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Nitrilium ions – synthesis and applications

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Nitrilium ions have been well-established in organic chemistry for many decades, but recent developments show them to be far more versatile than hitherto recognized. They are known as stable salts, can be generated in situ, or are present as transient intermediates. We provide a succinct, but comprehensive review on the synthesis, stability, and reactivity of nitrilium ions as synthons for imines, their use in the synthesis of a large spectrum of heterocycles, and their reactions with transition metal complexes. By offering this overview, we aim for a renewed focus on readily accessible and simple to use nitrilium ions as valuable reagents for the synthesis of organic compounds.

1. Introduction

Nitrilium ions 1 (Scheme 1) have been known for a long time as reactive intermediates in valuable organic transformations like the Beckmann rearrangement and the Ritter, von Braun, and Bischler–Napieralski reactions, while Meerwein and others reported on stable nitrilium salts half a century ago. This duality of reactivity versus stability is ideal to fully exploit the synthetic potential of such a simple synthon, but this is not quite what has happened in the past few decades. Although much has been accomplished, as illustrated by two earlier reviews,1 nitrilium ions are now being rediscovered because of their versatile reactivity, which is addressed in this review. By first sketching the historical perspective of nitrilium ions it becomes abundantly clear that this important synthon has tremendous synthetic value beyond its current boundaries.

2. Nitrilium ions

2.1. Reactive intermediates

The best-known reaction in which the nitrilium ion plays a prominent role is the Beckmann rearrangement that converts...
Reactions involving nitrilium ion intermediates.

oximes 2 into amides 3 (Scheme 1a). In this reaction, first reported in 1886,2 the protonated oxime eliminates water to give a nitrilium ion that hydrolyses to an amide. In some cases the nitrilium ion intermediate has been observed spectroscopically and even been isolated.4 Amides are also formed by hydrolysis of nitrilium ions in the closely related Ritter reaction,5 irrespective of whether they are obtained from a nitrile or a carbenium ion that is acid-generated from an alcohol or alkene (Scheme 1b).6 Nitrilium ions act also as intermediates in the von Braun reaction,7 which instead concerns the degradation of an amide on treatment with a bromide source to give an alkyl bromide (Scheme 1c). The degradation starts by converting a secondary N-alkyl amide 3 into imidoyl bromide 4, which is in equilibrium with nitrilium bromide 1-Br. The latter dissociates into a nitrile and a carbenium ion that reacts with the liberated bromide ion to give alkyl bromide 5.6c,8 Another transformation involving the nitrilium ion is the Bischler–Napieralski reaction9 that converts β-phenethylamides 6 into 3,4-dihydroisoquinolines 8 (Scheme 1d). In this reaction the amide is treated with a chloride to give an equilibrium mixture of imidoyl chloride 7 and nitrilium chloride 1-Cl that undergoes a phenyl-induced ring closure.6c,10 but if the phenyl group is not nucleophilic enough, the nitrilium ion can expel a nitrile to give either β-phenethylchloride by the von Braun amide degradation or styrene by the retro-Ritter reaction.6c,10 Nitrilium ions have been implicated in the Gattermann11 and Houben-Hoesch12 reactions (Scheme 1e) in which aromatic compounds are formylated or acylated under acidic conditions with hydrogen cyanide or a nitrile, respectively;13 even protonated nitrilium ion 9 (i.e., a dication) may be involved as the reaction with benzene occurs only in superacids.14 Nitrilium ions are also known to be intermediates in the hydrolysis of imidoyl chlorides15 and the acid catalyzed hydrolysis of isocyanides16 and ketenimines.17 Also the widely applied Ugi 4-component reaction18 for the synthesis of α-amino acrylamides 12, but not the related Passerini reaction,19 is considered to proceed through a nitrilium ion intermediate (Scheme 1f).20

These examples amply illustrate the relevance of nitrilium ion intermediates in organic synthesis. This review goes beyond these established reactions to expand the scope of nitrilium ions as imine synthons for the synthesis of N-heterocycles and N,P-ligands that have their merits in coordination chemistry.

