gold(i)-catalysed N-desulfonylation or regioselective 1,5-sulfonyl migration.



Scheme 70 Gold(i)-catalysed N-desulfonylation versus intramolecular 1,5-nitrogen to oxygen sulfonyl migration and the role of enolisation on the reaction outcome.

Scheme 71 Total synthesis of rhazinilam through gold-catalysed cycloisomerisation–sulfonyl migration and palladium-catalysed Suzuki–Miyaura coupling of pyrrolyl sulfonates.

larly. Notably, enolisation could be used as a switch between the *N*-desulfonylation pathways as demonstrated by the subjection of enolisable compound **493** and non-enolisable compound **494** to the optimised desulfonylation conditions (Scheme 70C). As expected the *N*-desulfonylation product **496** was obtained from non-enolisable **394**, while the enolisable **493** readily afforded the 1,5-sulfonyl migration product **495** in 90% yield.

The same group subsequently extended their gold-catalysed cycloisomerisation-sulfonyl migration cascade strategy to the formation of the key pyrrole ring in the total synthesis of the anticancer monoterpenoid indole alkaloid rhazinilam 500 (Scheme 71). 105 The required extension of the methodology to incorporate various N-alkylated N-sulfonyl 1-aminobut-3-yn-2proved successful, this time JohnPhosAuNTf2 proving more efficient than the Gagosz catalyst for both acyclic and cyclic substrates. Using this methodology the substrates 497 formed the desired 1,2,4-trisubstituted pyrrolyl sulfonates 498 in high yields (up to 93%) in less than 10 minutes. Crucial to the total synthesis was the subsequent palladium-catalysed coupling of the pyrrolyl tosylates and related sulfonates with boronic acids, a first-in-class example of a challenging Suzuki-Miyaura coupling of pyrrolyl sulfonates.

4.2. Non-metal-catalysed sulfonyl migration

In studies on the Diels–Alder cycloadditions of 2-methyl- and 2,3-dimethyl-1,3-butadienes with 1-arylsulfonyl-2(1*H*)-pyridones **503** as dienophiles, Fujita and co-workers observed significant amounts of the 1,3-nitrogen to oxygen sulfonyl migration by-products **505** (Scheme 72). In a later study, the Yang group observed that the thermally driven sulfonyl

Scheme 72 Generation of sulfonate by-products **505** *via* thermal 1,3-nitrogen to oxygen sulfonyl migration in Diels–Alder cycloadditions between 1-arylsulfonylpyridones and dienes.

migration of pyridones **506** can completely supress cyclo-addition when using dienophiles such as dimethyl acetylene-dicarboxylate **512**, methyl vinyl ketone **513**, ethyl vinyl ether **514** or methyl methacrylate **515**, whereas when methyl acrylate **507** is employed the cycloaddition is favoured albeit with significant amounts of sulfonyl migration product **510** also observed (Scheme 73). ¹⁰⁷

Scheme 73 Selective 1,3-nitrogen to oxygen tosyl migration of pyridones in the presence of dienophiles under thermal conditions.

Scheme 74 Synthesis of 3-sulfonyloxypyridines *via* oxidative ring expansion of α -furyl sulfonamides and formal 1,4-sulfonyl migration.

Perry and co-workers described an oxidative cascade, involving an oxidative ring expansion of α -furyl sulfonamides **516**, acid-catalysed aromatisation and a formal 1,4-sulfonyl migration from nitrogen to oxygen to generate 3-sulfonyloxypyridines **518** in moderate to excellent yields (Scheme 74). The authors propose that aromatisation of the pyridinone **517** occurs via acid-catalysed dehydration and enolisation to give the pyridinium salt intermediate **518**. Addition of triethylamine is believed to mediate the intermolecular 1,4-sulfonyl migration. When the reaction was quenched with methanol the 3-hydroxypyridine **519** was instead the major product, and sulfonyl migration product was not observed (Scheme 74).

The Smith group developed an isothiourea-catalysed, one-pot synthesis of 2,4,6-substituted pyridines 523 bearing a 2-sulfonate moiety, amenable to further transformations, from (phenylthio)acetic acid 522 and a range of α , β -unsaturated ketimines 521 (Scheme 75).

$$R^{2} \xrightarrow{\text{N}} \text{HO} \xrightarrow{\text{SPh}} \text{i) } (\text{CH}_{3})_{3} \text{CCOCI } (1.5 \text{ equiv}) \\ \text{ii)} \xrightarrow{\text{iPr}_{2} \text{NEt } (1.5 \text{ equiv})} \\ \text{521} \xrightarrow{\text{iPr}_{2} \text{NEt } (1 \text{ equiv})} \text{THF, 80°C, 16 h} \\ \text{Michael addition-lactamisation} \xrightarrow{\text{1,3-N-to-O}} \text{sulfonyl migration}$$

$$R^{2} \xrightarrow{\text{N}} \text{SPh} \xrightarrow{\text{SO}_{2} \text{Ar}} \text{Elimination}$$

$$R^{2} \xrightarrow{\text{N}} \text{SO}_{2} \text{Ar}$$

Scheme 75 Isothiourea-mediated one-pot synthesis of functionalised pyridines *via* 1,3-nitrogen to carbon sulfonyl migration.

Scheme 76 Synthesis of di-, tri-, and tetrasubstituted pyridines from (phenylthio)carboxylic acids and 2-[aryl(tosylimino)methyl]acrylates.

molecular Michael addition/lactam formation, elimination of thiophenol, and finally 1,3-*N*-to *O*-sulfonyl migration. The results of crossover studies indicated that the sulfonyl migration is consistent with an intramolecular process.

The group later extended this methodology by incorporating alkyl 2-[aryl(tosylimino)methyl]acrylates 526 as Michael acceptors to prepare 2,3,6-pyridine tosylates (Scheme 76). 110 Utilising α -substituted pheylthioacetic acids 527 in combination with Michael acceptors bearing no β-substituent also facilitated the generation of 2,3,5,6-functionalised pyridines 529. In these reactions the elimination of PhSH did not occur in either the presence of base or at elevated temperatures. To circumvent this, an additional oxidative step was added to the reaction sequence to generate the sulfoxide, which underwent elimination much more readily. Thermal conditions proved sufficient to enable the final N- to O-sulfonyl migration to afford the functionalised pyridines 529 in yields of 44-69% across three steps.

During a study relating to the sulfonylation of quinazoline-4(3H)-ones and related tetrahydrobenzothieno[2,3-d]pyrimidin-4(3H)-ones, Gütschow and co-workers observed an unexpected nitrogen to oxygen 1,3-sulfonyl migration during the cyclisation of 531 under thermal conditions; the O-sulfonylated isomer 533 was isolated as the major product, rather than the expected 532 (Scheme 77). The sulfonyl migration was further proved by heating 532 in acetonitrile and monitoring the reaction progress by HPLC. The sulfonyl migration was determined to proceed readily via first order kinetics to give the O-sulfonylated product 533. However, the heating of 534, bearing a hydrogen substituent at the 2-position, resulted in no reaction. These results support that the N-sulfonylated products are the thermodynamically favoured isomers when the 2-position is unsubstituted, while for substituted derivatives

Scheme 77 Generation of *O*-sulfonylated thieno[2,3-*d*]pyrimidines *via* unexpected thermal intramolecular 1,3-sulfonyl migration.

the *O*-sulfonylated isomers are thermodynamically favoured. Crossover experiments indicated that the 1,3-sulfonyl migration is most likely an intramolecular process.

Chi and co-workers developed a one-step, chemo-, stereoand enantioselective cascade reaction to synthesise multicyclic oxoquinoline-type heterocycles **538** *via* an N-heterocyclic carbene catalysed activation of the β sp³-carbon atom of the ester **536** as a key step (Scheme 78). ¹¹² During derivatisation of the oxoquinoline **538**, the group demonstrated that a 1,3-N- to O-sulfonyl migration proceeds readily under thermal conditions to afford the quinoline derivative **539** in 92% yield. The enantiomeric and diastereomeric ratios remained intact through the migration.

Trisubstituted pyridines **542**, bearing a 2-sulfonate moiety amenable to further synthetic manipulation, are accessible *via* a DMAP-catalysed activation of α -chloroacetic ester **540** in the presence of unsaturated imines **541** containing a tosyl protecting group that undergoes a thermal nitrogen- to oxygen 1,3-sulfonyl migration (Scheme 79). Optimal results were achieved using **541** bearing electron-withdrawing substituents,

Scheme 78 Access to oxoquinoline heterocycles *via* N-heterocyclic carbene-catalysed ester activation for selective reaction with an enone.

Scheme 79 Access to pyridines \emph{via} DMAP-catalysed activation of α -chloroacetic ester with unsaturated imines.

with a significant reduction in yield observed when electron-donating substituents were incorporated. Imines containing heterocyclic moieties also readily participated in the reaction, however the use of α -branched chloroacetates with an α -alkyl substituent completely inhibited the reaction pathway. The mechanism postulated involves the reaction of the DMAP-activated α -chloroacetic ester **540** with the unsaturated imine **541** leading to the lactam intermediate **543**. E2-elimination affords the adduct **544** which undergoes N- to O-sulfonyl migration at elevated temperature to give the desired product **542**. It is likely that the driving force for the sulfonyl migration is the aromatisation of the heterocyclic ring.

5. Oxygen to carbon sulfonyl migration

5.1 Photoinduced sulfonyl migration

The photoinitiated radical fragmentation and rearrangement of vinyl tosylates resulting in efficient formation of aromatic and aliphatic β -ketosulfones **546** and **549** was reported by Xie *et al.*¹¹⁴ Aromatic vinyl tosylates **545** and aliphatic vinyl tosylates **548** both underwent these visible-light promoted transformations with excellent and moderate to good yields respectively, albeit with different photoinitiators in each instance. Eosin B **547** proved optimal for the aromatic series, while 9-fluorenone **550** was preferable in the case of aliphatic vinyl tosylates (Scheme 80).

A trapping experiment, using the radical scavenger TEMPO, revealed complete suppression of the reaction, and 99% recovery of the starting material, indicative of a radical mechanism. Crossover experiments indicated that the 1,3-sulfonyl migration is an intermolecular process. A photoinduced chain mechanism was deemed likely as a result of quantum efficiency calculations, while DFT calculations for the initiation process were compatible with energy transfer between the initiator and the vinyl tosylate substrate. Considering this, the putative mechanistic pathway was presented (Scheme 81). Homolytic cleavage of the O–S bond in the vinyl tosylate 551 occurs through energy transfer from the

Scheme 80 Photoinduced rearrangement of vinyl tosylates to β -ketosulfones *via* 1,3-sulfonyl migration.

hv Initiation Energy Transfer Propagation Propagation
$$R^1$$
 SO_2R^3 SO_2R^3 SO_2R^3 R^2 SO_2R^3 R^2 SO_2R^3 R^2 SO_2R^3 R^2 R^2

Scheme 81 Proposed mechanism for the photoinduced rearrangement of vinyl tosylates to β -ketosulfones *via* 1,3-sulfonyl migration.

excited photosensitiser, to generate an enol radical 552 and a sulfonyl radical. The sulfonyl radical adds to another vinyl tosylate 551 affording the intermediate 553, which on elimination of a further sulfonyl radical affords the β -ketosulfone 554 and sulfonyl radical for the subsequent reaction cycle.

The Feng group reported an iridium-catalysed visible-light promoted oxo-sulfonylation of ynamides 555 with sulfonic acids 556, leading to functionalised α -sulfonylated amides 557 in moderate to good yields (Scheme 82). Generally, ynamides bearing an electron-rich aromatic ring delivered the

Scheme 82 Visible-light promoted oxo-sulfonylation of ynamides with sulfonic acids.

desired products in good yields, while substrates with an electron-deficient aromatic ring gave lower yields. Aryl halides, fused aromatics and heterocyclic substituents were well tolerated, while both electron-rich and electron-poor alkyl and aromatic sulfonic acid derivatives could be incorporated to furnish a diverse range of α -sulfonylated amides.

In order to garner information regarding the mechanism the authors carried out a series of control experiments (Scheme 83). Toluenesulfonic acid readily reacted with the ynamide 559 to give the vinyl tosylate 560 in almost quantitative yield (Scheme 83A). This vinyl tosylate could be converted into the α -sulfonylated amide 561 under the standard reaction conditions in high yields, confirming its role as an intermediate in the tandem reaction pathway (Scheme 83B). Performing the reaction in the presence of TEMPO, a radical scavenger, completely inhibited the reaction, supporting the generation of a radical intermediate in the rearrangement step

Scheme 83 Control experiments supporting a radical mediated oxygen to carbon sulfonyl migration in the synthesis of α -sulfonylated amides.

(Scheme 83C). A radical mechanism was additionally confirmed through the reaction of **560** with dilauroyl peroxide as a radical initiator in place of the iridium photocatalyst **558** which also led to **561**, albeit in a significantly lower yield (Scheme 83D). Crossover experiments indicated that the sulfonyl migration was an intermolecular process.

In further investigation of the working mode of the photocatalyst (single electron transfer vs. energy transfer), cyclic voltammetry experiments indicated that the vinyl tosylate intermediate 560 has a higher reduction potential than the excited state of the photocatalyst (PC*), indicating that a single electron transfer cannot occur under the standard conditions. Stern-Volmer quenching experiments confirmed that the vinyl tosylate 560, and not the ynamide 559 or tosic acid, could quench the excited photocatalyst. A DFT calculation of the triplet energy of 560 was calculated to be 100.1 kJ mol⁻¹, a value that is within the range expected to be accessed by the iridium photocatalyst (250.3 kJ mol⁻¹) as a triplet sensitiser. These results in combination support an energy transfer photocatalyst's working mechanism for the Furthermore, a light on/off experiment confirmed that the reaction requires continuous irradiation to achieve reaction completion, while the quantum yield of 10.0 for the rearrangement of 560 to 561 indicated a radical chain propagation mechanism.

