ChemComm

FEATURE ARTICLE

View Article Online
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Cite this: *Chem. Commun.*, 2018, **54**, 2580

Recent advances in molecular rearrangements involving aryne intermediates

Tony Roy[a] and Akkattu T. Biju *[b]

This *Feature Article* is aimed at highlighting the recent developments in the transition-metal-free molecular rearrangements involving arynes. The chemistry of arynes has shown incredible developments especially in transition-metal-free carbon–carbon and carbon–heteroatom bond-forming reactions in the last three decades. The rapid growth in this field is mainly due to the development of mild methods for the generation of arynes. One aspect of the recent developments in the chemistry of arynes involves the molecular rearrangements proceeding *via* this electrophilic intermediate. The molecular rearrangements have provided direct access to a library of valuable molecules, which cannot be accessed in a single step through other synthetic routes. Herein, we present a concise account on the developments that occurred in this field over the last three decades.

Received 27th November 2017,
Accepted 30th January 2018

DOI: 10.1039/c7cc09122b

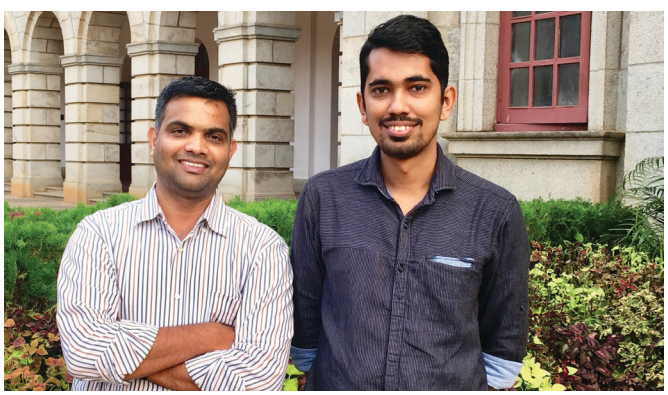
rsc.li/chemcomm

1. Introduction

The aryne chemistry has witnessed a resurrection in the last three decades and has been smartly utilized by synthetic chemists for the synthesis of various mono-, di- and even tri-substituted arenes.[1] Engaging arynes is one of the appropriate methods for the synthesis of benzo-fused heterocycles of molecular complexity and structural diversity.[2] The first hint on this century old intermediate was provided by Stoermer and Kahlert in 1902 and they postulated the existence of a 2,3-didehydrobenzofuran intermediate.[3] In arynes, due to the presence of a carbon–carbon triple bond in a six-membered ring, the unhybridized p-orbitals are not parallel to each other (compared to normal alkynes), and this strain makes them highly reactive. Due to the high reactivity of this intermediate, arynes are not isolable or bench stable and thus they have to be generated *in situ* in the reaction mixture. Arynes are traditionally generated under harsh reaction conditions which include the use of strong bases, metals and high temperature.

Some of the precursors used were explosive in nature, for instance, the diazonium compounds.[4] Decades later, in 1983, Kobayashi and co-workers uncovered a mild, efficient, and

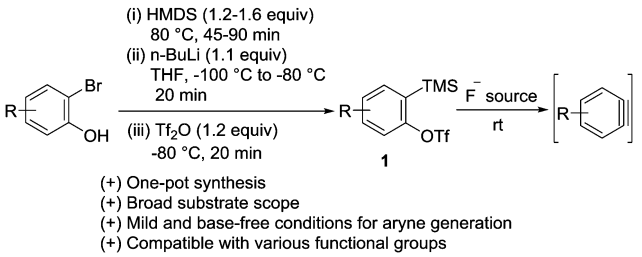
[a] *Organic Chemistry Division, CSIR-National Chemical Laboratory (CSIR-NCL), Dr. Homi Bhabha Road, Pune-411008, India*
[b] *Department of Organic Chemistry, Indian Institute of Science, Bangalore-560012, India. E-mail: atbiju@iisc.ac.in; Fax: +91-80-23600529; Tel: +91-80-22932646*



Akkattu T. Biju and Tony Roy

A. T. Biju received his BSc and MSc from Mahatma Gandhi University, Kerala, India and PhD under the guidance of Dr Vijay Nair at the CSIR-NIIST (Formerly RRL), Trivandrum, India. Subsequently, he has been a post-doctoral fellow with Prof. Tien-Yau Luh at the National Taiwan University, Taipei and an Alexander von Humboldt fellow with Prof. Frank Glorius at the Westfälische Wilhelms-Universität Münster, Germany. In June 2011, he began his independent research career at the CSIR-National Chemical Laboratory, Pune, India. From June 2017 onwards, he has been an Associate Professor at the Department of Organic Chemistry, Indian Institute of Science, Bangalore. His research focuses on the development of transition-metal-free carbon–carbon and carbon–heteroatom bond-forming reactions using aryne chemistry and N-heterocyclic carbene (NHC) organocatalysis, and their application in organic synthesis.

Tony Roy was born in 1989 in Kottayam (Kerala), India. He completed his BSc in chemistry at Mahatma Gandhi University, Kottayam, Kerala in 2011 and MSc from School of Chemical Sciences, Mahatma Gandhi University, Kottayam, Kerala in 2013. Currently, he is a PhD student (Inspire Fellow) in the research group of Dr A. T. Biju. His research focuses on molecular rearrangements involving arynes and related chemistry.



Scheme 1 Fluoride-induced generation of arynes.[5]

convenient method for aryne generation by the fluoride-induced 1,2-elimination of 2-(trimethylsilyl)aryl triflates (Scheme 1).[5] The mild conditions employed for the generation of arynes from **1** are compatible with a wide variety of functional groups.

Kobayashi's protocol for aryne generation from **1** has substantially modernized this field and this intermediate has been widely employed in rediscovering many of the classical aryne reactions, and also in uncovering new modes of reactivity of this electrophilic intermediate. The conventional reactivity of arynes can be classified into cycloaddition reactions, insertion reactions and transition-metal-catalyzed transformations. Cycloaddition reactions include Diels–Alder reactions, [2+2] cycloaddition reactions, and dipolar cycloadditions (Fig. 1). In the last two decades, aryne chemistry has contributed much towards the development of new multicomponent reactions as well. A wide range of nucleophiles such as isocyanides, N-heterocycles, phosphines and other heteroatom nucleophiles can add to the highly electrophilic arynes and the resultant aryl anion intermediate can be intercepted by a third-component, mainly carbonyls.[6] Recently, considerable efforts have been dedicated to molecular rearrangements involving arynes. The purpose of the article is to shed light on various molecular rearrangements involving the aryne intermediates thereby highlighting the power of these intermediates in organic chemistry.

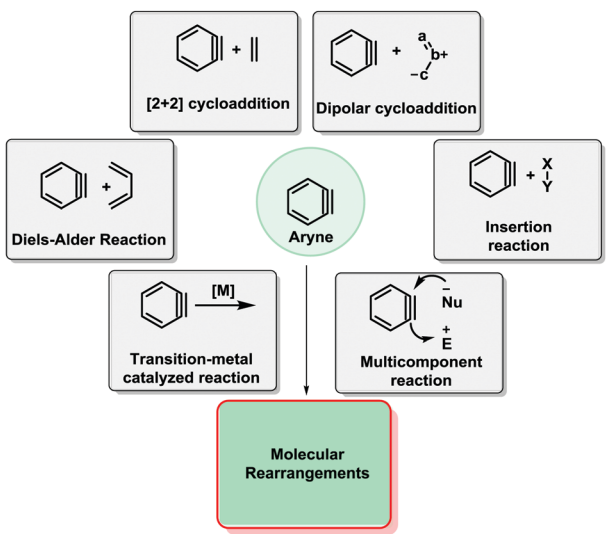
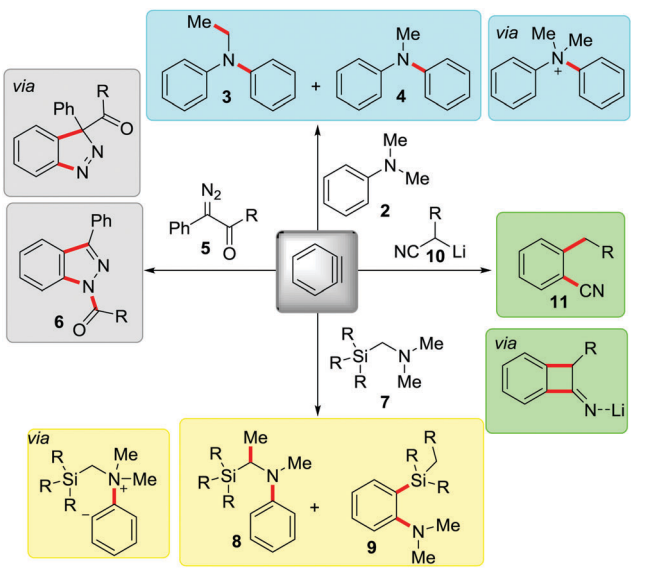


Fig. 1 Classification of aryne reactions.

2. Rearrangements involving aryne intermediates

The aryne chemistry has witnessed several interesting modes of reactivity throughout its development in the early stages. Notably, it included molecular rearrangement as well. In 1966, Lepley and co-workers found that when the aryne intermediate generated using *n*-BuLi and halobenzene was reacted with dialkylanilines, different products were formed *via* molecular rearrangement reactions.[7] For instance, the reaction of *N*,*N*-dimethylaniline **2** and aryne delivered *N*-ethyl diphenylamine **3** and *N*-methyl diphenylamine **4** (Scheme 2). These reactions proceed *via* the generation of the diarylamino methyl ylide, which undergoes either a methyl group migration (to form **3**) or a single methylene carbene loss (to deliver **4**). Interestingly, Biju and co-workers recently demonstrated that when the aryne was generated from the silyl triflate **1**, selective formation of **4** can be achieved *via* a demethylation pathway.[8]

In 1974, Yamazaki and co-workers found that aryne can react with diazo compound **5** yielding 1-benzoyl-3-phenylindazole **6**. The reaction is expected to proceed *via* the initial formation of the 1,3-dipolar adduct between **5** and aryne followed by successive 1,3-migration of the benzoyl group leading to the formation of the indazole **6**.[9] Moreover, in 1975, Sato and co-workers uncovered a novel rearrangement reaction of aryne with (dimethylaminomethyl) trialkylsilane **7**. The functionalized tertiary amine **8** was formed by [1,2] Stevens rearrangement *via* the nitrogen ylide intermediate.[10] The 1,2-disubstituted benzene **9** was formed by a unique rearrangement involving the migration of the silyl group to the aryl ring followed by the aryl shift from silicon to nearby carbon. Later, the reaction of aryne with various lithiated alkyl nitriles **10** leading to the synthesis of various *o*-alkylated benzonitriles **11** was demonstrated by Meyers and Pansegrau (Scheme 2).[11] Some of the interesting molecular rearrangement reactions involving arynes

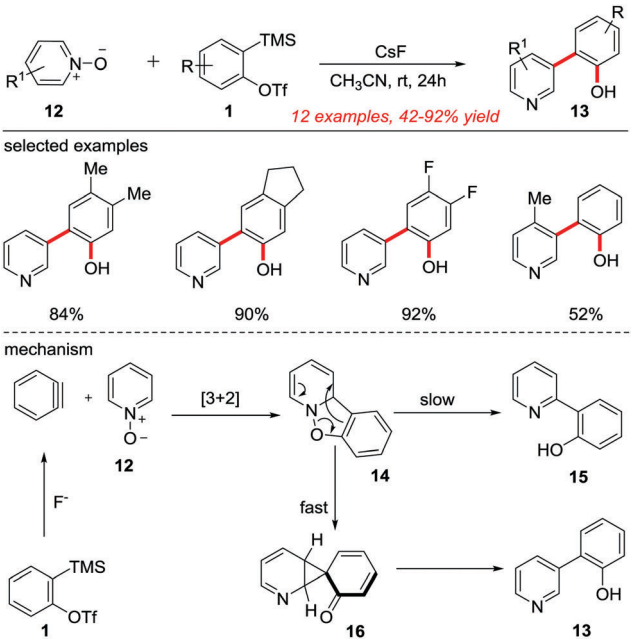


Scheme 2 Molecular rearrangements involving arynes: early reports.