2.2. Stable nitrilium salts

Stable nitrilium salts are equally well established as reactive intermediates that hydrolyze,6c,21 expel a nitrile, or undergo cyclization and are commonly generated from imidoyl halides or nitriles. Already in the 1950s, both Klages22 and Meerwein23 reported stable nitrilium salts by abstracting a Cl⁻ ion from imidoyl chlorides 13 with Lewis acids like SbCl₅, SnCl₅, TiCl₅, AlCl₃, BiCl₃, and BCl₃ (Scheme 2a);2c recently we have applied TMSOTf successfully.24 Imidoyl chlorides undergo first order dissociation in aqueous organic solvents to nitrilium ions, which, of course, hydrolyze instantly to amides.15 Meerwein was the first to show that nitriles can be N-alkylated with triethylxonium-BF₄ (14), known as Meerwein’s reagent, or its SbCl₅⁻ and AlCl₄⁻ derivatives (Scheme 2b).23 He also showed that the nitrilium ions are involved in the Beckmann

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**Koop Lammertsma**

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rearrangement by obtaining nitrilium-BF₄ salt 1 by heating the BF₃ adduct (16) of benzophenone oxime 15 and treating product 17 with additional BF₃ (Scheme 2c).⁴⁶

Subsequently, stable nitrilium salts have been shown to result from N-alkylating acetonitrile and benzonitrile with reagents such as HC(OEt)₂,SBCl₅ → (18, Scheme 2d),⁴⁵ the O-methylidienbenzofuranium-BF₄ salt,⁴⁶ methyl triflate,⁴⁷ MeSO₃F,²⁸ and EtSO₃F (Scheme 2e).²⁸ Protonation of nitriles with HF/AsF₅ or HF/SbF₅ in anhydrous HF has been recently accomplished.²⁹ N-Alkynilnitrilium salts are also formed on reacting alkyl halides with FeCl₃ or SbCl₅-coordinated nitriles ¹⁹ ²³,²⁶ (Scheme 2f) and even by treating a CN-containing phosphaylide with Meerwein salt,³¹ while a Cu²⁺-TPW(NO)₃(PMe₃) stabilized nitrilium ion (21) results from the corresponding coordinated acetonitrile 20 (Scheme 2g), obtained in situ from the µ⁴-benzene complex.³²

Light-induced fragmentation is another method as illustrated in the formation of the N-phenynilnitrilium ion 1 by photocleavage of benzimidate ester 22 (Scheme 2h).²¹a,b Even nitrilium ylides, such as 24, can be obtained by aqueous deprotonation of imidoyl chlorides 23 (Scheme 2i) and trapped by dipolarophiles like methyl acrylate.³³ There are a few cases of transition metal mediated syntheses of stable nitrilium ions, such as the nucleophilic attack of t-butylisocyanide on µ₂-η²-acetylide diiron complex 25 to give ion 26 (Scheme 2j).³⁴ Similar reactions have been reported for the allenyl [Fe₃(CO)₆(µ-PPh₃)] complex³⁵ and Os₃⁺ and Ru₃⁺ complexes,³⁶ a related Fe₂⁺-complexed nitrilium ion results from the attack of t-butylisocyanide on [Cp(CO)Fe]₂(µ-CO) (µ-CH)PF₆⁻.³⁷

Recently we have shown that treating thermally labile N-alkyl nitrilium triflates with DMAP renders moderately air-stable adducts 27 (Scheme 3), which much improves the handling of the nitrilium ion while retaining their reactivity.³⁸ For instance, solid DMAP adduct 27 (R = iPr) gave only 9% of the hydrolyzed product upon exposure to air for one month.