In light of these findings the following mechanism was proposed (Scheme 84). Electrophilic addition of sulfonic acid to ynamide 555 gives vinyl sulfonate 562 in a regioselective manner. Subsequently, activation of the sulfonate 562 occurs through the energy transfer process from the excited photocatalyst (PC*). Homolytic cleavage of the C–S bond of the activated vinyl sulfonate 562 generates the sulfonyl radical and enol radical 563. Selective addition of the sulfonyl radical to

R²SO₂OH 556 X N So₂R² hv So₂R² PC

Energy Transfer
PC

R¹

Ferror R²SO₂ R²

R²O₂S

Ferror R¹

R²O₂S

Ferror R¹

R²O₂S

Scheme 84 Proposed mechanism for the visible-light-promoted oxosulfonylation of ynamides with sulfonic acids.

the electron rich alkene group of vinyl sulfonate **562** leads to the α -sulfonylated amide **557** *via* β -scission of the radical intermediate **564**, which regenerates a sulfonyl radical enabling a radical chain propagation.

5.2. Thia-Fries rearrangement

The thia-Fries rearrangement is a sulfur based sub-class of the well-known Fries rearrangement, in which aromatic sulfonates or sulfonanilides rearrange to afford *ortho-* or *para-*substituted hydroxy or amino sulfones respectively. The rearrangement, named after Karl Fries, who published the seminal report in 1908, has subsequently been demonstrated under cationic, anionic and radical/light-induced conditions. Notably, over the last 20 years the most significant highlight in this area was the development of the anionic-thia Fries rearrangement for sulfonates at both aromatics and organometallics. An overview of the anionic Fries rearrangement, including the thia-Fries subclass, was recently undertaken by Korb and Lang. This section will further describe anionic and non-anionic thia-Fries rearrangement.

5.2.1. Anionic thia-Fries rearrangement. While attempting the palladium-catalysed cross-coupling of 1-chloro-2-naphthalene triflate 565 with a pyridyl zinc halide, generated in situ using LDA/ZnCl2, a notable side product was identified as the ortho-hydroxyarylsulfone 566. This result, reported by Lloyd-Jones in 2003, described the first example of an anionic thia-Fries rearrangement of aryl triflates. 117 Further optimisation revealed that it is in fact LDA, and hence a base, that mediates the rearrangement, with the ortho-hydroxyarylsulfone 566 obtained in 64% yield (Scheme 85). Aryl triflates bearing moderately electron-withdrawing groups, particularly ortho to the triflate, readily underwent the thia-Fries rearrangement, whereas analogues containing electron-donating groups at the ortho-position favoured aryne generation. Notably, solvent effects are crucial in controlling the reaction outcome. For example, o-chlorophenyl triflate 567 exclusively affords the thia-Fries rearrangement product 570 in the presence of THF, however, the use of DIPA which is an effective aryne scavenger gives a mixture of both the mono- and bis-anilines 568 and 569 (Scheme 85). However, even in instances in which excess DIPA is not employed one must contend with the generation of DIPA from the deprotonation of the aryl triflate.

Scheme 85 Discovery of the first anionic this-Fries rearrangement.

Scheme 86 Computed relative energies (in kcal mol⁻¹) for the elimination or thia-Fries rearrangement of **571** in a THF continuum.

In order to rationalise the reactivity of aryl triflates towards thia-Fries rearrangement or elimination, Lloyd-Jones and coworkers carried out computational studies and labelling studies. 118 Gas phase and single point calculations, including a continuum description of the THF solvent, were performed for the pathways leading to the rearrangement and elimination of [C₆H₄OTf]⁻ (Scheme 86). The sulfonyl migration was predicted to be a highly exothermic process (62.0 kcal mol⁻¹), while a 1,2-oxethietane intermediate 576 could not be located. Instead, the sulfonyl migration was observed to proceed via a single and early transition state 574 in which the C-S and S-O bond distances shorten and lengthen respectively, relative to the reference starting material 571. The significantly lower energy of the rearranged phenolate 575 relative to the reference substrate 571 excludes retro-Fries rearrangements as an operative mechanism. Alternatively, the loss of triflate is predicted to be only mildly exothermic (10.2 kcal mol⁻¹). Interestingly, the similar energies of the transition states 572 and 574 indicate that a thermodynamic rather than a kinetic process may be operational, due to reversible elimination of triflate.

To test whether reversible addition/elimination of the triflate group to the aryne was occurring, ¹⁸O-labelled triflate 577 was reacted under the standard conditions, however, only ¹⁸O-labelled phenol 578, generated through the expected anionic thia-Fries rearrangement was obtained, with no evidence for the ¹⁸O/¹⁶O scrambling product 579 that would be expected *via* a reversible process (Scheme 87a). A crossover experiment between ²H-lablelled triflate 580 and ³⁴S-labelled triflate 581 did not generate any of the ²H/³⁴S-lablled phenol 584 anticipated if an intermolecular mechanism was operational, hence the sulfonyl migration was deemed to be an intramolecular process (Scheme 87b).

The potential for a sulfinite based mechanism, in which one could consider an intramolecular attack of an anionic triflate at the sulfonyl oxygen to afford a trifluoromethylsulfinite 586, *via* intermediate 585, was also investigated as a plausible route (Scheme 88). As organosulfinites undergo isomerisation to sulfones *via* heterolytic ion-pair recombination, it

Scheme 87 (a) ¹⁸O-Scrambling experiment eliminating reversible aryne formation mechanism; (b) crossover experiment indicating an intramolecular sulfonyl migration.

Scheme 88 Evidence disconfirming the likelihood of a sulfinite-based mechanism for the anionic thia-Fries rearrangement.

would be expected that isomerisation would readily occur for a trifluoromethylsulfinite and a phenolate 586.¹¹⁹ However, anionic thia-Fries rearrangement of the deuterium labelled 588 afforded exclusively 589, with no evidence for isomerisation effectively ruling out the possibility of a sulfinite-based mechanism.

Notably, while both the elimination and rearrangement processes nominally produce diisopropylamine (DIPA) from the reaction between the aryl triflate and LDA, the concentration of free base can have a significant impact on the course of the reaction outcome due to the strong complexation of the DIPA to the lithium cation in the rearranged product as well as its consumption by the aryne to produce ArN(iPr)₂. Interestingly, carrying out the reaction of **588** in the presence of DIPA-free LDA affords the rearrangement product **589** in 30% yield and the aryne-derived amine **590** in 44% yield (Scheme 89). Repeating the reaction in the presence of **1,3**-diphenylisobenzofuran (DPIBF), an aryne trapping reagent, affords the naphthyne-DPIBF cycloadduct **591** in 99% yield with no thia-

Scheme 89 Effect of concentration of free DIPA on anionic thia-Fries rearrangement and aryne generation.

Fries rearrangement product 589 observed as a result of DPIBF bypassing DIPA consumption which leads to a rise in DIPA concentration (Scheme 89). Therefore, the presence of a metalated compound, required for aryne generation, is favoured when the lithium cation is stabilised by the amine. The amine, in this instance DIPA, can be formed through either the deprotonation process or by being employed in excess. This finding, that DIPA catalyses aryne formation, is in agreement with Huisgen and Sauer's earlier work on the kinetics of arvne formation from Ar-X which highlighted that HNR2 catalyses ortho metalation efficiently. 120

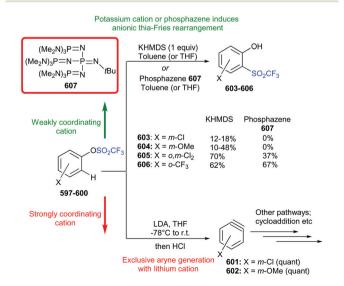
As a result of these findings two disparate mechanistic pathways are operational for the reaction of aryl triflates with LDA, namely an anionic pathway leading to anionic thia-Fries rearrangement and a DIPA-catalysed metalation pathway leading to aryne generation (Scheme 90). 118 In the first instance, the anion 593 which can adopt two conformations of similar energies, plays a key role in the sulfonyl group migration. For unsubstituted aryl triflates (X = H) the cisoid conformation that is required for rearrangement is slightly higher in energy (+0.4 kcal mol⁻¹) than its transoid counterpart, however this can be overcome through the incorporation of electron withdrawing moieties ortho (and para) to the triflate group which inhibits competing metalation. In contrast, meta substituents actively destabilise the aryl anion 593 which favours elimination to 596 via 595, while the employment of excess DIPA further facilitates elimination to generate the aryne 596, with a concomitant decrease in the thia-Fries rearrangement product 594.

In light of the clear evidence that metalation favours aryne generation the authors postulated that the use of more weakly coordinating metal cations, such as the larger potassium cation, would instead favour rearrangement. As such, by using

Scheme 90 Proposed mechanistic pathways for the reaction of aryl triflates with LDA; anionic thia-Fries rearrangement and aryne generation.

potassium hexamethyldisilazane (KHMDS) as base in place of LDA, the aryl tosylates 597-600 which had previously exclusively afforded aryne-based products with LDA (as well as LiHMDS) afforded the thia-Fries rearrangement products 603-606 albeit in low to moderate yields, highlighting the key role that the metal cation plays in distinguishing between the two pathways (Scheme 91).118 In certain instances, the nonionic base phosphazene 607,121 proved suitable in inducing thia-Fries rearrangement however stringently dry conditions are required or competing side reactions can occur.

Notably, Lloyd-Jones and co-workers have successfully utilised the anionic-thia Fries rearrangement in the development



Scheme 91 Inhibition of aryne pathway via use of less coordinating metal cations; anionic thia-Fries rearrangement in the presence of KHMDS and phosphazene 607.

Scheme 92 Regioselective synthesis of heteroaryl triflones via LDAmediated anionic thia-Fries rearrangement.

of sulfone containing BINOL and BINAPHOS ligands for use in catalytic enantioselective indium-mediated allylations¹²² and palladium-catalysed hydrophosphorylations. 123

The first example of the application of the anionic thia-Fries rearrangement in heteroaromatic compounds was reported by Shibata and co-workers in 2012. 124 Using LDA as base a series of rearranged nitrogen containing heterocycles including oxindole 608, pyrazolone 609, quinoline 610 and pyridine triflones 611 was synthesised in moderate to good yields, with all products existing as the enol-tautomer rather than the amido form as confirmed by NMR studies (Scheme 92). This transformation proceeds in higher yields than those in the pioneering work of Lloyd-Jones for the rearrangement of phenyl and naphthyl triflates. 117

In their studies on the reactivity of 3-triflyloxybenzyne 616, the Hosoya group observed that in the absence of an arynophile, 616 reacted with the solvent rather than dimerizing (Scheme 93). 125 Thus the reaction in THF afforded the chlorobutoxy triflone 619. The reaction proceeds by regioselective nucleophilic addition of THF to the benzyne 616 to afford the zwitterionic intermediate 617, which subsequently undergoes anionic thia-Fries rearrangement to give 618. Ring opening of the oxonium ion via addition of chloride from the Grignard reagent affords the rearranged triflone 619 upon protonation of the phenoxide anion (Scheme 93). The methodology was amenable to variation of the nucleophile; rearranged zwitterionic aryl triflones 613 and 614 were generated through regioselective nucleophilic addition of PPh₃ and PhS₂ to 3-triflyloxybenzyne 616, while Bn₂S afforded the non-ionic triflone 615, following debenzylation.

To broaden the applicability of 3-triflylbenzyne, the group further explored the reactivity in Diels-Alder cycloadditions of 3-triflyloxyarynes bearing an additional functionalisable group, such as a halide. 126 However, their initial attempt to generate the cycloadduct 621 from the triflate 620 and furan did not proceed efficiently using the previously optimised conditions, with a similar amount of the triflone 622 being generated via competing anionic thia-Fries rearrangement (Table 1, entry 1). The authors, therefore, screened for conditions to try to inhibit the thia-Fries rearrangement pathway. A significant improvement was attained by utilising non-polar solvents such

Scheme 93 Generation of aryl triflones via thia-Fries rearrangement.

as hexane and toluene, with further increases in yield and selectivity observed by increasing the amount of activator and decreasing the reaction temperature (Table 1, entries 6 and 7). While not fully understood, it is likely that the non-polar solvents destabilise the anionic intermediate required for thia-Fries rearrangement, while enhancing the Mg-C bond formation which facilitates the elimination to the aryne.

In a subsequent publication the Hosova group reported the isolation of the thia-Fries rearrangement by-product 626 in significant amounts (up to 32%) when using the 5,6-thienobenzyne precursor 624 in cycloaddition reactions (Scheme 94). 127 It is likely that this side reaction is facilitated by the strongly electron-withdrawing trifluoromethyl group, which contributes by stabilising the anionic intermediate generated via the iodine-magnesium exchange reaction. Interestingly, the analogous cycloadditions of 6,7-thienobenzyne precursors under the same conditions proceed with significantly greater selectivity, with no evidence for thia-Fries rearrangement observed.