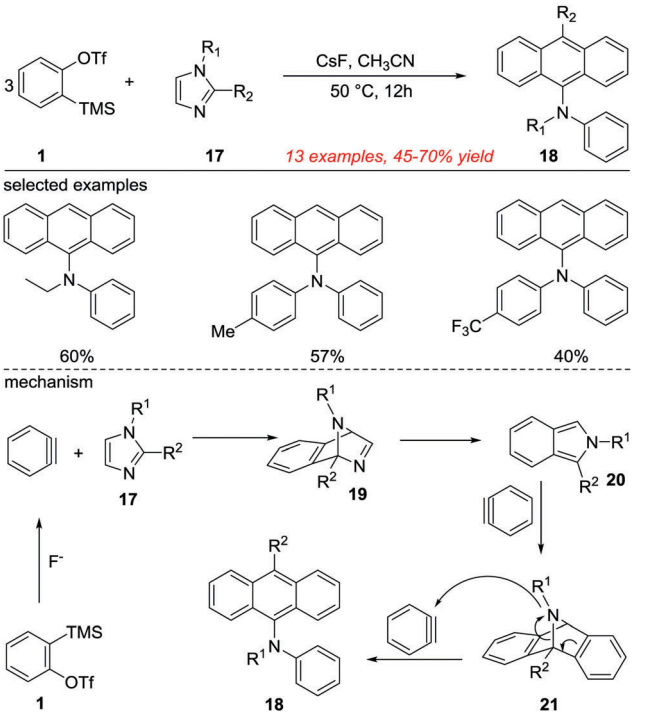
generated using Kobayashi's method are discussed in the following sections.

In 2006, Larock and co-workers uncovered a transition-metal-free and mild synthesis of substituted 3-(2-hydroxyphenyl)-pyridines **13** in a regioselective manner by the reaction of arynes generated from silylaryl triflates with pyridine *N*-oxides **12**. This regioselective coupling reaction proceeds in good yields with a broad substrate scope (Scheme 3).[12] CsF was used as the fluoride source in this rearrangement reaction with CH_3CN as the solvent, and the reaction proceeds smoothly at room temperature. However, the use of TBAF as the fluoride source ended up with a lower yield of the desired product. The reaction of pyridine *N*-oxide with different electronically dissimilar aryne precursors delivered the functionalized biaryls in good yields. Moreover, the scope is general with different pyridine *N*-oxides as well. Mechanistically, the reaction proceeds *via* the initial [3+2] cycloaddition between aryne and **12** leading to the oxazolopyridine intermediate **14**, which upon a simultaneous rearrangement results in the formation of the cyclopropane intermediate **16**. This intermediate opens up forming the pyrido-biaryls **13** in good yields. However, the other possible product **15** was not observed under the reaction conditions. Very recently, Sharma and co-workers developed a strategy for the construction of 3-aryl-2-substituted quinolines and 4-arylacridines *via* similar rearrangement involving arynes.[13]

Subsequently, Xie and Zhang demonstrated a tandem reaction of arynes with *N*-substituted imidazoles, where three molecules of aryne were incorporated in the final product. Although the reaction of arynes with *N*-substituted imidazoles leading to the synthesis of *N*-alkyl-*N*′-aryl imidazolium salts was reported by the Yoshida group,[14] under the optimized reaction conditions, the reaction afforded arylamines containing anthracene moiety **18** in moderate to good yields *via* multiple cycloaddition reactions and a final nucleophilic coupling (Scheme 4).[15]



Scheme 3 Reaction of aryne with pyridine *N*-oxides.[12]

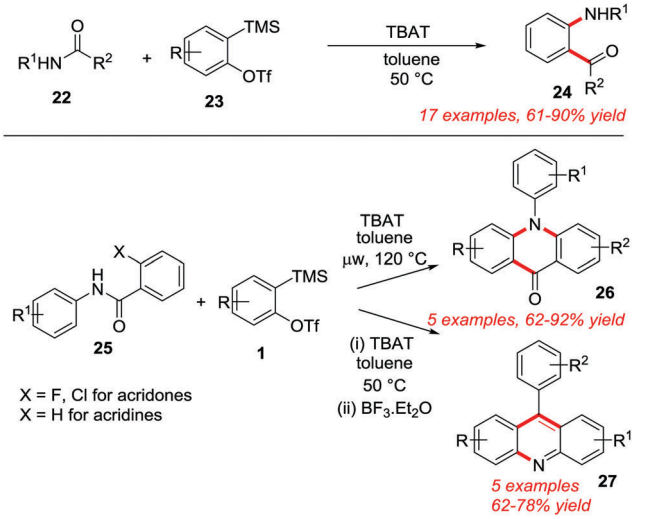


Scheme 4 Tandem reaction of aryne with imidazoles.[15]

It was observed that the temperature has a vital role to play in the present tandem process. At 50 °C the arylamine was obtained in good yield. CH_3CN was proved to be the best solvent. Using other solvents such as DME, THF and toluene did not improve the yield of **18**. Substrate screening has proved that the reaction is general with a variety of imidazole derivatives. The mechanism involves the initial Diels–Alder reaction of substituted imidazole **17** with the *in situ* generated aryne leading to the nitrogen-bridged isoquinoline intermediate **19**. Elimination of a molecule of HCN *via* the retro Diels–Alder reaction results in the formation of **20**. A second Diels–Alder reaction of the intermediate **20** with another molecule of aryne delivers the intermediate **21**. Finally, the intermolecular nucleophilic addition of intermediate **21** to the third molecule of aryne affords the desired product **18**.

In 2009, Greaney and co-workers demonstrated the insertion of arynes into the C=N bond of amides providing a direct synthetic route toward amino benzophenone products **24** in good yields (Scheme 5).[16] Interestingly, this insertion methodology can be used for the efficient one-pot synthesis of biologically active acridones and acridines. Interestingly, *o*-halo benzamides underwent an initial aryne σ-insertion, followed by an *in situ* S_NAr reaction forming acridones **26** in high yields under microwave irradiation at 120 °C in the presence of TBAT. Moreover, the amino benzophenone products could easily be transformed into acridines **27** through a Lewis acid mediated intramolecular Friedel–Crafts acylation and dehydration reaction.

Aryne insertion into various carbon heteroatom bonds resulted in a facile route toward different bifunctionalized arene products. In 2011, the Greaney group uncovered the insertion reaction of aryne into the C=S bond of thioureas

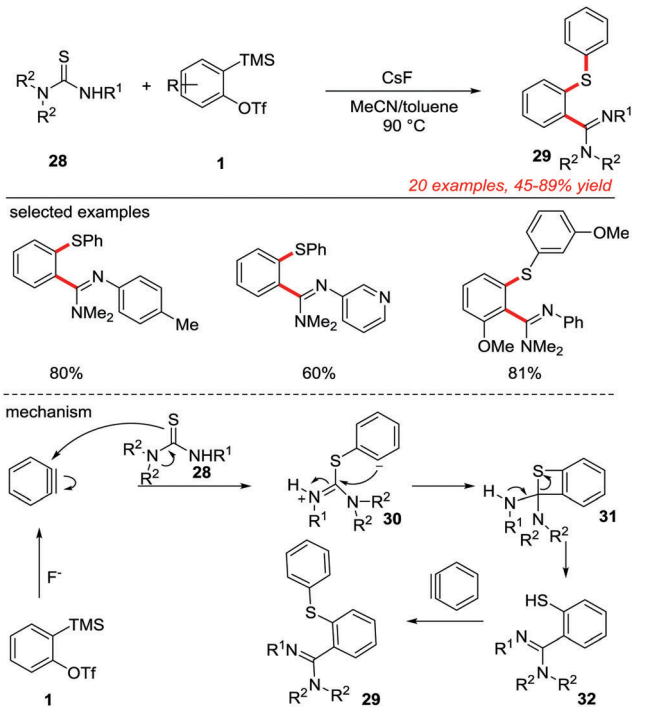


Scheme 5 Insertion of arynes into the amide bond.[16]

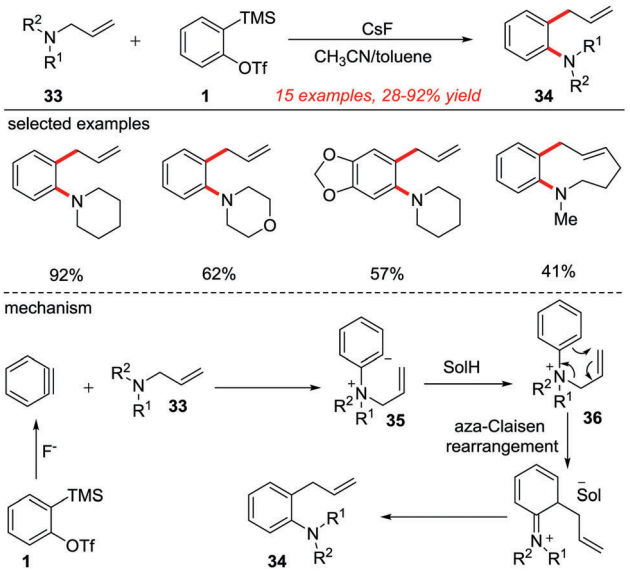
forming amidine products **29** (Scheme 6).[17] A mixture of acetonitrile and toluene was found to be the optimal solvent system. The reaction proceeds *via* the initial formation of the [2+2] adduct **31** *via* zwitterionic intermediate **30** followed by ring opening to give the thiol intermediate **32**. The arylation of the thiol **32** with a second molecule of aryne resulted in the formation of the amidine **29**.

2.1. Aza-Claisen rearrangements involving arynes

The aza-Claisen rearrangement of allyl aniline derivatives is considered to be an atom-efficient and potential protocol for



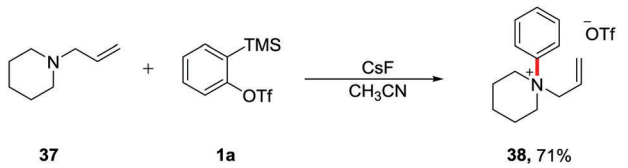
Scheme 6 Insertion of arynes into thioureas.[17]



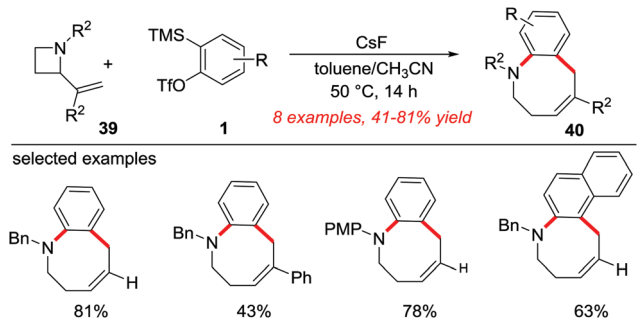
Scheme 7 Aryne aza-Claisen rearrangement.[18]

the synthesis of various 2-allyl anilines. Conventional aza-Claisen rearrangements require high reaction temperature or use of stoichiometric amounts of Lewis acids such as $BF_3.(OEt)_2$ to proceed. In 2009, Greaney and co-workers developed a simple protocol for this rearrangement employing arynes. The addition of aryne generated from **1** to tertiary allylamine **33** resulted in the aza-Claisen rearrangement under mild conditions to afford functionalized anilines **34** (Scheme 7).[18] A variety of piperidine and morpholine derived tertiary allylic amines were proven to be good substrates for this aryne aza-Claisen rearrangement reaction. The substitution in the aryne precursor did not affect the efficiency of the rearrangement reaction. Even cyclic allylic amines were also tolerable under the optimized conditions. The reaction is initiated by the nucleophilic attack of tertiary allylic amine to the aryne generating the 1,3 zwitterionic intermediate **35**. This intermediate gets protonated by the solvent to give the quaternary ammonium salt **36**. The salt **36** under the reaction conditions undergoes an aza-Claisen rearrangement to deliver the functionalized anilines **34**.