### 2.3. Structural properties

Nitrilium ions have a linear conformation with an N≡C triple bond, implying a formally positively charged nitrogen atom. Illustrative are the three X-ray crystal structures shown in Fig. 1.²⁴,³⁹ The average N≡C bond length of 1.135 Å for the nine nitrilium ions found in the Cambridge Structural Database²⁴,³¹,³⁵,³⁷,³⁹,⁴⁰ compares well with the 1.131 Å of a nitrilium ylide,³¹ the 1.138 Å of aryl nitriles,³² and the 1.136 Å of alkyl nitriles.³³ The average C–N≡C and N≡C=C bond angles of 174.5° and 177.1°, respectively, reflect the near linearity of the ions. The IR stretching vibrations observed for 21 nitrilium salts, carrying aryl and alkyl groups, range from 2300 to 2420 cm⁻¹ and are fully in line with the N≡C=C bond character.⁴⁺,²¹c,²⁴,²⁷a,⁴³ The observed ¹³C NMR chemical shifts of the –N≡C– carbon of 14 nitrilium ions²⁴,²⁸d,³⁰b,⁴⁴ range from 102.6 to 125.2 ppm and compare with the 116.4 ppm...
(CDCl₃) for acetonitrile;⁴⁵ C-aryl nitrilium ions (108.6-125.2 ppm) are generally deshielded from the C-aryl substituted ones (102.6-107.7 ppm). The ions typically have $^\text{j}(C,N)$ coupling constants of 42.1 to 50.0 Hz. It is worth noting that the $^{14}$N NMR resonance for [Me$^{\text{–}}$N$^{\equiv}$C–Me]$^-$ is 110 ppm deshielded from that of acetonitrile,⁴⁶ reflecting the difference in N-coordination.

### 3. Imine synthons

One of the early examples of using nitrilium salts to generate imines comes from Turrell et al., who synthesized aminoester 28 from [N-phenyl][phenyl]-1-SbF₅ and phenol (Scheme 4a).⁴³α Treating in situ generated 1-BF₄ with alcohols also gives 28, which on reduction (NaBH₄) converts readily into secondary amines.⁴⁶ Similarly, N-methyl-1-OTf reacts with alcohols to give 28 and forms thioamino-esters on using thiols.⁷² Moreover, the reaction of [N-methyl][methyl]-1-O₃SF forms the expected Z-iminium ions, which on deprotonation isomerizes to the E-imines.²⁸β Such behavior was also reported for the nucleophilic attack of acetate on nitrilium ions, which showed the selective formation of Z-N-acylacetamides with subsequent slow isomerization to the E-isomer.⁴⁸ Likewise, the reaction of an azide anion with nitrilium ions resulted selectively in Z-imidoylazides, which upon slow isomerization cyclized to the corresponding tetrazes.⁴⁸ Other O-nucleophiles can also be used, such as olefin-bound $^\text{η}_3$-acrolein osmium(ii) complexes in which the carbonyl oxygen attacks the nitrilium ion, resulting in a $^\text{η}_1$-vinyl osmium complex.³⁹

The reaction of N-aryl-1-SbCl₆,⁴³α N-aryl-1-FeCl₄,³⁰ and 1-OTf,²⁷β with primary or secondary amines gives amidines 29 upon deprotonation of the amidinium intermediate (Scheme 4b). The power of this method was demonstrated by Gordon et al. for the high-yield synthesis of otherwise inaccessible N-tert-butylamidines as precursors for bulky amidinate ligands.⁵¹ Also carbon-based nucleophiles can be used as illustrated by the reaction of [N-methyl][methyl]-1-BF₄ with pyrrole (Scheme 4c) that gives a mixture of the iminium ion 30 and imine 31; full conversion to 31 results in NaOH quenching. A study on the reactivity of pentaminoosmium(ii)-η⁴-pyrrrole complex 32 revealed that the pyrrrole group changes from the α to the β-position on addition of a nitrilium ion to give 33 (Scheme 4d).⁵² A similar β-addition to nitrilium ions was shown for the analogue η²-furan complexes.⁵³

C-Phenyl nitrilium salts 1-BF₄ reportedly react in high yield with imino-imidazoles 34 to bis-imino-imidazolium salt 35 (Scheme 4e) that are precursors for bis-imino N-heterocyclic carbones, but the parent imidoyl chloride shows no reactivity.⁵⁴ (N-Methyl)(methyl)-1-BF₄ has been shown to react in THF with a lithiated C-methyl imine to generate the BF₂-adduct of asymmetrically substituted β-diiamine 36 in poor yield (Scheme 4f).⁵⁵ Recently, we have shown that 1-OTf can be used as an imine synthon for the high-yield synthesis of iminophosphines 37, which can function as either anionic phosphamidinate ligands (for R² = H)²⁴ or as neutral 1,3-P,N-ligands (R² = Ph, tBu or Cy)⁵⁶ for transition metal coordination (Scheme 5).