In 2013, Greaney and co-workers reported a tandem anionic thia-Fries rearrangement-cyclisation of 2-(trimethylsilyl)phenyl trifluoromethanesulfonate benzyne precursors 629 to form phenoxathiine-dioxide derivatives 630 in moderate yields as single regioisomers (Scheme 95). 128 The phenoxathiine derivatives were only afforded when halogen substituents were present ortho to the triflate moiety, a result which is in line with Lloyd-Jones' earlier work that demonstrated that electronwithdrawing groups ortho to the sulfonate are crucial for anionic thia-Fries rearrangement. 117 However, in this instance the halogenated triflates 629 can undergo both thia-Fries rearrangement and aryne generation in the same reaction and further react together in a tandem manner. This observation is in direct contrast with Lloyd-Jones' observation that the two

Table 1 Influence of solvent on inhibition of thia-Fries rearrangement

Entry	TMSCH ₂ -metal (equiv.)	Solvent	Temp (°C)	Yield 621 (%)	Yield 622 (%)	621:622
1	TMSCH ₂ MgCl (1.5)	Et ₂ O	-30	44	44	_
2	TMSCH ₂ Li (1.5)	Et ₂ O	-30	32	24	57:43
3	TMSCH ₂ MgCl·LiCl (1.5)	Et ₂ O	-30	25	19	57:43
4	TMSCH ₂ MgCl·LiCl (1.5)	Toluene	-30	54	4	93:7
5	TMSCH ₂ MgCl·LiCl (1.5)	<i>n</i> -Hexane	-30	67	7	91:9
6	TMSCH ₂ MgCl·LiCl (2.4)	Toluene	-50	70	4	95:5
7	TMSCH ₂ MgCl·LiCl (2.4)	<i>n</i> -Hexane	-30	83	4	95:5

Scheme 94 [4 + 2] cycloadditions of 5,6-thienobenzyne precursors; competing anionic thia-Fries rearrangement of the phenylene ring.

626 (32%)

processes are orthogonal to each other at low temperatures. Considering this, the following mechanism was postulated (Scheme 95): C–Si bond cleavage is mediated by treatment with fluoride, which induces an anionic thia-Fries rearrangement of the resulting anion 631 to form the phenolate 632. The aryne 633, generated through the fluoride mediated elimination of the triflate and trimethylsilyl moieties, reacts with the phenolate 632 to generate the anionic intermediate 634. Cyclisation of 634 *via* nucleophilic addition of the phenyl anion onto the trifluoromethane sulfonate moiety affords the phenoxathiine-dioxide product 630. The dual mode of the triflate starting materials 629 with respect to anionic thia-Fries

Scheme 95 Formation of phenoxathiine-dioxide derivatives *via* tandem anionic thia-Fries rearrangement-cyclisation of 2-(trimethylsilyl)phenyl trifluoromethanesulfonate benzyne precursors.

rearrangement and aryne formation in the one pot was supported *via* crossover experiments.

5.2.2. Remote anionic thia-Fries rearrangement. The NaH-mediated remote anionic 1,5-thia-Fries rearrangement, which constitutes a formal 1,5-sulfonyl migration from oxygen to carbon, allowing the regioselective synthesis of 2-(2-hydroxyphenyl)-3-indole triflones and 3-sulfonyl indoles 636 was described by the Shibata group (Scheme 96). Notably, this first example of a remote anionic thia-Fries rearrangement tolerated both electron-withdrawing and electron-donating groups at various positions on the phenyl ring, while also tolerating the presence of bromo- and chloro-substituents due to the reaction not requiring strong alkyllithium bases. Strong base is not required for this reaction because, unlike conventional anionic Fries rearrangement, which is initated by a carbanion, this method is initiated by a nitranion.

No migration was observed with either *N*-methylindole **639** or 3-methylindole **640** when subjected to the optimised con-

Scheme 96 Remote anionic Fries rearrangement of sulfonates: regioselective synthesis of indole triflones.

ditions, while competition experiments demonstrated the likelihood of an intramolecular 1,5-sulfonyl migration. Therefore, the following mechanism was proposed (Scheme 96). Deprotonation of 635 by NaH affords the nitrogen anion 637, which undergoes intramolecular 1,5-sulfonyl migration to give intermediate 638, which following protonation and tautomerisation affords the rearranged indole 636.

The Shibata group also demonstrated the synthesis of a series of vinyl triflones 642 in a stereoselective manner via remote anionic thia-Fries rearrangement from a series of gemdibromovinyl substrates (Scheme 97).130 Employing two equivalents of n-BuLi, the requisite substrates 641 afforded exclusively E-vinyl triflones 642 in moderate to good yields, via 1,5-triflyl migration, with both electron-donating and electronwithdrawing substituents on the aryl ring well tolerated. The triflyl moiety was crucial to the transformation; no migration observed for the analogous methanesulfonates. Interestingly, the indole derivative 643 also readily underwent rearrangement, and is the first example of an anionic 1,6migration. The methodology could also be utilised in a tandem reaction with methyl formate as an electrophilic partner which led to cyclisation after the rearrangement, affording heteroaryl triflones 646 in moderate yields.

Based on these results the authors postulated that lithium-bromine exchange of the substrate **641** and *n*-BuLi affords the anion **647** (Scheme 98), which undergoes remote anionic thia-Fries rearrangement, induced by the electron-withdrawing nature of the trifluoromethyl group, to afford the phenolate **648**. The presence of the electron-withdrawing triflyl moiety activates the remaining bromine in **648** to undergo lithium-bromine exchange with the second equivalent of *n*-BuLi to

Scheme 97 1,5- and 1,6-triflyl migration of *gem*-dibromovinyl compounds.

Scheme 98 Proposed mechanism for the 1,5-triflyl migration of *gem*-dibromovinyl compounds.

afford the intermediate **649** which rapidly isomerises to the more thermodynamically stable intermediate **650**. This isomerisation explains the stereoselective generation of the *E*-vinyl triflones **642** and the cyclised products **646**.

5.2.3. Anionic thia-Fries rearrangement of organometallic complexes. In 2006, as part of their efforts to generate (η^6 -aryne)chromiumtricarbonyl complexes, the Butenschön group studied the reactions of chromiumtricarbonyl complexes of arene triflates. They were surprised to find that none of the expected product 652 was observed under standard basic conditions. Instead, they uncovered the first examples of anionic thia-Fries rearrangement of organometallic substrates to afford a series of *ortho*-(trifluoromethylsulfonyl)phenol chromium complexes 653 in high yields (Scheme 99). Notably, the reaction tolerates both electron-rich and *ortho*-substituted substrates 651 that would normally be expected to favour elimination of the triflate. The preference for the thia-Fries rearrange-

Scheme 99 First example of an anionic thia-Fries rearrangement at organometallics.

ment is likely attributable to the electron-withdrawing effect of the chromiumtricarbonyl moiety, which is better satisfied by the formation of the rearranged phenolate. The methodology was subsequently applied to the structurally complex estrone **654** (Scheme 99). Under standard basic conditions regioselective thia-Fries rearrangement occurred to afford the phenolic estrone complex **655** in 77% yield. Iodine-mediated decomplexation afforded the desired steroid **656** in 97% yield.

In an attempt to compensate for the highly electron-withdrawing tricarbonylchromium moiety, which was believed to be the main factor inhibiting aryne generation, the authors hypothesised that the introduction of further strongly electrondonating groups may generate more electron-rich triflates more susceptible to elimination. 132 Therefore, the triflate 657, bearing two methoxy substituents, was prepared and subjected to basic conditions in the presence of 2,5-dimethylfuran as trapping reagent (Scheme 100). The desired cycloadduct 658 was isolated in quantitative yield demonstrating the suitability of triflate 657 to undergo base-mediated triflate elimination. On the other hand, the analogous reaction of the tricarbonylchromium complex 659 instantaneously afforded the anionicthia Fries rearrangement product 660 exclusively, and upon acylation the product 661 was isolated in quantitative yield. As part of the same investigation, two (triphenylphosphine)dicarbonylchromium complexes, 662 and 663 were investigated. Despite the fact that it has been shown that replacement of one carbonyl ligand by triphenylphosphine reverses the electron-withdrawing effect of the chromium moiety, 133 when 662 or 663 were treated with LDA in THF at −78 °C in the presence of trapping reagents, the anionic thia-Fries rearrangement was again the exclusive pathway, leading to 664 and 665 in almost quantitative yields (Scheme 100). 132 As a result it can be con-

Scheme 100 Attempted compensation of the electron withdrawing effect of the tricarbonylchromium complex; no inhibition of the anionic thia-Fries rearrangement observed.

cluded that electronics do not exert a significant effect on the outcome of the reaction, with organochromium complexes favouring anionic thia-Fries rearrangement.

In a further attempt to favour aryne formation, the Butenschön group attempted to use ferrocene derivatives in lieu of chromium complexes, hoping that the more electronrich ferrocene derivatives might circumvent the problems encountered when using the highly electron-withdrawing tricarbonylchromium group. However, in spite of the more electron-rich substrate, ferrocenyl triflate 666 underwent a highly efficient anionic thia-Fries rearrangement instead of triflate elimination (Scheme 101). Lowering the temperature of the reaction from -78 °C to as low as -117 °C did not lead to any formation of ferrocyne product. This was the first example of an anionic thia-Fries rearrangement in a five-membered ring. The remarkable efficiency of the transformation was further

Scheme 101 Attempted use of electron-rich ferrocenyl triflate derivatives to achieve ferrocyne formation; first example of anionic thia-Fries rearrangement in a five-membered ring.

Scheme 102 Double anionic thia-Fries rearrangement of 1,1'-ferrocenediyl ditriflate **673**.

demonstrated by the reaction of the more electron-poor ferrocene triflate **670**, which also readily underwent rearrangement in quantitative yields (Scheme 101).

Interestingly, when 1,1'-ferrocenediyl ditriflate 673 was treated with 2.2 equivalents of LDA at -78 °C a double anionic thia-Fries rearrangement occurred giving 676 in 85% yield. 134 Although this reaction could yield two diasteromeric rearrangement products, *meso*-676 and *rac*-677, only the *meso* diastereomer was observed, *i.e.* the reaction proceeds with complete diastereoselectivity (Scheme 102). To further probe this exceptional diastereoselectivity the authors attempted to obtain the single anionic thia-Fries rearrangement product 675 by instead using 1 equivalent of LDA. However, the reaction gave an almost equimolar mixture of the starting material 673 and the double rearrangement product 674 after acylation, highlighting that the rate of the second anionic thia-Fries rearrangement is significantly faster than that of the first (Scheme 102).

In order to probe the effect of *ortho*-lithiation on the reaction outcome the authors prepared 2-(trimethylsilyl)ferrocenyl triflate **678** for comparison. Upon treatment with TBAF in acetonitrile at 25 °C, exclusive anionic thia-Fries rearrangement occurred immediately to afford **679** in 84% yield (Scheme 103).¹³⁵ Metalation of the *ortho*-position was con-

Scheme 103 First example of anionic thia-Fries rearrangement induced by *ortho* metalation.

sidered as an alternative to anion formation, hence the tributylstannyl compound **680** was treated with *n*-BuLi to induce metal exchange to the respective lithio compound. However, exclusive anionic thia-Fries rearrangement was again observed affording **679** in quantitative yield (Scheme 103). This was described as the first example of an anionic-thia Fries rearrangement induced by *ortho* metalation.

In light of the anionic thia-Fries rearrangement occurring for ferrocenyl triflates upon both ortho deprotonation as well as ortho metalation, the authors sought to determine how electron-rich the ferrocenyl triflate can be tailored to still allow the reaction. Even the more electron-rich methoxy derivative 681 also afforded exclusively the anionic-thia Fries rearrangement product 683 in quantitative yield (Scheme 104). 135 Therefore, it is clear that excess electron density in the ferrocene system does not prevent rearrangement. Sterics were hypothesised to be a possible factor that may favour ferrocyne formation via elimination, however, treatment of the trimethyl derivative 684 under standard basic conditions in the presence of anthracene as cycloaddition trapping reagent afforded exclusively the anionic thia-Fries rearrangement product 685 (Scheme 104). Notably, while triflate elimination is the most prominent method for the generation of arynes, there is little correlation between aromatic systems and their analogous organometallic derivatives. As a result, the procurement of organometallic arynes remains an ongoing research pursuit.

Prior to Lloyd-Jones' discovery of the anionic thia-Fries rearrangement in 2003, the Minami group observed an oxygen

Scheme 104 Exclusive anionic thia-Fries rearrangement of ferrocenyl triflates despite incorporation of electron-donating groups.

Scheme 105 O- to C-1,3-sulfonyl migration in iron-complexed nonaromatic cyclohexadienes.

to carbon 1,3-sulfonyl migration of both phosphonates and sulfonates in cyclohexadiene systems (Scheme 105). 136 Notably, iron coordination to the 1,3-diene with either a phosphate or sulfonate moiety allows ortho deprotonation of the position, which facilitates the overall 1,3-sulfonyl migration. The rearrangement proceeds rapidly and efficiently under basic conditions with 689 and 690 afforded in high yields after five minutes. However, when the migrating group contained acidic protons, e.g. a methanesulfonyl group, no migration was observed, and the iron dienol complex 691 was favoured instead. Crossover experiments for the phosphonate derivatives determined that the migration is likely an intramolecular process.

5.2.4. Non-anionic thia-Fries rearrangement. While the last two decades have seen considerable attention devoted to the development of the understanding of the anionic thia-Fries rearrangement, significantly less attention has been afforded to thia-Fries rearrangements via metal catalysis, microwave or photoirradiation techniques.