Direct evidence for the proposed mechanism was provided with the isolation of the quaternary ammonium salt **38** from the reaction of aryne generated from **1a** and tertiary amine **37** (Scheme 8). When the salt **38** was subjected to the reaction conditions, the rearranged aniline product was obtained, further confirming the proposed mechanism. Notably, ether solvents were not found to be beneficial for this rearrangement due to the lack of protonating ability of the ether solvent.



Scheme 8 Isolation of the quaternary salt from aryne and tertiary amine.

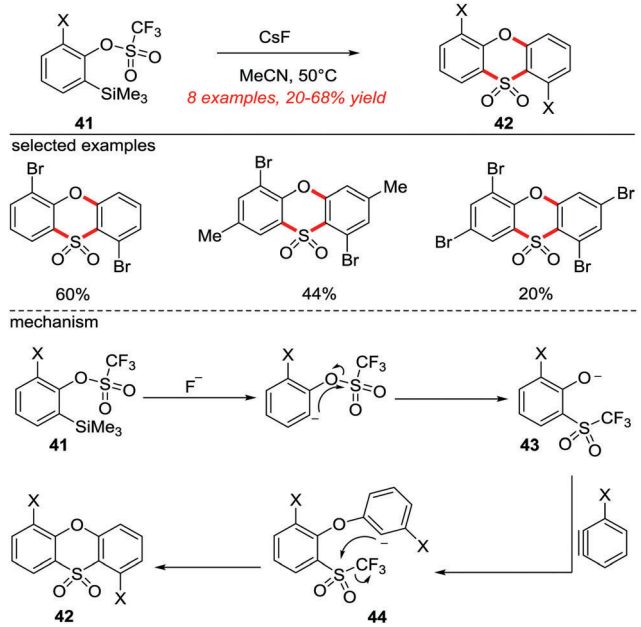


Scheme 9 Synthesis of 1-benzazocine derivatives using arynes.[19]

Inspired by the Greaney report on aryne aza-Claisen rearrangement, Saito and co-workers have disclosed the reaction of 2-vinylazetidines **39** with arynes resulting in the smooth synthesis of 1-benzazocine derivatives **40** *via* analogous rearrangement (Scheme 9).[19] It may be noted that dropwise addition of **39** and **1** to a solution of CsF in toluene/CH_3CN was required for the high yield of benzazocine **40** in this ring expansion reaction. The reaction proceeds *via* the addition of azetidine **39** to aryne generated from **1** followed by protonation of the aryl anion and a subsequent aza-Claisen rearrangement.

2.2. Thia-Fries rearrangement involving arynes

Later, Greaney and co-workers demonstrated the thia-Fries rearrangement involving arynes generated from the 2-(trimethylsilyl)aryl trifluoromethanesulfonate precursors, which resulted in the synthesis of phenoxathiin-dioxides **42** under mild reaction conditions (Scheme 10).[20] The presence of halogen at the 3-position of aryne precursors **41** was mandatory for the synthesis of phenoxathiin-dioxides. Conventionally, the synthesis of phenoxathiin-dioxides has been achieved by the preparation of the corresponding phenoxathiin and a subsequent oxidation, and the method employing arynes is a direct method to access them. The corresponding phenoxathiin-dioxide derivatives were formed in moderate to good yields in the presence of CsF as the fluoride source. The mechanism involves the initial fluoride induced desilylation of **41** followed by an intramolecular sulfonylation (thia-Fries reaction) to give the phenoxide intermediate **43**. The naked phenoxide adds as a nucleophile to the second molecule of aryne to form the aryl anion intermediate **44**. An intramolecular cyclization with the release of the CF_3 group leads to the formation of the phenoxathiin-dioxide product **42**. Cross-over experiments carried out using different aryne precursors resulted in the formation of both homo-coupled and hetero-coupled phenoxathiin-dioxides, thus indicating the role of the precursor **41** as a substrate for the thia-Fries rearrangement as well as for aryne generation.

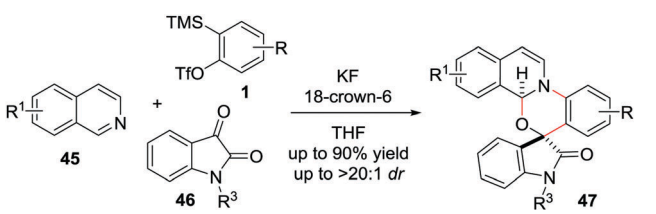


Scheme 10 Aryne thia-Fries rearrangement.[20]

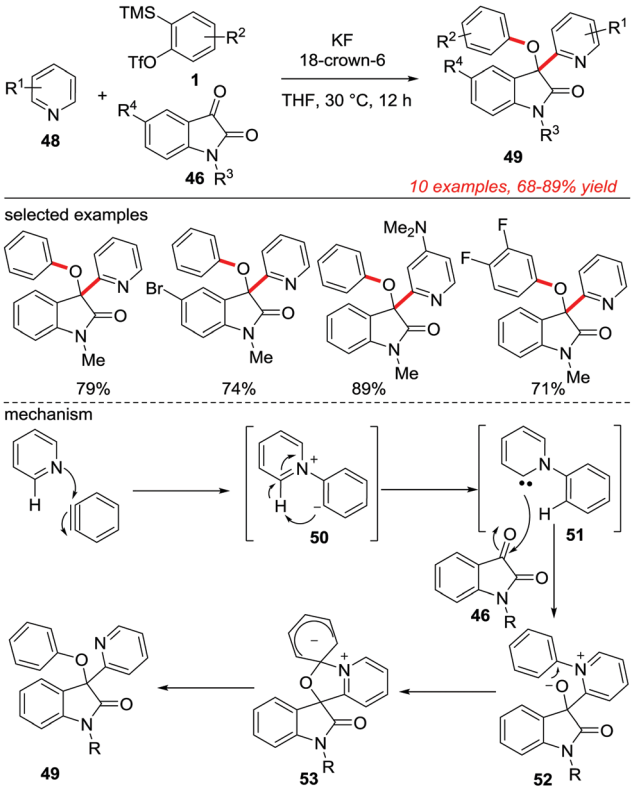
2.3. N-Heterocycles triggered rearrangements *via* arynes

In 2013, Biju and co-workers reported a transition-metal-free multicomponent reaction (MCR) involving arynes, N-heterocycles, and isatins.[21] During this study, an unusual rearrangement was observed when pyridine was used as the nucleophilic trigger. Employing isoquinoline **45** as the heterocyclic initiator of MCR and using *N*-substituted isatin **46** as the third component, the reaction afforded an inseparable mixture of spirooxazino isoquinoline derivatives **47** in good yield and diastereoselectivity (Scheme 11). The reaction proceeds *via* the initial generation of the 1,4-zwitterionic intermediate from isoquinoline and aryne followed by the interception with the electrophilic carbonyl group of isatin to afford the spiro compounds.[22]

On the other hand, engaging pyridine **48** as the nucleophilic trigger for the aryne MCRs did not afford the expected pyridooxazino derivatives, but instead furnished the indolin-2-one derivatives **49** in good yields (Scheme 12).[21] The reaction proceeds *via* a conceptually new pyridylidene intermediate, which was confirmed by mechanistic experiments. A C–H bond functionalization of pyridine and an intramolecular aryl transfer reaction were the noteworthy features of this unique aryne MCR. The scope of the methodology was well explored with variation of pyridines, arynes and isatins. The reaction was initiated with the nucleophilic attack of pyridine on aryne to generate the 1,4-dipolar intermediate **50**. The intermediate **50** undergoes an intramolecular proton transfer to generate the pyridylidene intermediate **51**. This highly nucleophilic pyridylidene intermediate **51** adds to the electrophilic carbonyl group of isatin



Scheme 11 MCR involving isoquinolines, arynes and *N*-substituted isatins.[21]



Scheme 12 MCR involving pyridine, arynes and *N*-substituted isatins.[21]

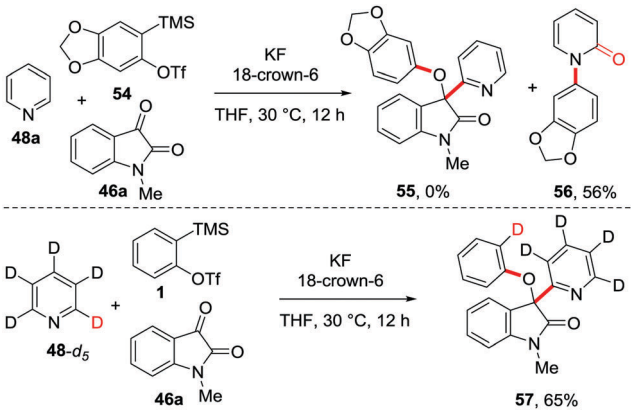
derivative **46** forming the intermediate **52**, which undergoes an intramolecular nucleophilic aromatic substitution (S_NAr) reaction to furnish indolin-2-one **49** *via* the intermediate **53**.

A couple of mechanistic experiments strongly suggest that the active species involved in the reaction is a pyridylidene intermediate **51**. When the reaction was performed using 4,5-disubstituted symmetrical aryne precursor **54**, the reaction furnished the *N*-aryl pyridin-2-one derivative **56** in 56% yield.

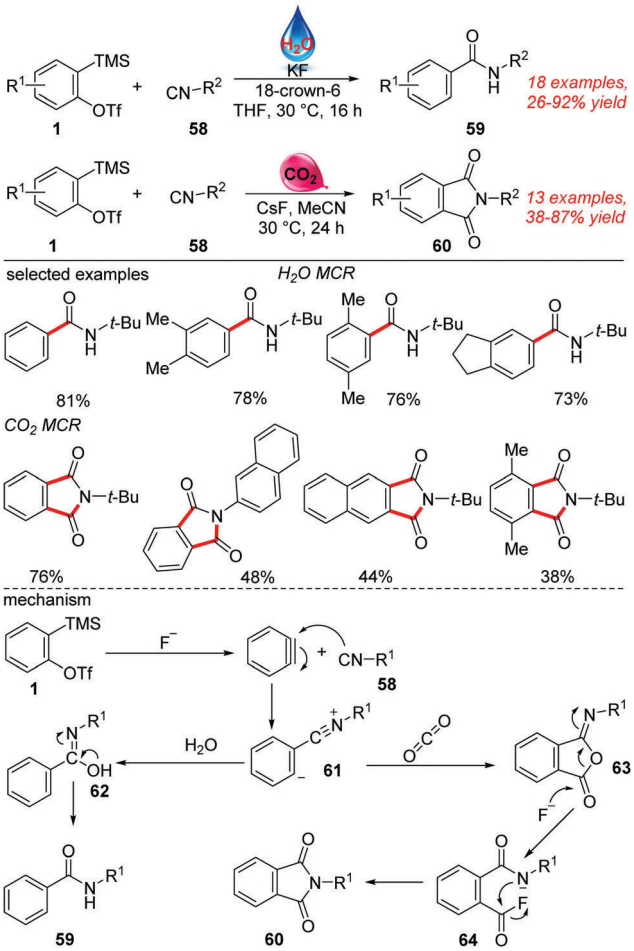
The corresponding indolin-2-one derivative **55** was not observed under this condition. Also, to strengthen the proposal of the active species pyridylidene **51** in this reaction, an experiment was carried out using [D_5]pyridine **48**-d_5, and deuterium incorporation was observed at the 2 position of the aryl group in the corresponding product **57** (Scheme 13).