### 4. Heterocycles

#### 4.1 From stable nitrilium ions

Various heterocyclic compounds have been synthesized by the nucleophilic attack on a nitrilium ion followed by intramolecular cyclization. For instance, when nitriles were reacted with [N-phenyl][phenyl]-1-TiCl₆ (Scheme 6a) or N-phenylimidoylchloride 40, using AlCl₃ for Cl-abstraction, the resulting intermediate 38 cyclized immediately to chinazoline 39 (Scheme 6b)⁵⁷ except when the N-phenyl group carried ortho-
methyl substituents. The method has been used for the synthesis of 2-aminochinoxaline (i.e., \(R^1 = NR^2R^2\); \(R^3, R^5 = \text{aryl or alkyl}\)) by using SnCl4 as a Lewis acid. A similar methodology is reportedly also suited for the synthesis of 3,4-dihydro-4-oxo-quinazoline 42 by the \(N\)-nucleophilic attack of methylanthranilate 41 at \(N\)-alkyl-1-FeCl4 or its trflate (Scheme 6c) as well as for imidazoles when propargylamine or \(\alpha\)-aminoesters are used.59

C1-Phenyl-substituted benzamidazole 43 was obtained from (N-methyl)(phenyl)-1-OTf and 2-aminoaniline with benzoxazole 44 and benzothiazole 45 resulting likewise from 2-amino-phenol and 2-aminothiophenol, respectively (Scheme 7a).13

In the reaction affording 43, the amine groups of 2-aminoaniline attack the nitrilium carbon atom sequentially with expulsion of methylammonium trflate. Reacting diaminomaleonitrile with (N-methyl)(methyl)-1-OTf afforded likewise 2-dimethyl-5-amino-4-(C-cyanoformimidoyl)imidazole and 6-carbamoylpyrroles on subsequent treatment with ketones.60

Reacting N-isopropyl-1-SbCl6 with acetylenes yielded 2-azonialkenes 46 after a 1,5-H shift (Scheme 7b). When instead 1,2-bis(methylthio)acetylene was used a subsequent slow cyclization occurred to give the 2H-pyrrolium salt 47.30

A variety of 4H-1,3-oxazinium salts 49 were obtained from the reaction of 2-aminoaniline with chalcone 48a (\(R^1, R^4 = \text{Ph}; R^3, R^5 = \text{H}\)), presumably by the attack of the carbonyl oxygen at the nitrilium salt followed by the \(N\)-nucleophilic attack at the resulting carbocation (Scheme 7c).61 6H-1,3-Oxazinium salts resulted instead with \(\alpha,\beta\)-unsaturated aldehydes (48b, \(R^1 = \text{H}\)), presumably via an initial \([2 + 2]\)-cycloaddition of the aldehyd and the nitrilium salt followed by ring opening and cyclization by \(O\)-nucleophilic attack. 3,4,5-Trisubstituted 1,2,4-oxadiolium salts 52 resulted from the \(O\)-nucleophilic attack of \(N\)-hydroxycarboximidoyl chloride 50 at \(N\)-alkyl-1-SbCl6 and heat induced cyclization of intermediate 51 (Scheme 7d).62 52 resulted in a single step at room temperature on using nitrile oxides instead of 50. Similarly, amide oximes 53 were shown to react with both \(N\)-alkyl- and \(N\)-aryl-1-SbCl6 to give 3,5-di-substituted 1,2,4-oxadiazoles 54 upon basic work-up and expulsion of an amine (Scheme 7e).63

\[\text{Scheme 7 Heterocycle synthesis from nitrilium ions.}\]