Moghaddam and Das almost simultaneously reported the high yielding thia-Fries rearrangement of aryl sulfonates 692 in the presence of anhydrous aluminium trichloride under microwave conditions (Scheme 106A). 137,138 Moghaddam's method involved using an AlCl₃-ZnCl₂ supported on silica gel in conjunction with microwave irradiation with similar efficiencies and yields. Das also demonstrated that the methodology could readily be used for the analogous reaction of aryl sulfonanilides with similar efficiencies and yields obtained. When Moghaddam et al. later attempted to extend their methodology to incorporate aryl benzylsulfonates, a pseudo-thia-Fries rearrangement was instead observed, with the ortho- and para-benzylated phenols 694, and the dibenzylated phenols 695 isolated. 139 Unlike the photochemical thia-Fries rearrangement, which is known to proceed via a radical mechanism, the authors postulated that the reaction occurs via initial heterolytic cleavage of the O-S bond to generate a phenolate and a benzylsulfonyl cation which decomposes by elimination of SO₂ to afford the active benzyl cation (Scheme 106). The cationic mechanism was supported by the capture of the hypothesised benzyl cation by the cation scavenger mesitylene to afford 702. Furthermore, no evidence for the presence of the benzyl radical coupling product diphenyl-

Scheme 106 Non-anionic thia-Fries rearrangement.

ethane 703 was observed, also supporting the cationic mechanism. Benson et al. subsequently reported the AlCl₃-mediated thermal thia-Fries type rearrangement of aryl sulfamates 696 to generate aryl sulfonamides 697 and 698 in moderate to high yields (Scheme 106B).140

Sharghi et al. reported the use of Al₂O₃/MeSO₃H, ¹⁴¹ and subsequently graphite/MeSO₃H¹⁴² mixtures as novel reagents for a solvent-free thermal thia-Fries rearrangement of aryl tosylates 704 to afford hydroxy aryl sulfones in high yields (Scheme 107A). An intermolecular ionic mechanism was presented by the authors, with the presence of a sulfonyl cation intermediate, confirmed via trapping of the cation with electron-rich m-xylene. Furthermore electron-poor meta- and paranitro derivatives 704 failed to undergo rearrangement providing further evidence for the proposed mechanism.

Crevatín et al. reported the photo-thia-Fries rearrangement for a series of 9H-carbazol-2-yl-sulfonates 707 to afford the

Scheme 107 Non-anionic thia-Fries rearrangement.

arysulfones 708 709 respective alkyland and (Scheme 107B). 143 Under photoirradiation, regardless of reaction solvent utilised (MeCN, MeOH, benzene, cyclohexane), the ortho-rearranged products 708 and 709 were obtained in a molar ratio of approx. 2:1, with 708 always being the favoured isomer. Semi-empirical and ab initio optimisation of the 2-hydroxy-9H-carbazole radical were used to rationalise the regioselectivity of the reaction, with a slightly higher charge density observed at C(1) when compared to C(3). Furthermore, hydrogen bonding with the carbazole N-H may assist with the migration to C(1); this is not possible for rearrangement to C(3) due to geometry.

Oxygen to oxygen sulfonyl migration

Cavazza and Pietra reported the first examples of fluxional sulfonates, in which a formal thermal 1,4-oxygen to oxygen sulfonyl migration for tosyl and mesyl substituents was observed for troponoid 710 and colchicinoid 712 derivatives (Scheme 108). In all instances an equilibrium was observed. For example, when the tosylate of β -thujaplicine 710 was heated in DMF at 100 °C a 1:1.09 mixture of 710 and 2-tosyloxy-6-isopropyltropone 711 was afforded after 2.5 hours. Isolation of pure 711, followed by heating under the aforementioned conditions, again afforded a 1:0.9 mixture of 710:711 confirming the equilibrium process. A similar effect was observed for the colchicine 712/isocolchicine 713 system, amongst other derivatives, in this case the equilibrium favoured the isomer bearing a double bond between C7a and C12a (712:713 *ca.* 1:2.4) (Scheme 108).

The mechanism can be rationalised *via* an intramolecular nucleophilic addition of the carbonyl oxygen atom to the electron-deficient sulfur atom of the sulfonyl moiety, generating a trigonal bipyramidal intermediate bearing negatively-charged oxygen atoms occupying the apical positions. Molecular mechanics calculations indicate that such an intermediate would have low strain, which is in contrast with the high strain that would be expected of a trigonal bipyramidal transition state

Scheme 108 Fluxional sulfonyl derivatives of troponoids and colchicinoids; observation of a formal 1,4-oxygen to oxygen sulfonyl migration.

formed *via* a concerted entering and leaving of the respective oxygen atoms. Also, the highly polarised character of the rate-determining transition state is borne out by the fact that a higher rate of reaction was observed in DMF than toluene.

In their efforts to access the aglaroxin C analogue 716, of the rocaglate family of natural products, Zhang et al. hypothesised that the tosyl-enol rocaglate 714 could undergo basemediated conjugate addition with benzamidine, followed by elimination of the tosyl moiety to give the enamine 715 which upon ring closure would afford the desired pyrimidinone product 716 (Scheme 109). 145 When the reaction was carried out using NaH as base, the isolated product was in fact the amidino-rocaglate 721. The authors attributed this transformation to an intercepted retro-Nazarov reaction. Deprotonation of 714 affords the anionic intermediate 717 which undergoes an intramolecular 1,4-oxygen to oxygen tosyl migration to give the enolate 718. Elimination of the tertiary tosylate generates the stabilised oxyallyl cation 719. Nucleophilic addition of amidine and subsequent cyclisation affords the product 721. Using this methodology, a series of amidino- and amino-rocaglates were synthesised (46 examples, up to 93% yield).

7. Carbon to carbon sulfonyl migration

7.1. N-heterocyclic carbene-catalysed sulfonyl migration

Atienza *et al.* described the N-heterocyclic carbene (NHC) catalysed 1,2-sulfonyl migration of 1,1-bis(sulfonyl)ethylene derivatives 722 and their subsequent reactivity with 1,3-dipoles (predominantly nitrones 723) to generate a series of highly functionalised isoxazolidine derivatives 724 as single diastereomers in good to excellent yields (Scheme 110). 466 Mechanistic

Scheme 109 Generation of amidino-rocaglate derivatives *via* an intercepted retro-Nazarov reaction; observation of a 1,4-oxygen to oxygen sulfonyl migration.

studies informed that the sulfonyl migration was an intermolecular process as supported by crossover experiments. Furthermore, the NHC catalyst 725 was not necessary for the [3 + 2]-dipolar cycloaddition to occur, however its presence was crucial for the isomerisation of the 1,1-bis(sulfonyl)ethylene derivative 722 to the rearranged *trans*-1,2-bis-alkene 731 as illustrated in Scheme 110. In addition, ¹³C-labelling of 732 highlighted that the 1,2-sulfonyl migration occurs prior to the cycloaddition step as evidenced by isolation of a mixture of labelled products 734 and 735. Notably, if only the ¹³C-labelled vinyl sulfone isomer was present at the cycloaddition step isotopic labelling would only be observed at one position in the product.

Yamada and co-workers described the N-heterocyclic-carbene-mediated cyclisation of sulfonylalkynols 736 with concomitant 1,2-sulfonyl migration to afford 5- and 6-membered

Scheme 110 N-Heterocyclic carbene-catalysed 1,2-sulfonyl migration of vinyl sulfones.

oxacycles 737 in high yields (Scheme 111).147 While N-formylalkynamides cyclised smoothly under the same conditions, N-sulfonylalkynamide derivatives required the use of NHC 740 in conjunction with proton sponge as the base. The mechanism is believed to proceed via the allenyl sulfone intermediate 742 which is generated in situ on reaction of the sulfonylalkynol 741 with base. Applying this intermediate to the standard reaction conditions led to isolation of the desired product in high yield. Nucleophilic addition of the NHC to 742, followed by a proton transfer affords the intermediate 743 which cyclises with accompanying tosylate extrusion to give 744. This tosylate reacts with another equivalent of the allene intermediate 742 to give the intermediate 745, which completes the formal 1,2-sulfonyl migration. A final cyclisation affords the desired vinyl sulfone 746. That tosylate initiates the productive cycle was supported by carrying out the reaction in

Scheme 111 NHC-mediated cyclisation of sulfonylalkynols forming oxacycles with accompanying 1,2-sulfonyl migration.

the presence of p-toluenesulfinate (2 mol%) in the absence of the NHC mediator. This experiment afforded the desired product 746 in 83% yield. The isolation of the disulfone 749 when the propargyl sulfone 747 was reacted under the standard conditions (in refluxing toluene) supports the formation of 745 as an intermediate in the reaction pathway. The group subsequently reported that the reaction can be carried out with either catalytic triphenylphosphine or DMAP in place of the N-heterocyclic carbene. 148

7.2. Triphenylphosphine-catalysed sulfonyl migration

Lu *et al.* described the triphenylphosphine-catalysed 1,2-sulfonyl migration of electron-deficient allenes 751 in their reaction with active methylene compounds to give vinyl sulfones in moderate yields (Scheme 112). While mechanistic studies were not undertaken the authors postulated that the migration occurs *via* the *in situ* generation of the sulfinate anion as described in Scheme 112. Upon its formation it is readily conceivable that the nucleophilic sulfinate could add to the allene 751 to form the vinyl anion 766, which can deprotonate the active methylene compound 762 to form the allylic sulfone 767. Subsequent addition of the anion 763 to 767 leads to elimination of the allylic sulfone, generating the desired rearranged product 768.

Scheme 112 Triphenylphosphine-catalysed 1,2-sulfonyl migration of electron-deficient allenes in their reaction with active methylene compounds affording vinyl sulfones.

Hampton and Harmata reported the use of triphenyl-phosphine as a nucleophilic catalyst in the isomerisation of allenic sulfones 769 to afford 2-arylsulfonyl 1,3-dienes with catalytic phenol used as a proton shuttle (Scheme 113). The formal carbon to carbon 1,2-sulfonyl migration was rationalised by the following mechanism as previously described: nucleophilic addition of triphenylphosphine to the β -carbon of the allene substrate 771 affords 772 which is protonated by phenol to give the phosphonium salt 773; the phenoxide anion deprotonates 773 which leads to the elimination of the tosylate anion, which undergoes nucleophilic addition to the β -carbon of the allene substrate 771 affording the anionic intermediate 775; subsequent protonation by phenol, and deprotonation of 776 releases tosylate for the next catalytic cycle while generating the desired product 777.

In a subsequent report the authors provided a series of supporting experiments confirming the likelihood of the presented mechanism (Scheme 114). Crossover experiments indicated an intermolecular sulfonyl migration, while the reaction was observed to proceed in the absence of triphenyl-phosphine when an external source of sulfinate anion was

Scheme 113 Isomerisation of allenic sulfones affording 2-arylsulfonyl 1,3-dienes catalysed by triphenylphosphine.

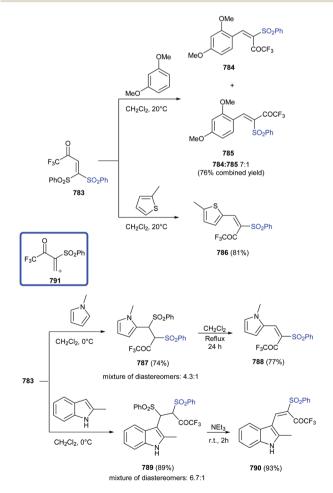
Scheme 114 Hampton and Harmata's supporting evidence for the proposed mechanism for the triphenylphosphine-catalysed isomerisation of allenic sulfones to 2-arylsulfonyl 1,3-dienes.

added in the presence of the proton shuttle phenol. While the phosphonium salt intermediates did not prove amenable to isolation, tentative evidence for the presence of either 778 or 779 was provided by ³¹P NMR for the reaction of the allene 771 with one equivalent of triphenylphosphine. In this reaction, the proposed intermediate, the disulfone 780 was isolated in 12% yield. To ensure that this intermediate could lead to the dienyl product 777, it was prepared independently and treated with *in situ* generated sodium phenoxide which afforded the desired product 777 in 91% yield. The authors were able to independently synthesise the phosphonium salt 782, which compared favourably to the ³¹P NMR data for the proposed intermediate 778 or 779. To prove unequivocally that this salt

was indeed an intermediate of the proposed reaction pathway it was reacted with the allene **781** in a crossover experiment in the presence of *in situ* generated sodium phenoxide. Notably, both **783** and **777** were formed consistent with the phosphonium salt **778** being an intermediate in the migratory process. DFT studies carried out by the Li group were consistent with the Hamata group's proposed mechanism for this process, and particularly support the role of phenol as proton shuttle. ¹⁵²

7.3. Miscellaneous sulfonyl migration

Krasovsky *et al.* developed a novel electrophilic reagent, β-trifluoroacetylketene diphenyldithioacetal *S,S'*-tetroxide **783**, that allowed access to a range of previously undescribed **1,1,1**-trifluoro-4-aryl-3-(phenylsulfonyl)but-3-en-2-ones **584–586**, **788** and **790** *via* Michael-like additions of electron-rich aromatic derivatives (Scheme 115).¹⁵³ The highly electrophilic reagent **783** readily reacted with **1,3**-dimethoxybenzene and 2-methylthiophene to afford the ketones **584–586** in high yields under mild conditions. Notably, the reaction occurs *via* an unusual **1,2**-sulfonyl migration and elimination of one sulfonyl moiety.



Scheme 115 β -Trifluoroacetylketene diphenyldithioacetal *S,S'*-tetroxide as a synthetic equivalent for **791** in electrophilic aromatic substitution; observation of a 1,2-carbon to carbon sulfonyl migration.