2.4. Isocyanides triggered rearrangements *via* arynes

Efficient utilization of CO_2 as a one-carbon source is one of the green methods for the synthesis of value-added products. Molecular rearrangements involving arynes with CO_2 as a reacting partner were unknown until 2014, when Biju and co-workers developed a transition-metal-free MCR involving arynes and isocyanides **58** with either CO_2 or H_2O as the third component. The use of H_2O as the third component resulted in the formation of benzamide derivatives **59** in moderate to good yields (Scheme 14).[23] With CO_2 as the third component, the reaction resulted in the formation of *N*-substituted phthalimides **60** in which the reaction proceeds *via* an interesting fluoride induced rearrangement. The scope of the reactions is



Scheme 13 Experiments to indicate the involvement of the pyridylidene intermediate.



Scheme 14 MCR involving isocyanides, arynes, and CO_2/H_2O.[23]

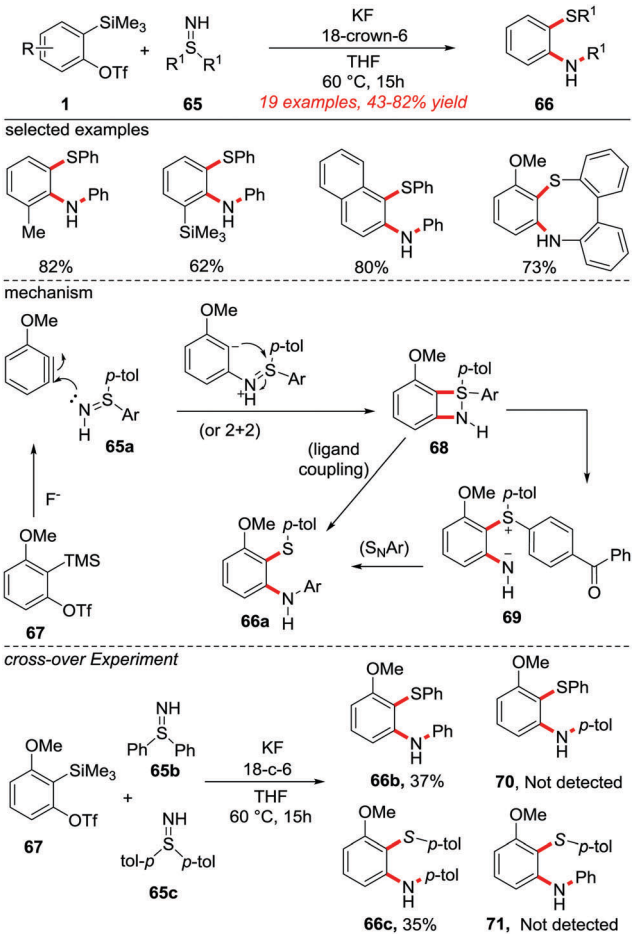
broad, and the aromatic amides and *N*-substituted phthalimides were formed in moderate to good yields.

The initial attack of the isocyanide **58** on the aryne generated *in situ* forms the 1,3-zwitterionic intermediate **61**. This intermediate undergoes a [3+2] cycloaddition with CO_2 leading to intermediate **63**. The reaction did not stop at this stage, but a

fluoride induced rearrangement transformed imino isobenzofuran **63** to the pthalimide **60** *via* the acylfluoride **64**. However, in the presence of H_2O, the intermediate **61** gets protonated and the hydroxyl anion attacks the iminium leading to intermediate **62**. Finally, a 1,3 hydrogen shift leads to the benzamide product **59**.

2.5. Sulfilimines triggered rearrangements *via* arynes

In 2015, a direct thioamination of arynes for preparing a diverse range of *o*-sulfanylanilines **66** was described by Hosoya and co-workers. The reaction of arynes generated from **1** with sulfilimines **65** was expected to give *N*-arylated sulfilimines. However, surprisingly, the reaction ended up with *o*-sulfanylanilines **66**, which are useful moieties in a broad range of fields. The methodology involves C–N and C–S bond formation and a migratory *N*-arylation. Thus a double heteroatom functionalization has been achieved with sulphur and nitrogen at the ortho position of the benzene ring (Scheme 15).[24] Under the optimized reaction conditions, various *o*-sulfanylaniline derivatives were prepared in moderate to good yields using different sulfilimines and differently substituted arynes. The reaction proceeds *via* the generation of the four-membered ring intermediate **68**, which is formed either *via* nucleophilic addition of sulfilimine **65a** to the aryne **67** followed by cyclization or *via* a direct [2+2] cycloaddition. Cleavage of the S–N bond of intermediate **68** and subsequent intramolecular *ipso*-substitution at the more electron-deficient aryl group provided the product. However, the authors did not exclude the possibility of a pathway involving direct ligand coupling on the sulfur of intermediate **68** (Scheme 15). A crossover experiment was performed and the result suggests that rearrangement of the aryl group from the arylthio moiety proceeded in an intramolecular manner. When the aryne precursor **67** was treated with sulfilimines **65b** and **65c**, the cross-over products **70** and **71** were not observed and the desired products **66b** and **66c** were formed in moderate yields.



Scheme 15 Direct thioamination of arynes.[24]

2.6. Oxythiolation of arynes

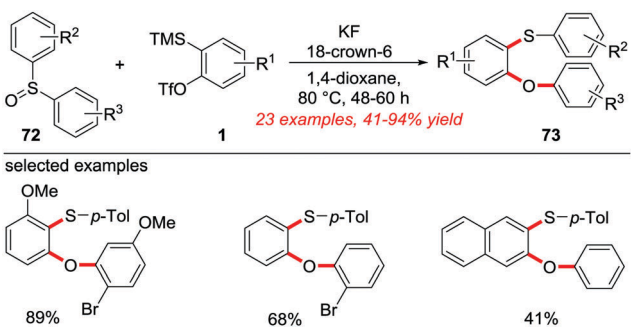
An efficient synthetic strategy for the oxythiolation of arynes has been developed by Hosoya and co-workers. The direct oxythiolation of arynes with diaryl sulfoxides **72** and subsequent migratory *O*-arylation provides a mild strategy to synthesize such highly functionalized 1,2-disubstituted benzenes **73** (Scheme 16).[25] The mechanism of this transformation is similar to that of the thioamination of arynes discussed above.[22] The reaction resulted in the formation of carbon–oxygen and carbon–sulfur bonds followed by the migratory *O*-arylation. The scope of the reaction was broad and the products were obtained in moderate to good yields.

2.7. C3-Arylation of indoles *via* arynes

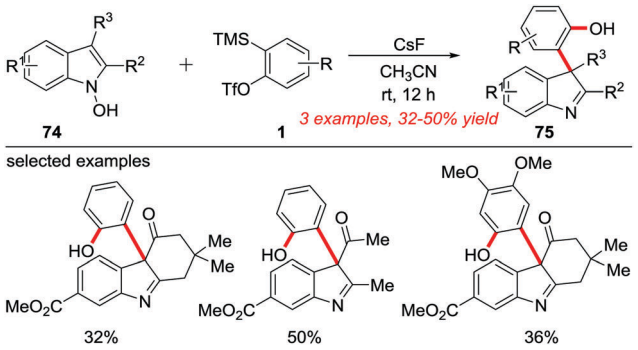
Recently, Chen and Wang reported the synthesis of C3-arylated indoles **75** by the reaction of *N*-hydroxyindoles **74** with arynes, and the reaction proceeds *via* a unique [3,3]-rearrangement (Scheme 17).[26] The C3-aryl indole formation took place instead of the expected 2-aminophenol products. Though the yields are not impressive, biologically relevant C3-aryl indole skeletons could be accessed using this new rearrangement involving arynes.

2.8. Benzylic-type rearrangement employing arynes

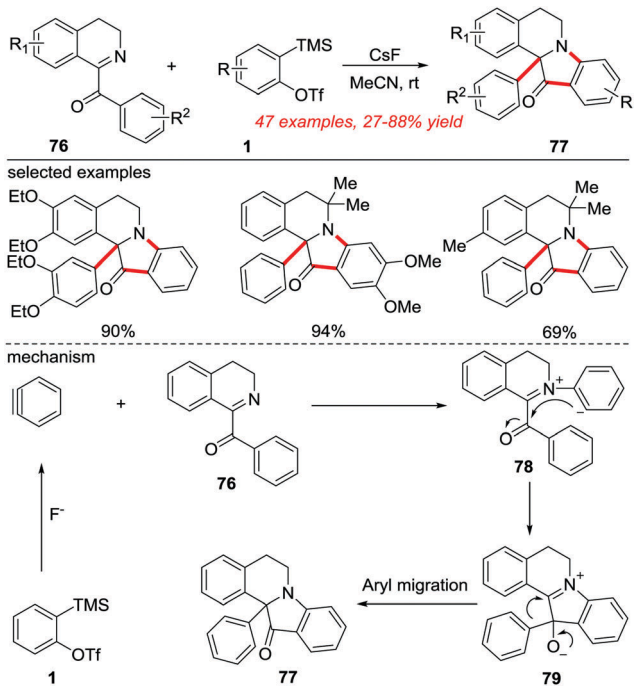
In 2016, Voskressensky and co-workers described the synthesis of indoxylisoquinolines **77** by the reaction of 1-aryloxy substituted 3,4-dihydroisoquinolines **76** and arynes *via* aryl-anion migration (Scheme 18).[27] This new rearrangement involving arynes provides a direct route to the synthesis of biologically valuable indoxylisoquinoline cores. The optimal conditions for



Scheme 16 Oxythiolation of arynes.[25]



Scheme 17 Synthesis of C3-aryl indole using arynes.[26]

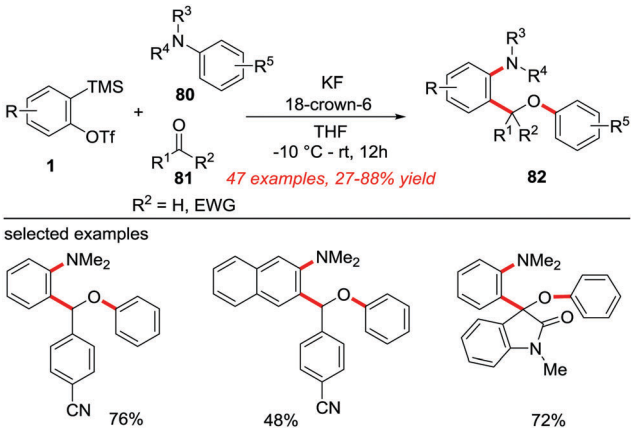


Scheme 18 Synthesis of indoxyl isoquinolines from arynes.[27]

this reaction consisted in the use of CsF as the fluoride source and CH_3CN as the solvent at room temperature. The scope of the reaction was general with variation in both the components and the yields are very high in most of the cases. Mechanistically, the reaction proceeds *via* the nucleophilic attack of the dihydroisoquinoline **76** on aryne leading to the generation of the zwitterion **78**. Intramolecular aryl anion attack to the carbonyl centre forms the intermediate **79**. This is followed by the migration of the aryl substituent to the iminium carbon forming the indoloisoquinolinones **77**. This migration resembles the benzylic rearrangement and quasi-Favorskii rearrangements of α-haloaryl ketones.

2.9. Smiles rearrangement involving arynes

In 2015, a transition-metal-free multicomponent coupling involving arynes generated from **1**, aromatic tertiary amines **80**, and carbonyls **81** was demonstrated by Biju and co-workers.