N-Aryl-1-SbCl6 reportedly reacts with alkenes to yield 3,4-dihydroquinolinium salts 56 with 3,4-dihydroquinolinium salts 56 (Scheme 8).64 The reaction was postulated to proceed by the electrophilic attack of the nitrilium ion on the alkene to give intermediate 55, followed by intramolecular electrophilic aromatic substitution. Support for 55 came from the isolation of Houben-Hoesch product 57 and formation of the ene-reaction product 58. Similarly, electron rich acetylenes were shown to provide quinolones.65

1,4,5-Tetrazolium salts 60 were stereoselectively formed on reacting azides with 1-SO3F (Scheme 9).66 The \(N\)-nucleophilic attack of azides on the nitrilium ion gives intermediate 55, which cyclizes to 1,4,5-tetrazolium salt 60. This salt can be converted to tetrazoline 61 by reduction with LiBH4 or reaction with organolithium reagents.

The reaction between \(N\)-iso-propyl-1-SbCl6 and 2-methylthiophene affording hetero-bicyclic 62 (Scheme 10) was postulated to proceed by an intermolecular ene-reaction followed by cyclization through the electrophilic attack on the heterocyclic double bond and subsequent tautomerization, albeit that the last step may also proceed by means of a concerted 6-(3,5)-ene cyclization.61

4.2. From in situ generated nitrilium ions

Heterocyclic compounds are equally well accessible by means of in situ generated nitrilium ions that undergo intramolecular cyclization. Exemplary is the synthesis of pyrazolo [3,4-\(d\)]pyrimidines 65 by treating C5-substituted \(N\)-pyrazolyl imidoyl chlorides 63 with SnCl4 in the presence of nitriles.

\[\text{Scheme 8 3,4-Dihydroquinolinium salts synthesis from N-aryl nitrilium ions and alkenes.}\]

\[\text{Scheme 9 The reaction of nitrilium ions with azides.}\]

\[\text{Scheme 10 Ene reactions with nitrilium ions.}\]
(Scheme 11, top), which proceeds analogous to the discussed synthesis of chinazolines (Scheme 6; top). Nitrilium ion 64, generated by Lewis acid induced Cl-abstraction, reacts with the nitrile to subsequently undergo cyclization by intramolecular electrophilic aromatic substitution.67 Likewise, hydrazine based imidoylchlorides 66 have been converted to 1H-1,2,4-benzotriazepines 69, but the reaction is sensitive to the hydrazine N-substituent (Scheme 11, bottom).68 Although 69 was formed when this substituent is a N-phenyl group, this is not the case with the N-methyl derivatives that gave instead 1,2,4-triazoles 70, apparently by the preferred electrophilic attack at the amine of intermediate 68. In the absence of an N-substituent, 66 also reacted to give triazole 70 besides the deprotonated dimer 71 of nitrilium ion 67.69

The biaryldiazonium-BF₄ salts 72 react with nitriles under expulsion of N₂ to give 73 as intermediates, which undergo an intermolecular electrophilic aromatic substitution to phenanthridines 74 (Scheme 12, top) that are tedious to isolate and often convert to picrates.70

Interestingly, the nitrilium ion resulting from the reaction of 1-naphthalenediazonium-BF₄ (75) with acetonitrile didn’t cyclize to 2-methylbenzo[c,d]indole, but reacted instead with another acetonitrile molecule to cyclize to 2,4-dimethylbenzo [h]quinazoline (76; Scheme 12, bottom);71 the reaction resembles Meerwein’s chinazoline synthesis shown in Scheme 6. Similar reactivity with the double uptake of a nitrile was found in the reaction with cyclobutanone when treated with triflic anhydride giving cyclobutaprymidines 77 as the product (Scheme 13).71

Heterocycles can also be generated in a Ritter-like reaction in which the nitrilium ion, generated in situ from a carbocation and a nitrile, undergoes intramolecular cyclization. Illustrative is the synthesis of dihydro-1,3-oxazine 80 from diol 78, which proceeds by generating an incipient carbocation that reacts with a nitrile to generate the transient nitrilium ion intermediate 79 (Scheme 14).72 A similar reaction occurred with dinitrilone succinonitrile as only one nitrile reacted with the dihydro-1,3-oxazine with a pendant nitrile group.73 Ritter-like reactions can also be used for the synthesis of 2-thiazolines,74 5,6-dihydro-1,3-thiazines,74 and non-nitrile functionalized dihydro-1,3-oxazines.75