As such, the electrophilic ketone **783** is a synthetic equivalent for the cationic synthon **791** in reactions with electron-rich aromatics. Interestingly, reaction of **783** with the more electron-rich 2-methylindole and *N*-methylpyrrole occured with rearrangement, but no elimination, at low temperatures to afford a mixture of diastereomeric ketones **787** and **788** with good stereoselectivity. Elimination of the β -phenylsulfonyl moiety could be induced thermally for pyrrole derived ketone **787**, whereas basic conditions were required for the analogous reaction of the indolyl derivative **789**. Mechanistic studies were not part of this investigation.

In their studies on the reactivity of carbanions derived from α-substituted-methyl tolyl sulfones with quinone methides 792 as Michael acceptors, Groszek and Lemek observed an unusual 1,2-tosyl migration when a para-nitro substituent was incorporated on the phenyl ring of the quinone scaffold 792 (Scheme 116). 154 The authors tentatively proposed the formation of the spirodienone 799 as an unstable intermediate, which undergoes a divergent reaction pathway due the electron-withdrawing nature of the nitro group. This nitro moiety significantly increases the acidity of the benzylic proton relative to the other substituents studied (Z = H, NMe₂, OMe). In the presence of excess base the nitro group facilitates deprotonation allowing the anion 800 to cyclise to the hypervalent sulfur intermediate 801 via nucleophilic addition to the sulfur of the sulfonyl moiety. 144,155,156 Subsequent ring-opening and protonation leads to aromatisation and the acquisition of the rearranged product 795.

Following their success achieving the enantioselective generation of chiral cyclopropenes from ethyl diazoacetate and various terminal alkynes using the Rh₂(OAc)(DPTI)₃ catalyst, ¹⁵⁷ the Corey group sought to extend this methodology to include tosyl derivatives to further study the effects of strain in unsaturated cyclopropenes. Using the highly selective rhodium catalyst the chiral tosyl substituted cyclopropenes 804-806 were afforded in 91%, 94% and 78% ee respectively (Scheme 117). 158 Interestingly, when the 2-n-amyl-2-cyclopropenyl 4-tolyl sulfone 804 was purified by chromatography on silica gel, or allowed to stir with silica gel in benzene, complete racemisation was observed. Measurements of the kinetics of the thermal racemisation of 804 at 70 °C in each of the solvents benzene, cyclohexane and acetonitrile afforded very similar first-order rate constants, indicating that a polar dissociation mechanism via the formation of a cyclopropenium toluene-sulfinate ion pair was unlikely. Instead, a reversible [2,3]-sigmatropic rearrangement was proposed by the authors (Scheme 117). The reverse process, that is a sulfinate-sulfone allylic rearrangement, is well-known in the literature.

Evidence supporting the reversible [2,3]-sigmatropic rearrangement of **804** in the solution phase was provided by carrying out a trapping experiment with anhydrous CD_3OD (Scheme 118). Methanolysis of **804**" or *ent-***804**" produced the isolable deuterated methyl toluenesulfinate **810**, and the cyclopropenol **808**, which despite being too unstable to isolate led to the β -deuterated α,β -enal **809** and the deuterated methyl acetal **811**. These results unequivocally support the generation

Scheme 116 Observation of a formal 1,2-sulfonyl migration from carbon to carbon *via* hypothesised hypervalent sulfur intermediate **801**.

of the sulfinate **804**", formed *via* the first 2,3-sulfone-sulfinate allylic rearrangement. The instability of the cyclopropenol **808** is a direct consequence of high ring strain (approx. 55 kcal mol⁻¹) and the availability of a carbonyl-forming elimination process that can alleviate the strain. Ring strain can also explain the ring cleavage process that converts the sulfone **804**" to the deuterated methoxy sulfone **813** *via* intermediate **812**. It is likely that the silica gel, acting as a weak protic acid, catalyses the racemisation through hydrogen bonding with one of the oxygen atoms of the migrating sulfonyl group in the transition state.

The synthetic value of sulfonyl migrations was utilised in Zakharov's enantioselective total synthesis of lycopodine **820.** ^{159,160} The observed 1,3-sulfonyl migration was the first

Scheme 117 Reversible 2,3-sulfone-sulfinate allylic rearrangement; formal 1.2-sulfonvl migration.

Scheme 118 Trapping experiment with CD₃OD confirming sulfinate 804" as an intermediate, evidence supporting a 2,3-sulfonesulfinate allylic rearrangement.

example of a rearrangement of this type involving an α-sulfonyl imine. The proposed mechanism for the rearrangement is as follows (Scheme 119). Treatment of the silyl enol ether 814 with zinc triflate likely affords the zinc complex 815

Scheme 119 The utilisation of a 1,3-sulfonyl migration in the enantioselective total synthesis of lycopodine.

which can tautomerise to the metallo-enamine 816, which is considered to be the intermediate that undergoes the 1,3migration of the sulfonyl moiety from C8 to C14. This rearrangement might occur through (i) heterolytic or homolytic cleavage of the C-S bond to yield an intimate ion-pair or radical pair respectively, followed by recombination at the C14 position; (ii) [2,3]-sigmatropic rearrangement to a sulfinate ester which reorganises to the sulfone 817; or (iii) formation of a 1,1-dioxothietane intermediate and subsequent ring opening. Protonation of the enamine in a diastereoselective fashion and epimerisation at C14 generates intermediate 818 which via an intramolecular Mannich reaction yields the tricyclic product 819.

The Robina group reported a sulfonyl moiety catalysed anionic [3 + 2] cycloaddition of allenyl sulfones 751 and sulfonyl imines 821 to afford 2-aryl-4-phenylsulfonyl-3-pyrrolines 822 in moderate yields (Scheme 120). 161 A nucleophilic mediator, in this instance NaNO2, was required for the reaction to occur. The authors suggested that in order to rationalise the high regioselectivity of the transformation that the intermediate 826 must be involved in the process. They reasoned that this could be achieved via conjugate addition of in situ generated benzenesulfinate anion to the allenyl sulfone 751. Nucleophilic addition of the anionic intermediate 823 to the N-sulfonylimine 824 forms the nitranion 825. A 5-endo-trig

Scheme 120 Sulfonyl moiety-catalysed anionic [3+2] cycloaddition of allenyl sulfones and sulfonyl imines affording 2-aryl-4-phenylsulfonyl-3-pyrrolines.

cyclisation, and subsequent β -elimination of the sulfonyl moiety affords the desired rearranged pyrroline 822. The route toward the initial formation of benzenesulfinate is unclear, however it is believed to be promoted by addition of the nucleophilic mediator NaNO₂ to 751, which could then react νia several pathways to afford the necessary sulfinate anion.

Alexakis reported an intriguing 1,2-carbon to carbon sulfonyl migration resulting from nucleophilic addition to bis activated vinyl-sulfones 828. 162,163 Various nucleophiles including aldehydes, ketones, malonates, keto-esters and nitro-esters activated by different organocatalytic sources (enamine, Brønsted base, thiourea) can promote this migration in moderate to excellent yields and enantioselectivities (Scheme 121). The authors reasoned that the mechanism likely proceeds via an anionic intermediate, formed upon Michael addition of the nucleophile and doubly activated vinyl sulfone. Indeed, anion trapping, by performing the reaction using cis-1,2-bis(phenylsulfonyl)ethene 832 in the presence of deuterium oxide, highlighted the existence of such an intermediate 837, with the products 834-836 displaying deuterium incorporation at the α -, β - and γ -positions in 31%, 13% and 41% respectively (Scheme 122). A control experiment using 1,1-bis-(phenylsulfone)ethene 833 led to deuterium incorporation at the α - and γ-positions only in 63% and 64% respectively.

Considering these observations, the following mechanism was postulated. Michael addition, or [2 + 2] cycloaddition,

Scheme 121 Organocatalyst mediated 1,2-carbon to carbon sulfonyl migration resulting from nucleophilic addition to bis activated vinyl-sulfones

Scheme 122 Mechanistic studies supporting the formation of the anion intermediate **837**.

affords the anionic intermediate **839**. Depending on the substrate and the relative conformation of the sulfone and the adjacent anion, two disparate mechanistic outcomes can be considered. If the lone pair and the sulfone moiety are preferentially antiperiplanar after an *anti*-addition, as can be seen in the Newman projection **848**, the elimination of sulfinic acid will be favoured. Alternatively, if the lone pair is in the proximity of the sulfonyl moiety after a *syn* addition as is the case for **846**, then the **1**,2-sulfonyl migration will preferentially occur (Scheme **123**). Protonation of the rearranged intermediate affords the desired product. Notably, the observation that the selectivity for the sulfonyl migration is enhanced by utilising larger nucleophiles is consistent with the proposed mechanism.

Subsequently, Rios demonstrated the application of this 1,2-sulfonyl migration in the asymmetric organocatalytic Michael addition of azlactones **850** to *cis*-1,2-bis(phenylsulfonyl)ethene **832** as a synthetically useful method for the generation of direct precursors to enantioenriched quaternary α -alkyl- α -amino acids **851** (Scheme 124). The thiourea-based catalyst of Takemoto and co-workers (S,S)-**852** was determined to be the optimal catalyst for the transformation, to 5 producing yields of up to 82% and enantiomeric excesses of up to 95%.

2-(Sulfonylmethyl)arylpyrroles **855** were observed to be accessible from α -allyl- β -ketosulfones **853** via a PdCl₂/CuCl₂/NH₄OAc-mediated domino Wacker-type aminocyclisation via selective 1,4-sulfonyl migration with moderate to good yields

Scheme 123 Proposed mechanism for the 1,2-sulfonyl migration; stereochemistry of the transient anion.

(Scheme 125).¹⁶⁶ Regardless of the conditions employed through optimisation, no evidence for the pyrrole 863, derived from a 1,3-sulfonyl migration was observed. Complexation of the PdCl₂/CuCl₂-catalyst system to the olefin 854 was found to yield the Wacker oxidation product 856. Condensation of 856 with NH₄OAc affords intermediate 857, which subsequently undergoes desulfonylation, cyclisation and tautomerisation to give 860. Elimination of ammonia leads to the generation of the fulvene skeleton 861, which undergoes regioselective addition of the sulfinate, which gives the pyrrole product 862 *via* protonation of 861, completing the overall 1,4-sulfonyl migration. Crossover experiments, whereby both the aryl group and the sulfonyl group were varied, supported the intermolecular nature of the sulfonyl migration and the presence of the fulvene skeleton 861 as a key intermediate.

The Yu group developed a copper-catalysed cyclisation of allenoates **864** with activated isocyanides **865**, that invloved 1,3-sulfonyl migration, leading to di- or tri-substituted pyrroles **866** in moderate to good yields (Scheme 126).¹⁶⁷ The authors proposed that the transformation starts with Cu₂O mediated C–H bond activation of the isocycanide **867** to give the copperisocyanide complex **868** with concomitant formation of H₂O.

Scheme 124 Application of a 1,2-sulfonyl migration in the synthesis of direct precursors to enantioenriched quaternary α -alkyl- α -amino acids.

Scheme 125 $PdCl_2/CuCl_2/NH_4OAc$ -mediated domino Wacker-type aminocyclisation of α -allyl- β -ketosulfones via selective 1,4-sulfonyl migration.

Subsequent [3 + 2]-dipolar cycloaddition of this intermediate with the allenoate 869 affords the intermediate 870, which following protonolysis leads to the formation of 871 and the regeneration of the copper catalyst. A copper-assisted elimination of tosylate produces the cationic intermediate 872, which upon recombination affords the rearranged pyrrole complex 873. The intermolecular nature of the sulfonyl migration was further established by means of crossover experiments. Protonolysis of 873 leads to the final pyrrole product 874 and regeneration of the copper catalyst.

Bi and co-workers described the silver-catalysed generation of 1,4,5-trisubstituted imidazoles 877 via isocyanide-isocyanide [3 + 2]-dipolar cycloaddition in which a 1,2-tosyl migration was observed (Scheme 127). 168 Notably, both electron-rich and electron-deficient aryl groups on the aryl isocyanides 875, as well as sterically demanding groups, were well tolerated with moderate to high yields obtained in all instances. Furthermore, both aryl and alkyl α-substituted tosylmethyl isocyanide derivatives 876 reacted readily. The addition of either TEMPO or BHT did not inhibit the reaction, indicating that the mechanism does not proceed via a radical process (Scheme 127). When the reaction was carried out in the presence of D₂O, 74% deuterium incorporation was observed, highlighting that trace amounts of water in the solvent may provide a proton in the imidazole products 877. No deuterated imidazole [D]-880 was isolated when the substrate [D]-879 was reacted under standard conditions, confirming that the active methine group is involved in proton abstraction.

Scheme 126 Copper-catalysed cyclisation of allenoates with activated isocyanides featuring a carbon–carbon 1,3-sulfonyl migration.

The authors postulated that coordination of the silver catalyst to the isocyanides **878** and **879** generates the silver complexes **881** (following abstraction of a proton and concurrent generation of AgHCO₃) and **882**, which subsequently undergo [3+2]-dipolar cycloaddition to give the cyclic nitrilium ion **884** (Scheme 128). 1,2-Tosyl migration affords the carbocation intermediate **885** followed by loss of the silver cation and subsequent protonation forms the rearranged imidazoles **880** with concomitant regeneration of the silver catalyst.