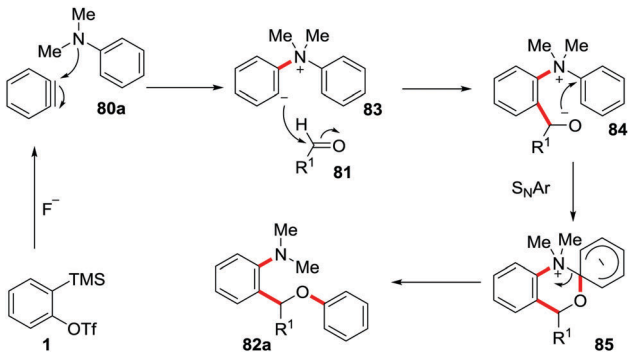


Scheme 19 MCCs involving arynes, carbonyls and tertiary amines.[28]

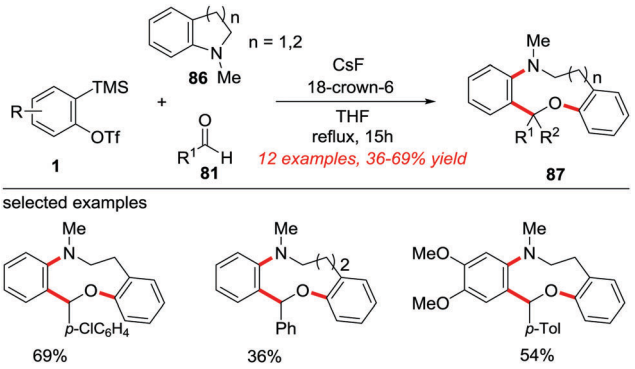
This protocol allows rapid access to *ortho*-functionalized tertiary amines **82** in moderate to good yields. The use of ketone as the carbonyl component and the similarity of the aryl–aryl tertiary amino group migration with the Smiles rearrangement are notable features of this reaction (Scheme 19).[28] The scope of this aryne MCC with various aldehydes and differently substituted arynes and tertiary amines has been well studied. In all the cases, the *ortho*-functionalized tertiary amines were obtained in good yields. Also activated carbonyls like various isatins, phenyl ethyl glyoxylate, *etc.* also worked well under optimized conditions.

A tentative mechanism of this reaction is presented in Scheme 20. The nucleophilic attack of tertiary amine **80a** on aryne generated from **1** results in the formation of the dipolar intermediate **83**. This intermediate generates the key tetrahedral intermediate **84** upon addition to the carbonyl group in **81**. An intramolecular nucleophilic aromatic substitution reaction (S_NAr) results in the formation of the desired product **82a** *via* the σ-complex **85**. Mechanistically, the aryl to aryl amino group migration process resembles the Smiles rearrangement (Scheme 20).

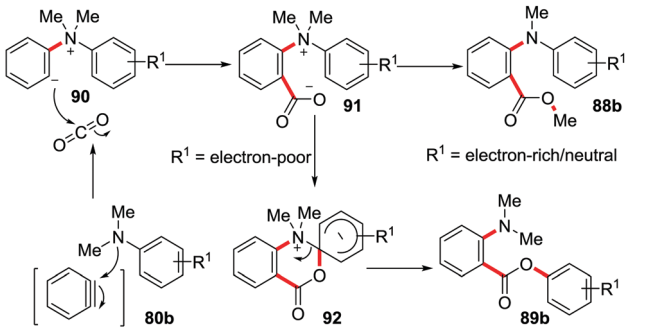
Subsequently, Okuma and co-workers investigated the three-component reaction of aromatic cyclic tertiary amines **86** with aryne and aldehydes. A similar Smiles rearrangement took place and the MCR afforded medium-sized dibenzannulated heterocycles. This reaction involving arynes appears to be a



Scheme 20 Proposed mechanism for aryne Smiles rearrangement.



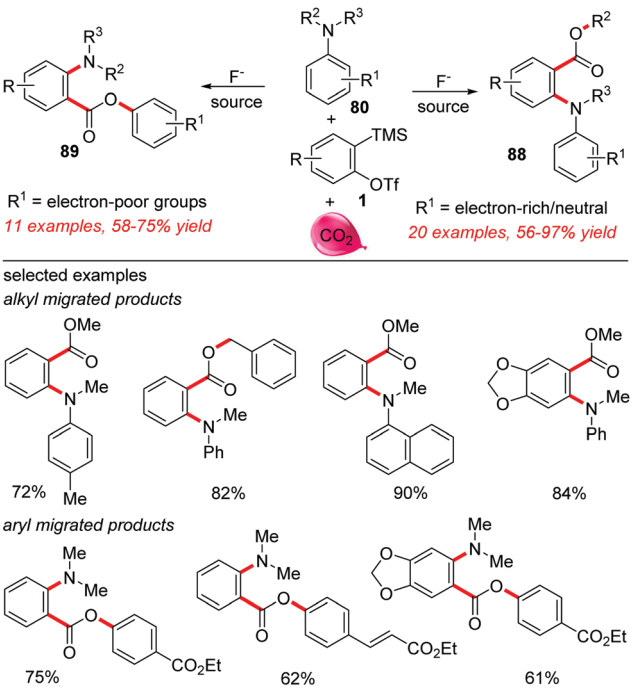
Scheme 21 MCC involving aryne, aldehydes and cyclic tertiary amines.[29]



Scheme 23 Proposed mechanism for the MCCs involving aryne, CO_2 and tertiary amines.

facile method for the synthesis of 9- and 10-membered cyclic dibenzo[1,5]oxazonines and dibenzo[1,5]oxazecines **87** (Scheme 21).[29] The scope of the reaction was explored using different aldehydes and moderate to good yields were obtained in most of the cases.

As a continuation of the aryne MCRs triggered by tertiary amines, Biju and co-workers disclosed transition-metal-free MCRs involving arynes, aromatic tertiary amines **80** and CO_2. When the amine coupling partner possesses an electron-releasing/neutral group, the reaction afforded 2-arylamino benzoates **88** *via* a nitrogen to oxygen alkyl group migration. On the other hand, employing electron-deficient amines in the reaction delivered 2-aminoaryl benzoates **89** in which the reaction proceeds *via* an aryl migration resembling the Smiles rearrangement (Scheme 22).[30,31] A series of *N*,*N*-dimethyl anilines with differently substituted electron-releasing/neutral/moderately electron-poor groups provided expected methyl migrated products in good yields. Similarly, *N*,*N*-dimethyl anilines with electron-withdrawing groups were well tolerated and delivered 2-aminoaryl benzoates *via* an aryl to aryl migration of the amino group.



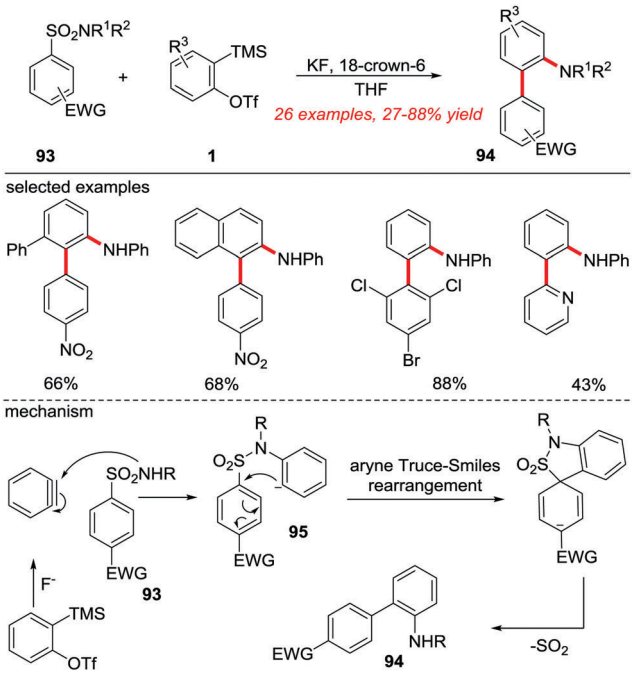
Scheme 22 MCC involving aryne, CO_2 and tertiary amines.[28]

The mechanism of this interesting substrate-controlled switchable reaction initiates with the addition of aromatic tertiary amines to arynes. The 1,3-zwitterionic intermediate **90** formed adds to CO_2 generating the key intermediate **91**. With electron-rich/neutral amines, the reaction underwent a methyl group transfer to furnish the 2-arylamino benzoate **88b**. However, an intramolecular nucleophilic aromatic substitution reaction (S_NAr) is observed in the case of tertiary amines having an electron-poor group attached, resulting in the aryl to aryl NMe_2 group migration leading to the synthesis of *N*,*N*-dimethyl aniline derivative **89b** proceeding *via* the σ-complex **92** (Scheme 23).

Given the important applications of the biaryl motif in numerous areas in organic synthesis, Greaney and co-workers disclosed a facile protocol for the synthesis of functionalized biaryls **94** employing arynes. Specifically, the reaction of aryl sulfonamides **93** with arynes proceeds *via* a unique aryl Truce–Smiles rearrangement resulting in the formation of amino biaryls with the extrusion of SO_2 (Scheme 24).[32,33] The reaction proceeds under mild conditions and has excellent scope with both aryl sulfonamides and arynes for the synthesis of sterically hindered tri- and tetra- *ortho*-substituted biaryl amines, which are usually difficult to access through cross-coupling reactions. It is noteworthy that the aryl anion generated is taking part in an *ipso* substitution. The reaction proceeds *via* the addition of aryl sulfonamide **93** to aryne generated from **1**, leading to the formation of the aryl anion intermediate **95**. This intermediate could then undergo a Smiles-type *ipso* substitution followed by SO_2 elimination to afford 2-amino biaryls **94**.

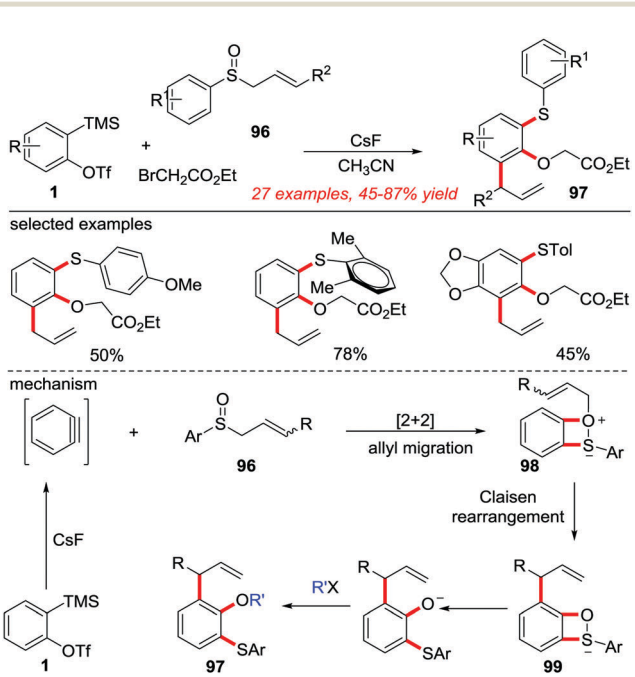
2.10. Aryne 1,2,3-trifunctionalization *via* Claisen rearrangement

Recently, Li and co-workers uncovered the 1,2,3-trisubstitution of arynes using aryl allyl sulfoxides **96** resulting in the formation of a variety of 1,2,3-trisubstituted arenes **97**. The reaction resulted in the construction of three new bonds including C–S, C–O, and C–C bonds in a single reaction at the consecutive positions of a benzene ring. The reaction conditions are mild



Scheme 24 The aryne Truce–Smiles rearrangement.[33]

and the reaction tolerates a broad range of functional groups. The authors anticipated functionalizing the 3-position of the aryne intermediate and convert this C–H bond to other types of bonds in a tandem process. For the first time, aryne 1,2,3-trifunctionalization with smartly designed aryl allyl sulfoxides **96** has been achieved (Scheme 25).[34] The scope of the reaction has been expanded to a variety of sulfoxides and aryne precursors leading to the formation of the trifunctionalized benzene derivatives **97** in moderate to good yields. Preliminary mechanistic study suggests that the reaction proceeds with the formal [2+2] cycloaddition of aryne with the S–O double bond of **96** followed by an allyl S → O migration leading to intermediate **98**. This intermediate undergoes an oxonium Claisen rearrangement to end up with intermediate **99**. The opening of the four-membered ring generates the phenoxide intermediate, which finally gets alkylated by the alkyl halides to deliver the trifunctionalized product **97**.