Diazoacycarbonyls 81 have been reacted with nitriles in the presence of AlCl₃ to give oxazoles 83,76 which was postulated to be formed via nitrilium intermediate 82 that undergoes intramolecular cyclization by the O-nucleophilic attack (Scheme 15). However, executing the reaction with less than 2 equivalents of AlCl₃ generated α-chlorocarbonyl as a byproduct, which could be prevented by using BF₃ instead.77

In situ generation of nitrilium ion 85 from amide 84 and POCl₃ was shown to lead to a cascade reaction resulting in 6H-[1]benzopyrano[4,3-b]quinolone 86 (Scheme 16; top).78 Similarly, generating ion 88 from amide 87 and trimethylsilylpolyphosphate (PPSE) led directly to pyrrolizidone 89 by the electrophilic attack of the nitrilium carbon on the olefin.79 Reduction of 89 with NaBH₄ initiates a second cyclization to give benzylidinepyrrolizidone 90 (Scheme 16; bottom).

Although the extensively reviewed Ugi reaction18c,20a,b,80 (Scheme 1f) is beyond the scope of the present review, there are Ugi-like reactions involving a nitrilium ion intermediate with subsequent cyclization to a heterocycle, i.e., by the intra-

Scheme 11 Synthesis of pyrazolo[3,4-d]pyrimidines (top) and 1H-1,2,4-benzotriazepines and 1,2,4-triazoles (bottom).

Scheme 12 Phenanthidine synthesis from diaryldiazonium salts and nitriles.

Scheme 13 Synthesis of cyclobutaprymidines.

Scheme 14 Ritter like synthesis of dihydro-1,3-oxazines.

Scheme 15 Lewis acid promoted reaction of diazacarbonyls and nitriles.
molecular nucleophilic attack of the isocyanide at the ion center (Scheme 17). Typically, the nucleophile is part of the amine reactant (H₂N^Nu), as is the case for the reactions of 2-aminopyridine, 2-aminopyrimidine, and other heterocyclic amidines that render bicyclic 3-aminoimidazoles 91 (Scheme 17a). Also pyrazole amidines have been shown to react in a 3-component reaction with benzaldehydes and isocyanides to give 3-aminoimidazoles 92 (Scheme 17b). Asymmetric pyrazole tetrazole derivatives have been employed to synthesize heterocycles 93 (Scheme 17c). The intramolecular nucleophile can also be another amine group, as was shown for the reaction of 2,3-diaminomaleonitrile with ketones and isocyanides to afford heterocycle 94 (Scheme 17d); the reaction of ethylenediamine with aldehydes (R₂ = H) could be converted to quinoxalines on oxidation with DDQ. Oxygen nucleophiles can also be used, as has been shown for the reaction of 2-aminophenol, the cyclic ketone N-methyl-4-piperidone, and isocyanides that afforded bicyclic 96 (Scheme 17f). An alternative route to C,N-cyclic heterocycles is the synthesis directly from C,N-cyclic N′-acyl azo-methine imines and isonitriles. Imine 99 was shown to react with isocyanides under acidic conditions to give aminooxazoles 100 (Scheme 18). The nucleophile in the intramolecular reaction does not need to be part of the amine component, as was demonstrated for 2-isocyanobenzamide (101) with its amide oxygen attacking the nitrilium carbon of intermediate 102 to give 4-imino-4H-3,1-benzoxazines 103 (Scheme 19). The nucleophilic attack of isocyanides on N-formyl,methyl-substituted enamides gave nitrilium ylide, which after tautomerization and oxidation with molecular oxygen, underwent an intermolecular acyl transfer from nitrogen to oxygen, to afford the pyridine derivatives 106 (Scheme 20).