The Xu group disclosed the first example of the preparation of *ortho*-alkylaryl triflones **889** *via* the insertion of arynes into C–SO₂CF₃ bonds through a tandem nucleophilic attack/intramolecular carbon to carbon 1,3-sulfonyl migration (Scheme 129). Using KF/18-crown-6 as fluoride source a series of *ortho*-alkylaryl triflones **889** were generated in moderate to high yields, with the presence of an electron-withdrawing substituent on the benzyl triflones **888** essential for efficient reaction. A plausible mechanism involves the fluoride-mediated generation of the aryne **890** and carbanion **891**,

Scheme 127 Silver-catalysed formation of 1,4,5-trisubstituted imidazoles via isocyanide–isocyanide [3 + 2]-dipolar cycloaddition with accompanying 1,2-tosyl migration.

Scheme 128 Proposed mechanism for silver-catalysed formation of 1,4,5-trisubstituted imidazoles *via* isocyanide–isocyanide [3 + 2]-dipolar cycloaddition.

Scheme 129 Preparation of ortho-alkylaryl triflones via insertion of C–SO₂CF₃ bonds into arynes through a tandem nucleophilic attack/intramolecular carbon to carbon 1,3-sulfonyl migration.

which upon nucleophilic addition forms the intermediate **892** (Scheme 129). Subsequent carbon to carbon 1,3-sulfonyl migration of the triflyl group, presumably *via* an intramolecular process, akin to an anionic thia-Fries rearrangement, affords the rearranged *ortho*-alkylaryl triflone **889**. Notably, the corresponding reaction of substituted benzyl methanesulfones did not afford the desired aryl methanesulfones, highlighting the importance of the triflyl group in the transformation.

Access to novel atropisomeric 3-tosyl-1-enyl-cyclopropyldiphenylphosphine oxide derivatives 896 and 897 via a one-pot transition metal free coupling of N-tosylhydrazones 894 and phosphinyl allenes 895 was recently developed by Wu and coworkers. 170 Notably, the multistep cascade reaction occurs by initial radical hydrazonyl N-S bond cleavage, followed by sequential radical C(sp³)-OAr bond cleavage, carbon to carbon 1,3-sulfonyl migration and atropisomeric cyclopropanation to afford the desired products in moderate to high yields in excellent diastereoselectivity (Scheme 130). The initial radical cleavage of the hydrazonyl N-S bond is enabled by the combination of catalytic 1,10-phenanthroline and potassium carbonate, and while significant attention was afforded to the elucidation of the mechanism for this step it is beyond the scope of this review. Consequently, we will focus exclusively on the attempts to elucidate the mechanism for the sulfonyl migration step. For clarity, the full proposed mechanism is included in Scheme 131.

A radical mechanism was invalidated by the addition of TEMPO, under otherwise standard conditions, to the isolable intermediate 898 which afforded the rearranged product 899 with no inhibition observed (Scheme 130A). A stoichiometric amount of K_2CO_3 was shown to be necessary for optimal conversion to rearranged product, with a reduction in the amount of base inhibiting the cascade process (Scheme 130B). This finding strongly suggests that the base promotes the sulfonyl migration. A crossover experiment between 898 and sodium

4-methoxybenzenesulfinate 900 afforded a statistical mixture of products 899 and 901 supporting an intermolecular sulfonyl migration (Scheme 130C). A kinetic isotope effect value (k_H/k_D) of 1.5 was determined for the parallel reactions of 904 and 904-D⁶ under standard conditions, with incorporation of deuterium observed over all the alkenyl positions (Scheme 130D). This KIE suggests that the rate-determining step probably involves the sulfonyl rearrangement but does not involve the previous C(sp³)-H bond cleavage. With this experimental evidence in mind the following mechanism is postulated (Scheme 130E): base induced elimination of the tosyl moiety affords the tosyl anion and the allene 906, which isomerises to 907 in the presence of stoichiometric base. 171 Nucleophilic addition of the tosyl anion promotes the elimination of the base and completes the formal 1,3-sulfonyl migration to afford 899.

Our group has an ongoing interest in the reactivity of α-thio-β-chloroacrylamides, 172 a family of highly functionalised sulfur-containing compounds that can undergo a large range of synthetic transformations such as oxidation, 173 additionsubstitution, 174 Diels-Alder cycloaddition 275 and [3 + 2]dipolar cycloaddition.^{2,176} Notably, during studies regarding their reactivity as dipolarophiles in [3 + 2]-dipolar cycloaddition reactions with both electron-rich and electron-poor terminal α-diazoalkanes it was observed that the degree of oxidation at sulfur played a critical role in the outcome of the reaction. While the outcome of the cycloadditions at the sulfide and sulfoxide level can be readily rationalised due to the nucleophilic character of sulfides and the leaving group potential of sulfoxides, the observation of a formal carbon to carbon 1,2-sulfonyl migration for the sulfone derivatives is unprecedented in pyrazoline heterocyclic structures (Scheme 132).

While the mechanism for the formation of the rearranged pyrazoles 923 is not fully understood, several mechanistic routes can be considered based on the confirmed regiochemistry of the products (Scheme 133). In all instances, regioselective [3 + 2]-dipolar cycloaddition of the crude α -sulfonylβ-chloroacrylamide 925 leads to the initial pyrazoline 926 which readily undergoes elimination of HCl to give the intermediate cycloadduct 927. It is likely that this elimination is facilitated by the presence of the electron-withdrawing ester moiety, with an E_{1c}B elimination likely. To rationalise the formal 1,2-sulfonyl migration a [1,5]-sigmatropic rearrangement can be considered based on an earlier report by Fuchs et al. in which they reported the thermally induced rearrangement of a five-membered γ-sulfonyl enone to the rearranged sulfone in almost quantitative yield. The authors rationalised the transformation through the formation of an enol intermediate which undergoes [1,5]-sigmatropic rearrangement. Notably, however, this reaction was carried out in toluene at 145 °C in a sealed tube, whereas the rearrangement observed in our work to generate 929 occurred at room temperature. Recently, Valdés and co-workers reported the synthesis of chiral pyrazoles through the [3 + 2]-dipolar cycloaddition of α-chiral tosylhydrazones with alkynes. 178 Interestingly, they observed that the initial cycloadduct underwent [1,5]-sigmatro-

Scheme 130 Proposed mechanism for sulfonyl migration including experimental evidence.

Scheme 131 Overall proposed mechanism for the synthesis of atropisomeric 3-tosyl-1-enyl-cyclopropyl-diphenylphosphine oxide derivatives.

Scheme 132 [3 + 2]-dipolar cycloaddition of α -sulfenyl/sulfinyl/sulfonyl-β-chloroacrylamides with electron rich and electron deficient diazoalkanes

pic rearrangement with migration of the alkyl group. Significantly, they observed that the [1,5]-sigmatropic rearrangement, which has two regioisomeric outcomes, preferentially, but not exclusively, results in migration to nitrogen rather than the C(4) carbon. Forcing conditions were also required for this transformation.

Alternatively, two sequential [2,3]-sigmatropic rearrangements of the sulfonyl moiety can be envisaged followed by rearomatisation via tautomerisation at the end of the sequence to afford the pyrazole 929 (Scheme 133). The second [2,3]-sigmatropic rearrangement is somewhat akin to an allylic sulfinate-sulfone rearrangement. It is also plausible that homolytic cleavage of the weak N-O bond of the intermediate 930 could generate a radical pair 931 which on recombination forms the more stable C-S bond.

8. Summary and outlook

In this review, we have comprehensively collected reports of sulfonyl migrations over the past 20 years, highlighted the development of insight into synthetic and mechanistic aspects of these sulfonyl shifts, and categorised them based on the migration type, namely nitrogen-carbon, nitrogen-oxygen, nitrogen-nitrogen, oxygen-carbon, oxygen-oxygen carbon-carbon. While most sulfonyl migrations prior to the beginning of the 21st century were discovered as side reactions, and regularly as isolated cases, the last 20 years has seen a significant increase in the number of reports focusing on development of synthetic methodology based on the sulfonyl

Mechanistic Pathway B: Sequential [2,3]-sigmatropic rearrangements

Scheme 133 [3 + 2]-dipolar cycloadditions of ethyl diazoacetate and α -sulfonyl- β -chloroacrylamides; observation of an unprecedented carbon to carbon 1,2-sulfonyl migration [a: -CONHTol not drawn in structure 927].

Enantiomeric excess

Electron paramagnetic resonance

Electron withdrawing group

Change in Gibbs free energy

Gas chromatography

Photochemical energy

kilocalorie per mole

Intermediate

Electrospray ionisation-mass spectrometry

Fast atom bombardment mass spectrometry

High performance liquid chromatography

High resolution mass spectrometry

Equivalents

Hours

migration. Efforts to understand the mechanisms of these often 'unexpected' reactions have garnered significant recent attention including by means of crossover studies, competition experiments, isotopic-labelling, density functional theory calculations and electron paramagnetic resonance spectroscopy, although many sulfonyl migrations are only partially understood at this point. Despite progress in this area, the potential for formal 1,2-, 1,3-, 1,4-, 1,5-, 1,6- and 1,7-sulfonyl migrations, both in an inter- and intramolecular fashion, via both radical and polar processes render challenging the prediction of the outcome of such reactions in a manner that would facilitate their predictable use in synthesis. Notwithstanding, the clear evidence discussed herein for the utility of sulfonyl migration, particularly in the synthesis of highly functionalised heterocycles, and notably in total synthesis, highlights the synthetic potential of sulfonyl migrations. Therefore, we believe that significant attention will be afforded to this expanding field of research in years to come.

ee

equiv.

ESI-MS

EPR

Et

EWG

 ΔG

GC

HPLC

HRMS

kcal mol⁻¹

h

hv

IM

FABMS

Abbreviations

Å Angstrom Ac Acetyl **AIBN** Azobisisobutyronitrile Ar Aryl В Base BHT Dibutylhydroxytoluene 1,1'-Bi-2-naphthol **BINOL** Benzyl Bn ΒP Biphenyl BQ 1,4-Benzoquinone **BTAC** Behentrimonium chloride iBu iso-Butyl n-BuLi n-Butyllithium tBu tert-Butyl BzBenzoyl $^{\circ}C$ Degrees celsius mCPBA meta-Chloroperbenzoic acid Cyclohexyl Cy DBU 1,8-Diazabicyclo[5.4.0]undec-7-ene DCE Dichloroethane DFT Density functional theory DIAD Diisopropyl azodicarboxylate Diisopropylamine DIPA 4-Dimethylaminopyridine **DMAP** DMEAD Di-2-methoxyethyl azodicarboxylate **DMF** Dimethylformamide Dimethylsulfoxide **DMSO DPBIF** 1,3-Diphenylisobenzofuran DPE 1,1-Diphenylethylene dr Diastereomeric ratio DTBP Di-tert-butylhydroperoxide $E_{1C}B$ Elimination unimolecular conjugate base **ECR** Electrocyclic ring-closure **EDG** Electron-donating group

KHMDS Potassium bis(trimethylsilyl)amide KIE kinetic isotope effect kJ mol⁻¹ kilojoule per mole LC-MS Liquid chromatography-mass spectrometry Lithium diisopropylamine LDA LED Light emitting diode LFP Laser flash photolysis LiTMP Lithium tetramethylpiperidine Me Methyl Acetonitrile MeCN Mesityl Mes min Minutes mol% Mole percent Ms Mesyl MS Molecular sieves N-Bromosuccinimide NBS NHC N-Heterocyclic carbene N-Hydroxyphthalimide **NHPI** nm Nanometer **NMR** Nuclear magnetic resonance Nitrobenzenesulfonyl Ns PC Photocatalyst PC* Excited photocatalyst PES Potential energy surface Ph Phenyl 1,10-Phenanthroline phen Phth Phthaloyl Piv Pivaloyl **PMB** p-Methoxybenzyl iPr Isopropyl Propyl nPr P.T. Proton transfer PTSA p-Toluenesulfonic acid **Pyridine** pyr RDS Rate-determining step rt Room temperature SET Single-electon transfer Tetra-n-butylammonium bromide **TBAB TBAF** Tetra-*n*-butylammonium fluoride **TEMPO** (2,2,6,6-Tetramethylpiperidin-1-yl)oxyl Τf Triflyl

THF Tetrahydrofuran TIPS Triisopropylsilyl **TMS** Trimethylsilyl

Tolyl Tol

TS Transition state

Tosyl Ts μW Microwave

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Financial support from the Synthesis and Solid State Pharmaceutical Centre supported by Science Foundation Ireland, co-funded under the European Regional Development Fund (grant number: 12/RC/2275) is gratefully acknowledged.