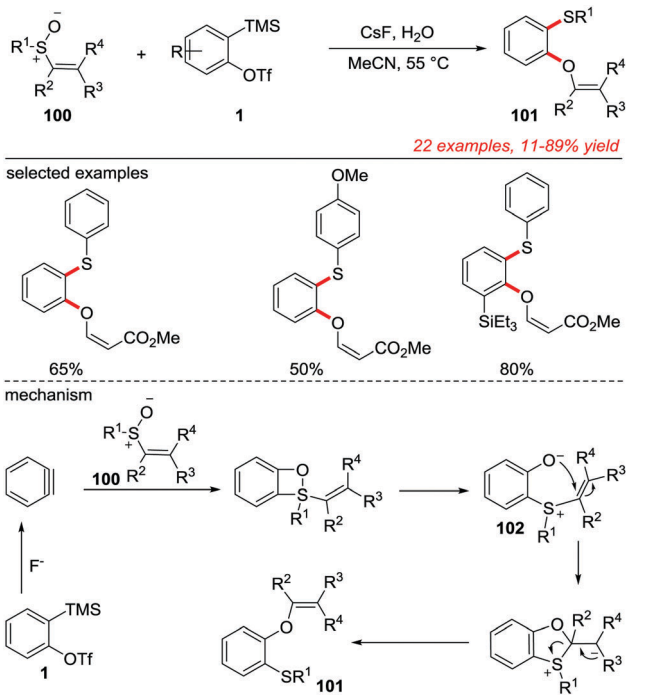
Scheme 25 Aryne 1,2,3-trifunctionalization.[34]

2.11. Vinyl sulfoxide triggered rearrangements *via* arynes

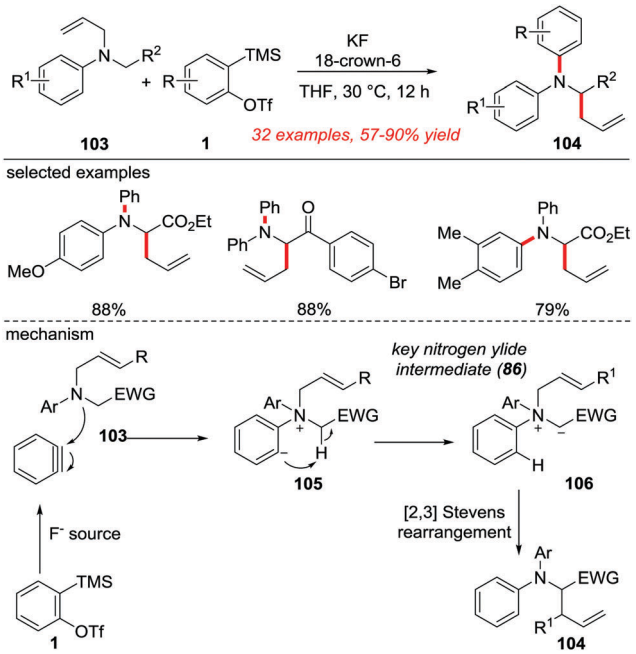
Recently, Studer and co-workers showed that *in situ* generated arynes react with aryl vinyl sulfoxides **100** leading to an S–O bond insertion to provide *ortho*-aryl sulfinyl aryl vinyl ethers **101** (Scheme 26).[35] This interesting transformation proceeds with complete stereospecificity in moderate to good yields. Water has a specified role controlling the fluoride-mediated disproportionation of the sulfoxide to the corresponding sulfide and sulfone. The reaction proceeds *via* the initial [2+2] cycloaddition followed by the ring opening sequence to end up with the intermediate **102**. An intramolecular oxa-Michael reaction followed by a ring opening forms the *ortho*-aryl sulfinyl aryl vinyl ethers.

2.12. Stevens rearrangement involving arynes

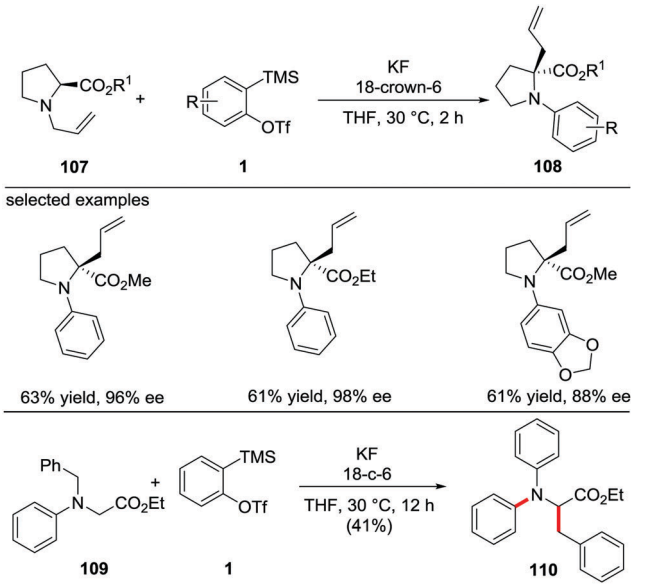
Recently Biju and co-workers developed a transition-metal-free and mild [2,3] Stevens rearrangement of tertiary allylic amines **103** for the synthesis of functionalized homoallylic amines **104** in moderate to good yield and with a broad substrate scope. The key nitrogen ylide intermediate in this reaction was generated by the *N*-arylation of allyl amines using arynes followed



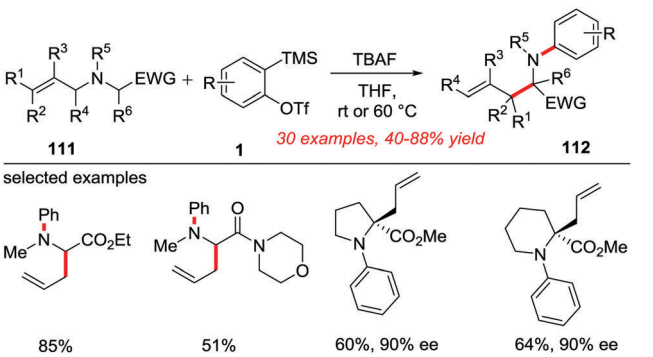
Scheme 26 Reaction of arynes with vinyl sulfoxides.[35]



Scheme 27 The aryne [2,3] Stevens rearrangement.[37]



Scheme 28 Stereospecific aryne [2,3] Stevens rearrangement and aryne [1,2] Stevens rearrangement.[37]



Scheme 29 Aryne mediated [2,3] Stevens rearrangement.[39]

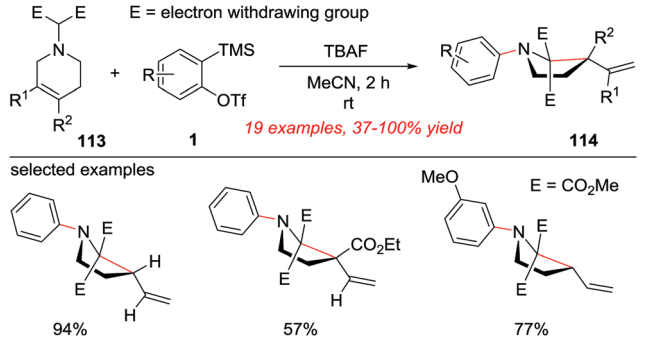
by a proton abstraction (Scheme 27).[36,37] The feasibility of this aryne [2,3] Stevens rearrangement was then examined with electronically different allylic anilines as well as with differently substituted arynes. The scope of this rearrangement involving arynes was found to be general delivering homoallylic amines with high yields in most of the cases. It is noteworthy that the aryne aza-Claisen product was not observed under the present reaction conditions. The nucleophilic addition of the allyl amine to aryne generated from **1** leads to the formation of the zwitterion **105**. It is followed by an intramolecular proton abstraction to form the key nitrogen ylide intermediate **106**.[38] This intermediate **106** rearranges to the corresponding homoallylic amines *via* a [2,3] Stevens rearrangement.

The aryne [2,3] Stevens rearrangement using chiral proline derived allyl amines **107** with arynes resulted in the enantiospecific synthesis of homoallylic amines **108** in good yield and enantioselectivity (Scheme 28). The reaction proceeds with the retention of enantiopurity as well as the inversion of configuration. The observation of the transfer of chirality from carbon to nitrogen initially and then back to carbon in the later stage is noteworthy in this case. Moreover, preliminary studies on aryne [1,2] Stevens rearrangement are demonstrated. An ylide induced benzyl shift occurred from nitrogen to carbon in an allyl benzylamine **109** upon treatment with aryne leading to the synthesis of α-benzylic amine **110** in moderate yield.

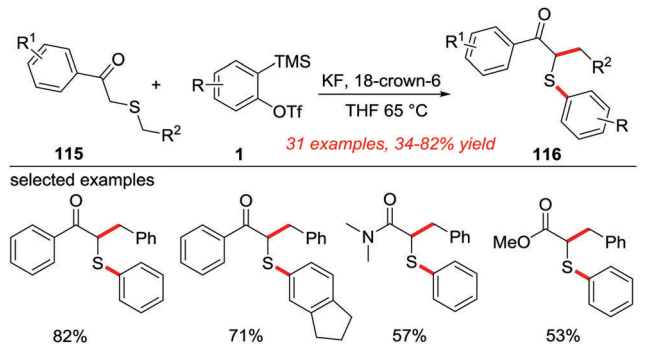
Independent investigations by Tian and co-workers uncovered the closely related aryne [2,3] Stevens sigmatropic rearrangement of quaternary allylic ammonium ylides in the reaction of tertiary allylic amines **111** with arynes generated from **1** (Scheme 29).[39] The reaction *via* the *in situ* activation of tertiary amines using arynes facilitated the synthesis of functionalized homoallylic amines **112** in good yields. This reaction was useful for the construction of quaternary stereocentres in high enantiopurity, and for the diastereoselective synthesis of cyclopropane derivatives.

Subsequently, a conceptually similar aryne capture followed by [2,3] Stevens rearrangement for the synthesis of novel *N*-aryl proline analogues was demonstrated by Sweeney and co-workers. The reaction of *N*-(2-malonyl)tetrahydropyridines **113** with arynes furnished *N*-aryl-2-acylpyrrolidines **114** in good yields, and the reaction proceeds *via* an aryne induced nitrogen ylide intermediate (Scheme 30).[40] TBAF was chosen as the fluoride source for the aryne generation and CH_3CN as the solvent. The reaction resulted in the ring contraction of the nitrogen heterocycle and the scope of the reaction is general with various cyclic allylic amines and arynes.

An efficient method for the synthesis of multisubstituted β-keto thioethers *via* Stevens rearrangement of simple β-keto thioethers **115** with arynes has been developed very recently by Guo, He and co-workers. α-Benzyl thioethers **116** were formed in one-pot synthesis under mild and transition-metal-free conditions (Scheme 31). The mechanism involves the formation of the sulphur ylide[41] from **115** and aryne followed by a [1,2]



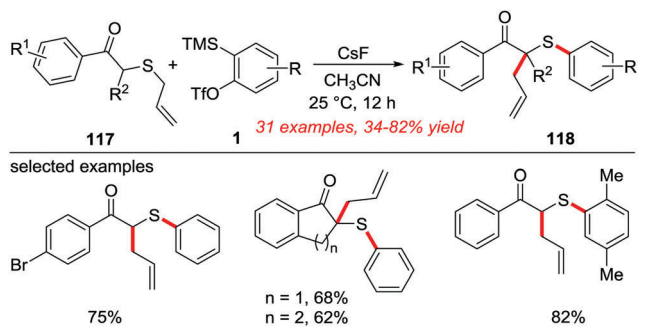
Scheme 30 Synthesis of *N*-aryl-pyrrolidines using aryne [2,3] Stevens rearrangement.[4]



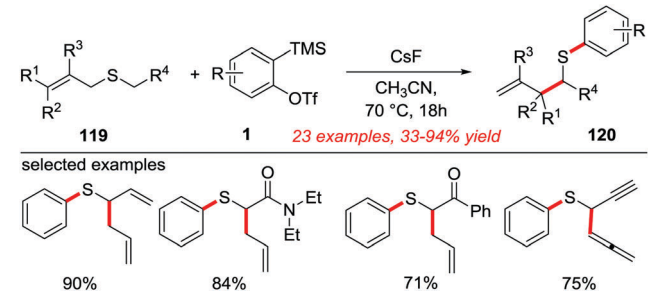
Scheme 31 [1,2] Stevens rearrangement involving arynes.[42]

Stevens rearrangement to afford multisubstituted β-keto thioethers.[42] Various benzyl thioethers were subjected to the optimised conditions leading to the 1,2 rearrangement products in moderate to good yields. The reaction worked well with various aryne precursors as well.