5. Miscellaneous reactions

The reaction of nitrilium salts with a range of amides has been studied. Although tertiary amides gave N-acylimidinium salts 107 as the sole product (Scheme 21a), isomeric mixtures were obtained with secondary amides. Reacting 1-SbCl₅ with a range of ketones resulted in the insertion of the nitrilium ion.
ion to give 108 (Scheme 21b, left),\textsuperscript{44b} except for tropone that gave instead cycloaddition product 109 (Scheme 21b; right),\textsuperscript{17} presumably by the attack of the oxygen on the nitrilium carbon followed by cyclization. When \(N,N\)-dimethylaniline oxide was reacted with \(C\)-methyl-1-X a mixture of ortho- and para-\(N,N\)-dimethylaniline acetamides 110 and \(N,N\)-dimethylaniline was obtained (Scheme 21c), likely by the \(O\)-nucleophilic attack on the nitrilium ion followed by the dissociation and recombination of the AcN-R fragment.\textsuperscript{33c} Nitrilium ions 1-FeCl\(_4\) with an \(\alpha\)-hydrogen on the \(C\)-substituent can be deprotonated at \(-80^\circ\) C to ketene imines 111 (Scheme 21d),\textsuperscript{98} but di- or trimerization occurs at higher reaction temperatures.

Non-interconverting azoniaallenes, \(R_2C=N\overset{+}{=}CR-N=CH-NR_2\) (112), and triazinium salts 113 have reportedly been formed on reacting aminonitriles with nitrilium ions that carry an \(N\)-\(\alpha\)-hydrogen (Scheme 21e).\textsuperscript{99} The azoniaallenes were postulated to be formed by an ene reaction, while the triazinium salts were considered to be the product of a concerted or stepwise \([2 + 2 + 2]\) cycloaddition.

Nitriles can be converted to aldehydes by means of a nitrilium ion strategy. The nitriles are first converted to \(N\)-isopropyl-1-FeCl\(_4\) by treatment with FeCl\(_3\) and isopropylchloride, followed by reduction with triethylsilane to imines and subsequent hydrolysis to aldehydes.\textsuperscript{100} The method is suited for a wide range of alkyl and aryl nitriles and gives aldehydes in nearly quantitative yields.

6. Reactions with transition metal complexes

Nitrilium ions coordinate to transition metals in a manner similar to the isoelectronic and isostructural acetylenes. Exemplary is the \(\eta^3\)-coordination of \((N\text{-methyl})(phenyl)-1\)-BF\(_4\) to vanadocene (114; Scheme 22a).\textsuperscript{101} Similar \(\eta^2\)-nitrilium complexes have been reported for TpW(NO)(PMe\(_3\)), which were synthesized by alkylating the nitrile complexes (Scheme 2g).\textsuperscript{32} Nitrilium Ir-carbene complexes 116 can be accessed by reacting iridium(III) hydride complex 115 with various \(N\)-methyl-1-OTf (Scheme 22b).\textsuperscript{102}

Nitrilium ions can react by means of a formal \([2 + 2]\) cycloaddition with a \(W\equiv C\) triple bond as in tungsten complex 117 to form imino-carbene complex 118; the molecular structure showed the imino-carbene unit to be \(\eta^3\)-coordinated to the transition metal (Scheme 22c).\textsuperscript{103}
7. Conclusion and perspectives

Stable, isolable nitrilium ions can be readily synthesized by alkylating nitriles or by Lewis acid-induced chloride abstraction from imidoyl chlorides with typically SbCl$_6^-$, BF$_4^-$, a metal halide, fluorosulfate or triflate as a counter anion. Not only are the nitrilium ions convenient synthons to generate diverse nitriles, they also provide access to otherwise cumbersome to synthesize anionic phosphamidinates and neutral 1,3-P,N-ligands applicable in transition metal complexes used for homogeneous catalysis. Moreover, a broad spectrum of nitrilium ions also react with ketones, amides, aniline oxides, N-nitroso compounds, and aminonitriles, and coordinate with transition metal complexes.

We hope that the recent advances to access nitrilium ions by very simple synthetic protocols as well as the ability to improve the handling of thermally unstable ones by DMAP-complexation will stimulate the advancement of these remarkably useful synthons in organic synthesis.

Conflicts of interest

The authors declare no competing financial interest.

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