References

- 1 E. J. Corey and X. M. Cheng, The Logic of Chemical Synthesis, Wiley, 1989.
- 2 A. J. Flynn, A. Ford, U. B. R. Khandavilli, S. E. Lawrence and A. R. Maguire, Eur. J. Org. Chem., 2019, 5368-5384.
- 3 The Chemistry of Sulphones and Sulphoxides, ed. S. Patai, Z. Rappoport and C. Stirling, John Wiley & Sons, Chichester, 1988.
- 4 B. M. Trost and C. A. Kalnmals, Chem. Eur. J, 2019, 25, 11193-11213.
- 5 P. D. Magnus, Tetrahedron, 1977, 33, 2019-2045.
- 6 N. S. Simpkins, Chem. Soc. Rev., 1990, 19, 335-354.
- 7 N. S. Simpkins, Sulfones in Organic Synthesis, Pergamon Press, Elmsford, NY, 1993.
- 8 A. Padwa, Z. Ni and S. H. Watterson, Pure Appl. Chem., 1996, 68, 831.
- 9 J.-E. Bäckvall, R. Chinchilla, C. Nájera and M. Yus, Chem. Rev., 1998, 98, 2291-2312.
- 10 P. L. Fuchs and T. F. Braish, Chem. Rev., 1986, 86, 903-
- 11 N. S. Simpkins, Tetrahedron, 1990, 46, 6951-6984.
- 12 T. G. Back, K. N. Clary and D. Gao, Chem. Rev., 2010, 110, 4498-4553.
- 13 Y. M. Markitanov, V. M. Timoshenko and Y. G. Shermolovich, J. Sulfur Chem., 2014, 35, 188-236.
- 14 Y. Fang, Z. Luo and X. Xu, RSC Adv., 2016, 6, 59661-59676.
- 15 C. Stefan, S. Simon, W. Jean-Marc and P. Patrick, Curr. Org. Synth., 2012, 9, 806-827.
- 16 C. M. So and F. Y. Kwong, Chem. Soc. Rev., 2011, 40, 4963-
- 17 S. Searles and S. Nukina, *Chem. Rev.*, 1959, **59**, 1077–1103.
- 18 I. Nakamura, U. Yamagishi, D. Song, S. Konta and Y. Yamamoto, Angew. Chem., Int. Ed., 2007, 46, 2284–2287.

- 19 I. Nakamura, U. Yamagishi, D. Song, S. Konta and Y. Yamamoto, Chem. - Eur. J., 2008, 3, 285-295.
- 20 I. Nakamura, Y. Mizushima, U. Yamagishi and Y. Yamamoto, *Tetrahedron*, 2007, **63**, 8670–8676.
- 21 A. Fürstner and P. W. Davies, J. Am. Chem. Soc., 2005, 127, 15024-15025.
- 22 W. Rao, D. Susanti and P. W. H. Chan, J. Am. Chem. Soc., 2011, 133, 15248-15251.
- 23 W. T. Teo, W. Rao, M. J. Koh and P. W. H. Chan, J. Org. Chem., 2013, 78, 7508-7517.
- 24 H.-S. Yeom, E. So and S. Shin, Chem. Eur. J., 2011, 17, 1764-1767.
- 25 J. Liu, P. Chakraborty, H. Zhang, L. Zhong, Z.-X. Wang and X. Huang, ACS Catal., 2019, 9, 2610-2617.
- 26 B. Prabagar, R. K. Mallick, R. Prasad, V. Gandon and A. K. Sahoo, Angew. Chem., Int. Ed., 2019, 58, 2365-2370.
- 27 Y. T. Lee and Y. K. Chung, J. Org. Chem., 2008, 73, 4698-4701.
- 28 Y. Hu, R. Yi, F. Wu and B. Wan, J. Org. Chem., 2013, 78, 7714-7726.
- 29 Y. Zhao, H. Wang, X. Li, D. Wang, X. Xin and B. Wan, Org. Biomol. Chem., 2016, 14, 526-541.
- 30 D. Arunprasath, B. Devi Bala and G. Sekar, Adv. Synth. Catal., 2019, 361, 1172-1207.
- 31 Y. Xia and J. Wang, Chem. Soc. Rev., 2017, 46, 2306-2362
- 32 H. Wang, Y.-H. Deng and Z. Shao, Synthesis, 2018, 50, 2281-2306.
- 33 S. Mao, Y.-R. Gao, X.-Q. Zhu, D.-D. Guo and Y.-Q. Wang, Org. Lett., 2015, 17, 1692-1695.
- 34 J. Ni, Y. Xue, L. Sun and A. Zhang, J. Org. Chem., 2018, 83, 4598-4605.
- 35 Q. Sun, L. Li, L. Liu, Q. Guan, Y. Yang, Z. Zha and Z. Wang, Org. Lett., 2018, 20, 5592-5596.
- 36 F. Wang, P. Xu, S.-Y. Wang and S.-J. Ji, Org. Lett., 2018, 20, 2204-2207.
- 37 Y. Zheng, L. Qiu, K. Hong, S. Dong and X. Xu, Chem. -Eur. J., 2018, 24, 6705-6711.
- 38 P.-X. Zhou, Y.-Y. Ye, L.-B. Zhao, J.-Y. Hou, X. Kang, D.-Q. Chen, Q. Tang, J.-Y. Zhang, Q.-X. Huang, L. Zheng, J.-W. Ma, P.-F. Xu and Y.-M. Liang, Chem. - Eur. J., 2014, 20, 16093-16096.
- 39 P.-X. Zhou, Y. Zhang, C. Ge, Y.-M. Liang and C. Li, J. Org. Chem., 2018, 83, 4762-4768.
- 40 B. Prasad, R. Adepu, S. Sandra, D. Rambabu, G. R. Krishna, C. M. Reddy, G. S. Deora, P. Misra and M. Pal, Chem. Commun., 2012, 48, 10434-10436.
- 41 Y. Zhu, T. Hai-Tao and Z.-P. Zhan, Adv. Synth. Catal., 2013, 355, 1291-1296.
- 42 Y. Zhu, J.-J. Hong, Y.-B. Zhou, Y.-W. Xiao, M. Lin and Z.-P. Zhan, Org. Biomol. Chem., 2014, 12, 3797–3801.
- 43 M. Padmanaban, L. C. R. Carvalho, D. Petkova, J.-W. Lee, A. S. Santos, M. M. B. Marques and N. Maulide, Tetrahedron, 2015, 71, 5994-6005.
- 44 J. Wang, K.-I. Son and J. Xu, Monatsh. Chem., 2016, 147,

Review

- 45 R. Han, L. He, L. Liu, X. Xie and X. She, *Chem. Asian J.*, 2016, **11**, 193–197.
- 46 B. Wang, S. Jin, S. Sun and J. Cheng, *Org. Chem. Front.*, 2018, 5, 958–961.
- 47 K. K. Park, J. J. Lee and J. Ryu, *Tetrahedron*, 2003, **59**, 7651–7659.
- 48 X. Hong, J. M. Mejía-Oneto, S. France and A. Padwa, *Tetrahedron Lett.*, 2006, 47, 2409–2412.
- 49 X. Hong, S. France and A. Padwa, *Tetrahedron*, 2007, **63**, 5962–5976.
- 50 C. Simal, T. Lebl, A. M. Z. Slawin and A. D. Smith, *Angew. Chem.*, *Int. Ed.*, 2012, 51, 3653–3657.
- 51 P.-P. Yeh, J. E. Taylor, D. G. Stark, D. S. B. Daniels, C. Fallan, J. C. Walton and A. D. Smith, *Org. Biomol. Chem.*, 2017, 15, 8914–8922.
- 52 I. Bernar, D. Blanco-Ania, S. J. Stok, L. Sotorríos, E. Gómez-Bengoa and F. P. J. T. Rutjes, *Eur. J. Org. Chem.*, 2018, 2018, 5435–5444.
- 53 J. Wrobel, A. Dietrich, S. A. Woolson, J. Millen, M. McCaleb, M. C. Harrison, T. C. Hohman, J. Sredy and D. Sullivan, J. Med. Chem., 1992, 35, 4613–4627.
- 54 S. Zhang, L. Li, Y. Hu, Z. Zha, Z. Wang and T.-P. Loh, *Org. Lett.*, 2015, 17, 1050–1053.
- 55 G. S. Lal, G. P. Pez and R. G. Syvret, *Chem. Rev.*, 1996, **96**, 1737–1756.
- 56 Y. Takeuchi, T. Suzuki, A. Satoh, T. Shiragami and N. Shibata, *J. Org. Chem.*, 1999, **64**, 5708–5711.
- 57 E. Torti, S. Protti, D. Merli, D. Dondi and M. Fagnoni, *Chem. Eur. J.*, 2016, **22**, 16998–17005.
- 58 E. Torti, S. Protti, M. Fagnoni and G. Della Giustina, *ChemistrySelect*, 2017, 2, 3633–3636.
- 59 D. P. Ojha and K. R. Prabhu, Org. Lett., 2015, 17, 18-21.
- 60 Z. Luo, Y. Fang, Y. Zhao, X. Xu, C. Feng, Z. Li, X. Zhang and J. He, *Tetrahedron Lett.*, 2016, 57, 4105–4108.
- 61 S. Parisotto, G. Garreffa, C. Canepa, E. Diana, F. Pellegrino, E. Priola, C. Prandi, V. Maurino and A. Deagostino, *ChemPhotoChem*, 2017, 1, 56–59.
- 62 M. Kimura, Y. Horino, Y. Wakamiya, T. Okajima and Y. Tamaru, *J. Am. Chem. Soc.*, 1997, **119**, 10869–10870.
- 63 Y. Horino, M. Kimura, Y. Wakamiya, T. Okajima and Y. Tamaru, *Angew. Chem., Int. Ed.*, 1999, **38**, 121–124.
- 64 M. Kimura, Y. Horino, M. Mori and Y. Tamaru, *Chem. Eur. J.*, 2007, **13**, 9686–9702.
- 65 Y. Horino, M. Kimura, M. Naito, S. Tanaka and Y. Tamaru, *Tetrahedron Lett.*, 2000, 41, 3427–3431.
- 66 M. Bendikov, H. M. Duong, E. Bolanos and F. Wudl, *Org. Lett.*, 2005, 7, 783–786.
- 67 K. A. DeKorver, W. L. Johnson, Y. Zhang, R. P. Hsung, H. Dai, J. Deng, A. G. Lohse and Y.-S. Zhang, *J. Org. Chem.*, 2011, 76, 5092–5103.
- 68 X. Xin, D. Wang, X. Li and B. Wan, *Angew. Chem., Int. Ed.*, 2012, 51, 1693–1697.
- 69 X. Yu, X. Xin, B. Wan and X. Li, *J. Org. Chem.*, 2013, 78, 4895–4904.
- 70 X. Xin, H. Wang, X. Li, D. Wang and B. Wan, *Org. Lett.*, 2015, 17, 3944–3947.

- 71 Z. Jiang, P. Lu and Y. Wang, *Org. Lett.*, 2012, **14**, 6266–6269.
- 72 Y. Zhu, W.-T. Lu, H.-C. Sun and Z.-P. Zhan, *Org. Lett.*, 2013, 15, 4146–4149.
- 73 F. Ji, H. Peng, X. Zhang, W. Lu, S. Liu, H. Jiang, B. Liu and B. Yin, *J. Org. Chem.*, 2015, **80**, 2092–2102.
- 74 J. Shi, D. Qiu, J. Wang, H. Xu and Y. Li, *J. Am. Chem. Soc.*, 2015, **137**, 5670–5673.
- 75 D. Qiu, J. Shi and Y. Li, Synlett, 2015, 26, 2194-2198.
- 76 D. Qiu, J. He, X. Yue, J. Shi and Y. Li, Org. Lett., 2016, 18, 3130–3133.
- 77 H. Tanimoto, K. Yokoyama, Y. Mizutani, T. Shitaoka, T. Morimoto, Y. Nishiyama and K. Kakiuchi, *J. Org. Chem.*, 2016, **81**, 559–574.
- 78 H. Tanimoto, T. Shitaoka, K. Yokoyama, T. Morimoto, Y. Nishiyama and K. Kakiuchi, *J. Org. Chem.*, 2016, 81, 8722–8735.
- 79 H. Tanimoto, S. Ueda, T. Morimoto and K. Kakiuchi, *J. Org. Chem.*, 2018, **83**, 1614–1626.
- 80 G. Di Mauro, B. Maryasin, D. Kaiser, S. Shaaban, L. González and N. Maulide, *Org. Lett.*, 2017, 19, 3815–3818.
- 81 I. Colomer, M. Velado, R. Fernández de la Pradilla and A. Viso, *Chem. Rev.*, 2017, 117, 14201–14243.
- 82 J. K. Laha, S. Sharma, R. A. Bhimpuria, N. Dayal, G. Dubey and P. V. Bharatam, *New J. Chem.*, 2017, 41, 8791– 8803.
- 83 T. Javorskis and E. Orentas, *J. Org. Chem.*, 2017, **82**, 13423–13439.
- 84 Y. Wang, L. Zheng and T. R. Hoye, *Org. Lett.*, 2018, **20**, 7145–7148.
- 85 A. R. P. Henderson, J. R. Kosowan and T. E. Wood, *Can. J. Chem.*, 2017, **95**, 483–504.
- 86 K. Selvaraj and K. C. K. Swamy, J. Org. Chem., 2018, 83, 15043–15056.
- 87 Y. Shen, Q. Li, G. Xu and S. Cui, *Org. Lett.*, 2018, **20**, 5194–5197.
- 88 P. P. Onys'ko, O. A. Suvalova, Y. V. Rassukana, T. I. Chudakova and A. D. Sinitsa, *Tetrahedron Lett.*, 2003, 44, 1855–1857.
- 89 S. S. Michaelidou and P. A. Koutentis, *Tetrahedron*, 2010, 66, 3016–3023.
- 90 Y. Zhu, S. Wen, G. Yin, D. Hong, P. Lu and Y. Wang, Org. Lett., 2011, 13, 3553–3555.
- 91 S. Swaminathan and K. V. Narayanan, *Chem. Rev.*, 1971, 71, 429-438.
- 92 F. Zhou, X. Liu, N. Zhang, Y. Liang, R. Zhang, X. Xin and D. Dong, *Org. Lett.*, 2013, 15, 5786–5789.
- 93 F. Zhou, N. Zhang, X. Xin, X. Zhang, Y. Liang, R. Zhang and D. Dong, *RSC Adv.*, 2014, 4, 18198–18204.
- 94 H. Tsuchikawa, Y. Maekawa and S. Katsumura, *Org. Lett.*, 2012, **14**, 2326–2329.
- 95 Y. Maekawa, T. Sakaguchi, H. Tsuchikawa and S. Katsumura, *Tetrahedron Lett.*, 2012, 53, 837–841.
- 96 X. Liu, N. Zhang, J. Yang, Y. Liang, R. Zhang and D. Dong, J. Org. Chem., 2013, 78, 3323–3328.