Subsequently, the aryne thia [2,3] Stevens rearrangement of allylthioethers was uncovered by Biju and co-workers. The key sulfur ylide intermediate[43] for this rearrangement was generated by the *S*-arylation of allylthioethers **117** followed by hydrogen transfer (Scheme 32).[44] Various allylthioethers having a benzoyl moiety at the β-position of allylthioether and cyclic ketone-derived allylthioether were well tolerated under the optimized conditions in this transition-metal-free process. In the latter case, the synthesis of



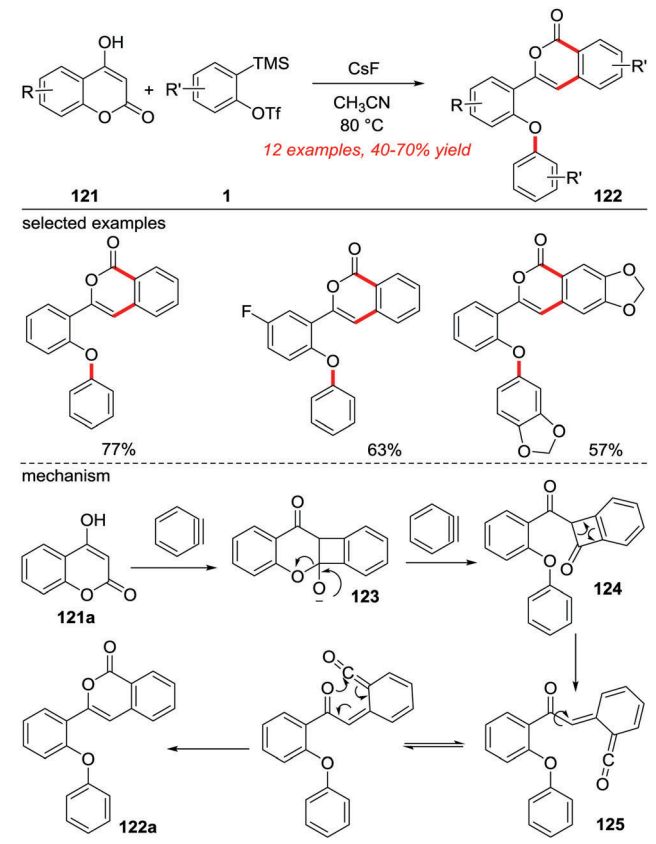
Scheme 32 Aryne [2,3] Stevens rearrangement of allylthioethers.[44]



Scheme 33 [2,3] Stevens rearrangement of allyl and propargyl thioethers.[45]

quaternary β-keto allylthioethers was accomplished. In all cases, the rearranged products **118** were formed in moderate to good yields. New carbon–carbon and carbon–sulfur bonds were formed in this transformation.

Tan, Xu and co-workers very recently demonstrated a highly efficient aryne induced [2,3]-sigmatropic rearrangement of allyl and propargyl thioethers **119**. In this case, the key sulfonium ylide is generated by the *S*-arylation of arynes. The reaction enabled the synthesis of a wide variety of functionalized sulfides **120** in moderate to good yields (Scheme 33).[45] The use of propargyl thioethers in this interesting [2,3]-sigmatropic rearrangement facilitated the synthesis of sulphides functionalized with allenes. The reaction worked well with different



Scheme 34 Synthesis of 3-substituted isocoumarins employing arynes.[46]

substitution patterns on allylthioether and various substituted arynes.

2.13. Hydroxy coumarin triggered rearrangement *via* arynes

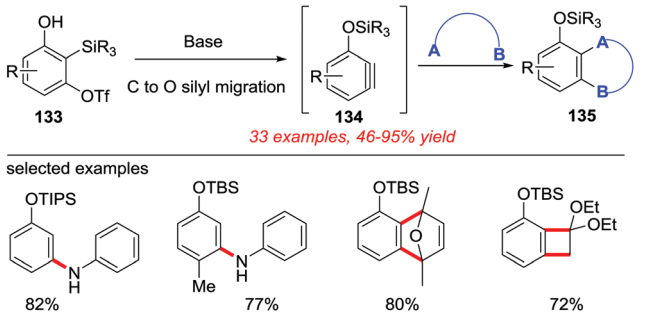
Very recently, a transition-metal-free route towards 3-substituted isocoumarins **122** from 4-hydroxycoumarin **121** and arynes was developed by Gogoi and co-workers. Mechanistically, this new aryne reaction proceeds *via* the breaking and formation of several carbon–carbon and carbon–heteroatom bonds (Scheme 34).[46] A variety of 3-substituted isocoumarins have been synthesised from differently substituted 4-hydroxycoumarins and aryne precursors. The 3-substituted isocoumarins were formed in moderate to good yields. Mechanistically, 4-hydroxycoumarin reacts with aryne in a formal [2+2] mode to form the intermediate **123**. This intermediate opens up and adds to another molecule of aryne generating the benzocyclobutanone **124**. The intermediate **124** undergoes rapid rearrangement to the corresponding ketene intermediate **125**. Finally, a ring closure forms the desired six-membered isocoumarin.

2.14. Ketoximes triggered rearrangements *via* arynes

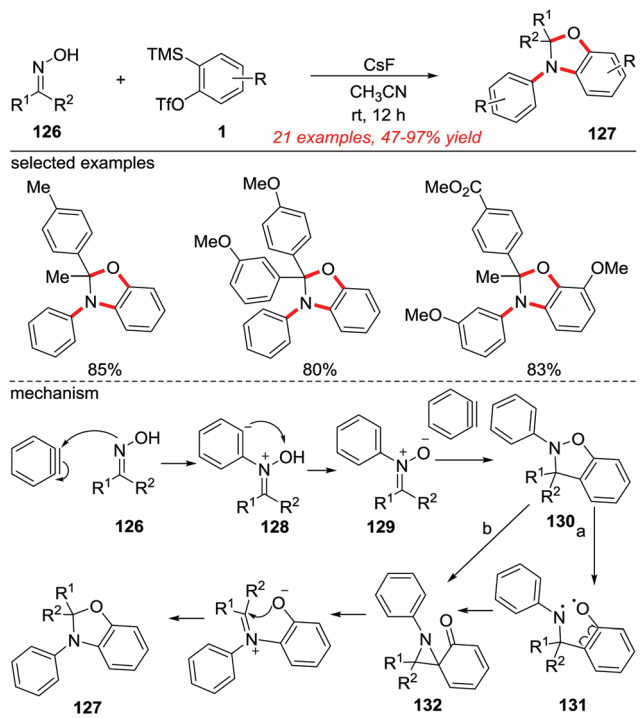
In 2017, Yao and co-workers demonstrated an efficient method for the synthesis of dihydrobenzo[*d*]oxazoles **127** through a rearrangement employing arynes. The reaction proceeds *via* the generation of a keto-nitrone intermediate generated *in situ* from a ketoxime **126** and an aryne. Interestingly, a thermal rearrangement of the dihydrobenzo[*d*]isoxazole products to the corresponding dihydrobenzo[*d*]oxazoles is observed (Scheme 35).[47] This methodology provides a rapid and efficient way of synthesizing diverse dihydrobenzo[*d*]oxazoles under mild and transition-metal-free conditions. Mechanistically, the reaction proceeds *via* the nucleophilic attack of the nitrogen atom of oxime **126** to aryne to generate the zwitterionic intermediate **128**. The aryl anion abstracts a proton from the hydroxyl group to form the nitrone **129**. It is followed by a [3+2] cycloaddition between nitrone **129** and a second molecule of the aryne giving dihydrobenzo[d]isoxazole **130**. Under thermal conditions, NO-cleavage takes place affording a spiral aziridine intermediate **132**. The NO cleavage possibly can happen either with a radical fission (*via* **131**, pathway a) or with an ionic fission (pathway b). The intermediate **132** further rearranges to deliver dihydrobenzo[d]oxazole **127**.

2.15. Brook rearrangement *via* arynes

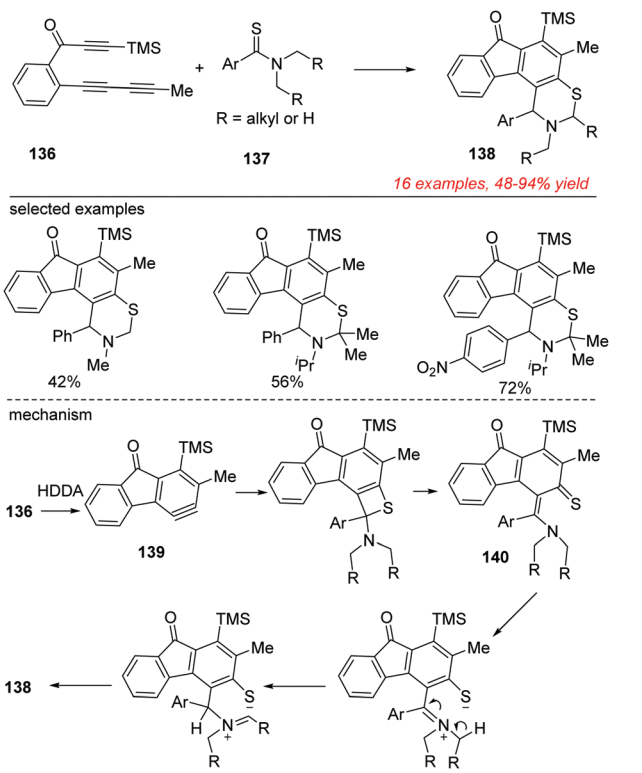
Very recently Kim and co-workers demonstrated a conceptually new 3-hydroxyl 2-(trialkylsilyl)phenyl triflate **133** as the benzyne precursor for the generation of arynes. In the presence of a base, C-sp^2 to *O* 1,3-Brook rearrangement occurs leading to the



Scheme 36 Synthesis of 3-substituted isocoumarins employing arynes.[48]



Scheme 35 Synthesis of dihydrobenzo[*d*]oxazole using arynes.[47]



Scheme 37 Reactions of HDDA-derived benzynes with thioamides.[50]

generation of the aryne **134** in solution, which could be utilized for insertion and cycloaddition reactions giving access to various di- and tri-substituted arenes **135** (Scheme 36).[48] The authors have performed cross-over experiments, and they indicate that the anionic 1,3-silyl migration in this system is intramolecular.[49]

2.16. Rearrangement involving HDDA arynes

The aryne formation using the hexadehydro-Diels–Alder (HDDA) cycloisomerization strategy has emerged as an alternative way to generate this intermediate.[50] Very recently the Hoye group uncovered the reaction of thioamides **137** with arynes generated using HDDA cycloisomerization for the synthesis of functionalized dihydrobenzothiazines **138** (Scheme 37).[51] Mechanistically, the reaction proceeds *via* the initial [2+2] cycloaddition followed by the ring opening pathway to form the intermediate **140**. An intramolecular 1,3 proton transfer followed by the thiolate addition to the iminium delivers the dihydrobenzothiazine **138**.

3. Conclusions

Recent developments in various molecular rearrangements employing arynes have been the focal theme of this Article, thus highlighting the rich and fascinating chemistry of this highly electrophilic intermediate in transition-metal-free reactions. Recently there has been a considerable increase in the application of aryne chemistry in various molecular rearrangements such as the Smiles rearrangement, Claisen rearrangement, Stevens rearrangement, *etc.* The products obtained by the rearrangements involving arynes could not be easily accessed following other procedures. Moreover, employing arynes is a convenient protocol for performing these rearrangements under mild conditions. The rapid development in rearrangement reactions involving arynes is expected to urge synthetic chemists to redirect the chemistry of arynes from conventional reactivities to the new modes of reactivity. Arynes could be applied in many conventional rearrangement reactions thereby diversifying the applications of this potential intermediate. It is expected that the utility of arynes in rearrangement reactions will be continued, and result in surprising outcomes in future. It is reasonable to believe that the potential of this intermediate is still not completely explored and one can expect more astonishing developments in the years to come.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

Generous financial support from the Indian Institute of Science, Bangalore in the form of a start-up grant (for ATB) is kindly acknowledged. TR would like to thank DST for the award of Inspire Fellowship. We thank Dr Trinadh Kaicharla for providing insightful comments.

Notes and references

1 For recent reviews on aryne chemistry, see: (*a*) J. Shi, Y. Li and Y. Li, *Chem. Soc. Rev.*, 2017, **46**, 1707; (*b*) O. J. Diamond and T. B. Marder, *Org. Chem. Front.*, 2017, **4**, 891; (*c*) F. I. M. Idiris and C. R. Jones, *Org. Biomol. Chem.*, 2017, **15**, 9044; (*d*) J.-A. García-López and M. F. Greaney, *Chem. Soc. Rev.*, 2016, **45**, 6766; (*e*) C. Holden and M. F. Greaney, *Angew. Chem., Int. Ed.*, 2014, **53**, 5746; (*f*) A. V. Dubrovskiy, N. A. Markina and R. C. Larock, *Org. Biomol. Chem.*, 2013, **11**, 191; (*g*) D. Pérez, D. Peña and E. Guitián, *Eur. J. Org. Chem.*, 2013, 5981; (*h*) P. M. Tadross and B. M. Stoltz, *Chem. Rev.*, 2012, **112**, 3550; (*i*) C. M. Gampe and E. M. Carreira, *Angew. Chem., Int. Ed.*, 2012, **51**, 3766; (*j*) A. Bhunia, S. R. Yetra and A. T. Biju, *Chem. Soc. Rev.*, 2012, **41**, 3140; (*k*) H. Yoshida, J. Ohshita and A. Kunai, *Bull. Chem. Soc. Jpn.*, 2010, **83**, 199; (*l*) R. Sanz, *Org. Prep. Proced. Int.*, 2008, **40**, 215. For a review on hetarynes, see: (*m*) A. E. Goetz, T. K. Shah and N. K. Garg, *Chem. Commun.*, 2015, **51**, 34.
2 (*a*) T. Kaicharla and A. T. Biju, Transition-Metal-Free Synthesis of Benzo-Fused Five and Six-Membered Heterocycles Employing Arynes, in *Green Synthetic Approaches for Biologically Relevant Heterocycles*, ed. G. Brahmachari, Elsevier, 2014, p. 45; (*b*) Y. Chen and R. C. Larock, Arylation Reactions Involving the Formation of Arynes, in *Modern Arylation Methods*, ed. L. Ackermann, Wiley-VCH Verlag GmbH & Co. KgaA, Weinheim, Germany, 2009, p. 401.
3 R. Stoermer and B. Kahlert, *Ber. Dtsch. Chem. Ges.*, 1902, **35**, 1633.
4 (*a*) M. Stiles and R. G. Miller, *J. Am. Chem. Soc.*, 1960, **82**, 3802; (*b*) L. Friedman and F. M. Logullo, *J. Am. Chem. Soc.*, 1963, **85**, 1549.
5 (*a*) Y. Himeshima, T. Sonoda and H. Kobayashi, *Chem. Lett.*, 1983, 1211. For a modified procedure, see: (*b*) D. Peña, A. Cobas, D. Pérez and E. Guitián, *Synthesis*, 2002, 1454.
6 (*a*) S. S. Bhojgude, A. Bhunia and A. T. Biju, *Acc. Chem. Res.*, 2016, **49**, 1658; (*b*) A. Bhunia and A. T. Biju, *Synlett*, 2014, 608; (*c*) S. S. Bhojgude and A. T. Biju, *Angew. Chem., Int. Ed.*, 2012, **51**, 1520.
7 A. R. Lepley, A. G. Giumanini, A. B. Giumanini and W. A. Khan, *J. Org. Chem.*, 1966, **31**, 2051.
8 S. S. Bhojgude, T. Kaichala and A. T. Biju, *Org. Lett.*, 2013, **15**, 5452.
9 T. Yamazaki, G. Baum and H. Shechter, *Tetrahedron Lett.*, 1974, **15**, 4421.
10 Y. Sato, T. Toyo'oka, T. Aoyama and H. Shirai, *J. Chem. Soc., Chem. Commun.*, 1975, 640.
11 A. I. Meyers and P. D. Panesgrau, *Tetrahedron Lett.*, 1984, **25**, 2941.
12 C. Raminelli, Z. Liu and R. C. Larock, *J. Org. Chem.*, 2006, **71**, 4689.
13 A. K. Dhiman, R. Kumar, R. Kumar and U. Sharma, *J. Org. Chem.*, 2017, **82**, 12307.
14 H. Yoshida, S. Sugiura and A. Kunai, *Org. Lett.*, 2002, **4**, 2767.
15 C. Xie and Y. Zhang, *Org. Lett.*, 2007, **9**, 781.
16 D. Pintori and M. F. Greaney, *Org. Lett.*, 2010, **12**, 168.
17 K. Biswas and M. F. Greaney, *Org. Lett.*, 2011, **13**, 4946.
18 A. A. Cant, G. H. V. Bertrand, J. L. Henderson, L. Roberts and M. F. Greaney, *Angew. Chem., Int. Ed.*, 2009, **48**, 5199.
19 T. Aoki, S. Koya, R. Yamasaki and S. Saito, *Org. Lett.*, 2012, **14**, 4506.
20 C. Hall, J. L. Henderson, G. Ernouf and M. F. Greaney, *Chem. Commun.*, 2013, **49**, 7602.
21 A. Bhunia, T. Roy, P. Pachfule, P. R. Rajamohanan and A. T. Biju, *Angew. Chem., Int. Ed.*, 2013, **52**, 10040.
22 For a related aryne MCR, see: A. Bhunia, D. Porwal, R. G. Gonnade and A. T. Biju, *Org. Lett.*, 2013, **15**, 4620.
23 T. Kaicharla, M. Thangaraj and A. T. Biju, *Org. Lett.*, 2014, **16**, 1728.
24 S. Yoshida, T. Yano, Y. Misawa, Y. Sugimura, K. Igawa, S. Shimizu, K. Tomooka and T. Hosoya, *J. Am. Chem. Soc.*, 2015, **137**, 14071.
25 T. Matsuzawa, K. Uchida, S. Yoshida and T. Hosoya, *Org. Lett.*, 2017, **19**, 5521.
26 Z. Chen and Q. Wang, *Org. Lett.*, 2015, **17**, 6130.
27 A. V. Varlamov, N. I. Guranova, R. A. Novikov, V. V. Ilyushenkova, V. N. Khrustalev, N. S. Baleeva, T. N. Borisova and L. G. Voskressensky, *RSC Adv.*, 2016, **6**, 12642.
28 S. S. Bhojgude, D. B. Baviskar, R. G. Gonnade and A. T. Biju, *Org. Lett.*, 2015, **17**, 6270.
29 K. Okuma, H. Kinoshita, N. Nagahora and K. Shioji, *Eur. J. Org. Chem.*, 2016, 2264.
30 For a review see: T. J. Snape, *Chem. Soc. Rev.*, 2008, **37**, 2452.
31 S. S. Bhojgude, T. Roy, R. G. Gonnade and A. T. Biju, *Org. Lett.*, 2016, **18**, 5424.

32 For a work on Truce-Smiles rearrangement, see: O. K. Rasheed, I. R. Hardcastle, J. Raftery and P. Quayle, *Org. Biomol. Chem.*, 2015, **13**, 8048.
33 C. M. Holden, S. M. A. Sohel and M. F. Greaney, *Angew. Chem., Int. Ed.*, 2016, **55**, 2450.
34 Y. Li, D. Qiu, R. Gu, J. Wang, J. Shi and Y. Li, *J. Am. Chem. Soc.*, 2016, **138**, 10814.
35 Y. Li and A. Studer, *Org. Lett.*, 2017, **19**, 666.
36 (*a*) T. S. Stevens, E. M. Creighton, A. B. Gordon and M. MacNicol, *J. Chem. Soc.*, 1928, 3193. For recent reviews, see: (*b*) T. H. West, S. S. M. Spoehrle, K. Kasten, J. E. Taylor and A. D. Smith, *ACS Catal.*, 2015, **5**, 7446; (*c*) G. Lahm, J. C. O. Pacheco and T. Opatz, *Synthesis*, 2014, 2413; (*d*) J. B. Sweeney, *Chem. Soc. Rev.*, 2009, **38**, 1027; (*e*) E. A. Ilardi, C. E. Stivala and A. Zakarian, *Chem. Soc. Rev.*, 2009, **38**, 3133; (*f*) P. Somfai and O. Panknin, *Synlett*, 2007, 1190.
37 T. Roy, M. Thangaraj, T. Kaicharla, R. V. Kamath, R. G. Gonnade and A. T. Biju, *Org. Lett.*, 2016, **18**, 5428.
38 For a report on aryne induced nitrogen ylide, see, T. Roy, T. Manikandan, R. G. Gonnade and A. T. Biju, *Chem. Commun.*, 2016, **52**, 9044.
39 J. Zhang, Z.-X. Chen, T. Du, B. Li, Y. Gu and S.-K. Tian, *Org. Lett.*, 2016, **18**, 4872.
40 S. G. Moss, I. A. Pocock and J. B. Sweeney, *Chem. – Eur. J.*, 2017, **23**, 101.
41 For reports on aryne induced generation of sulphur ylides, see: (*a*) H.-D. Xu, M.-Q. Cai, W.-J. He, W.-H. Hu and M.-H. Shen, *RSC Adv.*, 2014, **4**, 7623; (*b*) H.-Y. Li, L.-J. Xing, M.-M. Lou, H. Wang, R.-H. Liu and B. Wang, *Org. Lett.*, 2015, **17**, 1098; (*c*) M.-M. Lou, H. Wang, L. Song, H.-Y. Liu, Z.-Q. Li, X.-S. Guo, F.-G. Zhang and B. Wang, *J. Org. Chem.*, 2016, **81**, 5915.
42 X.-B. Xu, Z.-H. Lin, Y. Liu, J. Guo and Y. He, *Org. Biomol. Chem.*, 2017, **15**, 2716.
43 For a related work, see: Y. Li, C. Muck-Lichtenfeld and A. Studer, *Angew. Chem., Int. Ed.*, 2016, **55**, 14435.
44 T. Manikandan, R. N. Gaykar, T. Roy and A. T. Biju, *J. Org. Chem.*, 2017, **82**, 4470.
45 J. Tan, T. Zheng, K. Xu and C. Liu, *Org. Biomol. Chem.*, 2017, **15**, 4946.
46 K. Neog, D. Dutta, B. Das and P. Gogoi, *Org. Lett.*, 2017, **19**, 730.
47 T. Yao, B. Ren, B. Wang and Y. Zhao, *Org. Lett.*, 2017, **19**, 3135.
48 Y.-J. Kwon, Y.-K. Jeon, H.-B. Sim, I.-Y. Oh, I. Shin and W.-S. Kim, *Org. Lett.*, 2017, **19**, 6224.
49 For a related report see: (*a*) T. R. Hoye, B. Baire and T. Wang, *Chem. Sci.*, 2014, **5**, 545; (*b*) Z.-A. Huang, F. Tang, Y.-J. Xu and C.-D. Lu, *Synlett*, 2015, 891.
50 T. R. Hoye, B. Bare, D. Niu, P. H. Willoughby and B. P. Woods, *Nature*, 2012, **490**, 208.
51 V. Palani, J. H. Chen and T. R. Hoye, *Org. Lett.*, 2016, **18**, 6312.