- 97 A. Stukalov, V. V. Suslonov and M. A. Kuznetsov, *Eur. J. Org. Chem.*, 2018, 2018, 1634–1645.
- 98 S. G. Jarboe, M. S. Terrazas and P. Beak, *J. Org. Chem.*, 2008, 73, 9627–9632.
- 99 S. S. K. Boominathan, G. C. Senadi, J. K. Vandavasi, J. Y.-F. Chen and J.-J. Wang, *Chem. Eur. J.*, 2015, **21**, 3193–3197.
- 100 A. Diallo, Y.-L. Zhao, H. Wang, S.-S. Li, C.-Q. Ren and Q. Liu, Org. Lett., 2012, 14, 5776–5779.
- 101 T. Narender, S. Sarkar, K. Rajendar and S. Tiwari, *Org. Lett.*, 2011, 13, 6140–6143.
- 102 G. G. Rajeshwaran and A. K. Mohanakrishnan, Org. Lett., 2011, 13, 1418–1421.
- 103 P. Xie, Y. Huang and R. Chen, *Chem. Eur. J.*, 2012, **18**, 7362–7366.
- 104 S. Miaskiewicz, B. Gaillard, N. Kern, J.-M. Weibel, P. Pale and A. Blanc, *Angew. Chem., Int. Ed.*, 2016, 55, 9088–9092.
- 105 F. Sirindil, J.-M. Weibel, P. Pale and A. Blanc, *Org. Lett.*, 2019, **21**, 5542–5546.
- 106 R. Fujita, K. Watanabe, W. Ikeura, Y. Ohtake, H. Hongo, Y. Harigaya and H. Matsuzaki, *Tetrahedron*, 2001, 57, 8841–8850.
- 107 S.-S. P. Chou, H.-C. Wang, P.-W. Chen and C.-H. Yang, Tetrahedron, 2008, 64, 5291–5297.
- 108 R. Hodgson, A. Kennedy, A. Nelson and A. Perry, *Synlett*, 2007, 1043–1046.
- 109 D. G. Stark, L. C. Morrill, P.-P. Yeh, A. M. Z. Slawin, T. J. C. O'Riordan and A. D. Smith, *Angew. Chem., Int. Ed.*, 2013, 52, 11642–11646.
- 110 D. G. Stark, T. J. C. O'Riordan and A. D. Smith, *Org. Lett.*, 2014, **16**, 6496–6499.
- 111 M. D. Mertens, M. Pietsch, G. Schnakenburg and M. Gütschow, *J. Org. Chem.*, 2013, **78**, 8966–8979.
- 112 Z. Fu, K. Jiang, T. Zhu, J. Torres and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2014, 53, 6506–6510.
- 113 L. Hao, X. Chen, S. Chen, K. Jiang, J. Torres and Y. R. Chi, *Org. Chem. Front.*, 2014, **1**, 148–150.
- 114 L. Xie, X. Zhen, S. Huang, X. Su, M. Lin and Y. Li, *Green Chem.*, 2017, **19**, 3530–3534.
- 115 L. Wang, C. Lu, Y. Yue and C. Feng, *Org. Lett.*, 2019, 21, 3514–3517.
- 116 M. Korb and H. Lang, *Chem. Soc. Rev.*, 2019, **48**, 2829–2882.
- 117 J. P. H. Charmant, A. M. Dyke and G. C. Lloyd-Jones, *Chem. Commun.*, 2003, 380–381, DOI: 10.1039/B210648E.
- 118 A. M. Dyke, D. M. Gill, J. N. Harvey, A. J. Hester, G. C. Lloyd-Jones, M. P. Muñoz and I. R. Shepperson, *Angew. Chem.*, *Int. Ed.*, 2008, 47, 5067–5070.
- 119 S. Braverman and Y. Duar, *Tetrahedron*, 1990, **46**, 2975–2990
- 120 R. Huisgen and J. Sauer, Chem. Ber., 1959, 92, 192-202.
- 121 R. Schwesinger and H. Schlemper, *Angew. Chem., Int. Ed. Engl.*, 1987, **26**, 1167–1169.
- 122 R. Kargbo, Y. Takahashi, S. Bhor, G. R. Cook, G. C. Lloyd-Jones and I. R. Shepperson, *J. Am. Chem. Soc.*, 2007, **129**, 3846–3847.

- 123 K. Barta, G. Franciò, W. Leitner, G. C. Lloyd-Jones and I. R. Shepperson, *Adv. Synth. Catal.*, 2008, **350**, 2013–2023
- 124 X.-H. Xu, X. Wang, G.-k. Liu, E. Tokunaga and N. Shibata, *Org. Lett.*, 2012, **14**, 2544–2547.
- 125 S. Yoshida, K. Uchida, K. Igawa, K. Tomooka and T. Hosoya, *Chem. Commun.*, 2014, **50**, 15059– 15062.
- 126 K. Uchida, S. Yoshida and T. Hosoya, *Synthesis*, 2016, 48, 4099–4109.
- 127 T. Morita, S. Yoshida, M. Kondo, T. Matsushita and T. Hosoya, *Chem. Lett.*, 2016, 46, 81–84.
- 128 C. Hall, J. L. Henderson, G. Ernouf and M. F. Greaney, *Chem. Commun.*, 2013, **49**, 7602–7604.
- 129 X.-H. Xu, M. Taniguchi, A. Azuma, G. K. Liu, E. Tokunaga and N. Shibata, *Org. Lett.*, 2013, **15**, 686–689.
- 130 X.-H. Xu, M. Taniguchi, X. Wang, E. Tokunaga, T. Ozawa, H. Masuda and N. Shibata, *Angew. Chem., Int. Ed.*, 2013, 52, 12628–12631.
- 131 Z. Zhao, J. Messinger, U. Schön, R. Wartchow and H. Butenschön, *Chem. Commun.*, 2006, 3007–3009, DOI: 10.1039/B606092G.
- 132 G. Werner and H. Butenschön, Eur. J. Org. Chem., 2012, 2012, 3132-3141.
- 133 G. Jaouen and R. Dabard, *J. Organomet. Chem.*, 1974, 72, 377–388.
- 134 G. Werner, C. W. Lehmann and H. Butenschön, *Adv. Synth. Catal.*, 2010, 352, 1345–1355.
- 135 G. Werner and H. Butenschön, *Organometallics*, 2013, 32, 5798–5809.
- 136 T. Okauchi, T. Teshima, K. Hayashi, N. Suetsugu and T. Minami, J. Am. Chem. Soc., 2001, 123, 12117– 12118.
- 137 F. M. Moghaddam and M. G. Dakamin, *Tetrahedron Lett.*, 2000, 41, 3479–3481.
- 138 B. Das, P. Madhusudhan and B. Venkataiah, *J. Chem. Res.*, 2000, **2000**, 200–201.
- 139 F. M. Moghaddam, A. A. Hoor and M. G. Dekamin, J. Sulfur Chem., 2004, 25, 125–130.
- 140 G. A. Benson, P. J. Maughan, D. P. Shelly and W. J. Spillane, *Tetrahedron Lett.*, 2001, **42**, 8729–8731.
- 141 H. Sharghi and Z. Shahsavari-Fard, *Phosphorous, Sulfur, Silicon. Relat. Elem.*, 2005, **180**, 2491–2501.
- 142 H. Sharghi and Z. Shahsavari-Fard, *Helv. Chim. Acta*, 2005, 88, 42–52.
- 143 L. K. Crevatín, S. M. Bonesi and R. Erra-Balsells, *Helv. Chim. Acta*, 2006, 89, 1147–1157.
- 144 M. Cavazza and F. Pietra, Tetrahedron Lett., 2003, 44, 1895–1897.
- 145 W. Zhang, J. Chu, A. M. Cyr, H. Yueh, L. E. Brown, T. T. Wang, J. Pelletier and J. A. Porco, *J. Am. Chem. Soc.*, 2019, 141, 12891–12900.
- 146 R. L. Atienza, H. S. Roth and K. A. Scheidt, *Chem. Sci.*, 2011, 2, 1772–1776.
- 147 Y. Wang, R. Oriez, S. Kuwano, Y. Yamaoka, K. Takasu and K.-i. Yamada, *J. Org. Chem.*, 2016, **81**, 2652–2664.

- 148 Y. Wang, R. Oriez, S. Ou, Y. Miyakawa, Y. Yamaoka, K. Takasu and K. Yamada, *Heterocycles*, 2017, 95, 314–321.
- 149 C. Lu and X. Lu, Tetrahedron, 2004, 60, 6575-6579.
- 150 C. S. Hampton and M. Harmata, *Org. Lett.*, 2014, **16**, 1256–1259.
- 151 C. S. Hampton and M. Harmata, J. Org. Chem., 2015, 80, 12151–12158.
- 152 B. Yuan, R. He, W. Shen, Y. Xu, X. Liu and M. Li, *ChemistrySelect*, 2016, 1, 2971–2978.
- 153 A. L. Krasovsky, S. V. Druzhinin, V. G. Nenajdenko and E. S. Balenkova, *Tetrahedron Lett.*, 2004, 45, 1129–1132.
- 154 G. Groszek, S. Błażej, A. Brud, D. Świerczyński and T. Lemek, *Tetrahedron*, 2006, **62**, 2622–2630.
- 155 A. E. Reed and P. v. R. Schleyer, *J. Am. Chem. Soc.*, 1990, 112, 1434–1445.
- 156 D. V. Sevenard, A. A. Kolomeitsev, B. Hoge, E. Lork and G.-V. Röschenthaler, *J. Am. Chem. Soc.*, 2003, **125**, 12366– 12367.
- 157 Y. Lou, T. P. Remarchuk and E. J. Corey, *J. Am. Chem. Soc.*, 2005, **127**, 14223–14230.
- 158 R. A. Weatherhead-Kloster and E. J. Corey, *Org. Lett.*, 2005, 8, 171–174.
- 159 H. Yang, R. G. Carter and L. N. Zakharov, *J. Am. Chem. Soc.*, 2008, **130**, 9238–9239.
- 160 H. Yang and R. G. Carter, J. Org. Chem., 2010, 75, 4929-4938.
- 161 E. Moreno-Clavijo, A. T. Carmona, H.-U. Reissig, A. J. Moreno-Vargas, E. Alvarez and I. Robina, *Org. Lett.*, 2009, 11, 4778–4781.
- 162 A. Quintard and A. Alexakis, *Chem. Eur. J.*, 2009, 15, 11109–11113.
- 163 A. Quintard and A. Alexakis, Org. Biomol. Chem., 2011, 9, 1407–1418.

- 164 N. Bravo, A.-N. R. Alba, G. Valero, X. Companyó, A. Moyano and R. Rios, New J. Chem., 2010, 34, 1816– 1820.
- 165 T. Okino, Y. Hoashi and Y. Takemoto, *J. Am. Chem. Soc.*, 2003, **125**, 12672–12673.
- 166 M.-Y. Chang, Y.-C. Cheng and Y.-J. Lu, *Org. Lett.*, 2014, **16**, 6252–6255.
- 167 K. Lu, F. Ding, L. Qin, X. Jia, C. Xu, X. Zhao, Q. Yao and P. Yu, *Chem. Eur. J.*, 2016, **11**, 2121–2125.
- 168 H. Wang, R. K. Kumar, Y. Yu, L. Zhang, Z. Liu, P. Liao and X. Bi, Chem. – Eur. J., 2016, 11, 2841–2845.
- 169 X. Zhao, Y. Huang, F.-L. Qing and X.-H. Xu, RSC Adv., 2017, 7, 47–50.
- 170 Y.-Z. Chen, T. Liu, J. Zhu, H. Zhang and L. Wu, *Org. Chem. Front.*, 2018, 5, 3567–3573.
- 171 L.-X. Shao, Y.-P. Zhang, M.-H. Qi and M. Shi, *Org. Lett.*, 2007, **9**, 117–120.
- 172 M. Kissane and A. R. Maguire, Synlett, 2011, 1212-1232.
- 173 M. Kissane, D. Lynch, J. Chopra, S. E. Lawrence and A. R. Maguire, *Tetrahedron: Asymmetry*, 2008, **19**, 1256–1273.
- 174 M. Kissane, M. Murphy, E. O'Brien, J. Chopra, L. Murphy, S. G. Collins, S. E. Lawrence and A. R. Maguire, *Org. Biomol. Chem.*, 2011, 9, 2452–2472.
- 175 M. Kissane, D. Lynch, J. Chopra, S. E. Lawrence and A. R. Maguire, *Org. Biomol. Chem.*, 2010, **8**, 5602–5613.
- 176 M. Kissane, S. E. Lawrence and A. R. Maguire, *Org. Biomol. Chem.*, 2010, **8**, 2735–2748.
- 177 M. H. Nantz and P. L. Fuchs, *J. Org. Chem.*, 1987, 52, 5298–5299.
- 178 M. C. Pérez-Aguilar and C. Valdés, *Angew. Chem., Int. Ed.*, 2015, **54**, 13729–13733.