Additions to Metal-Activated Organonitriles†

Vadim Yu. Kukushkin*,† and Armando J. L. Pombeiro*,‡

Department of Chemistry, St. Petersburg State University, 198504 Stary Petergof, Russian Federation, and Centro de Química Estrutural, Complexo I, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

Received November 8, 2001

Contents

† St. Petersburg State University. E-mail: kukushkin@VK2100.spb.edu.
‡ Instituto Superior Técnico. E-mail: pombeiro@ist.utl.pt.

I. Introduction

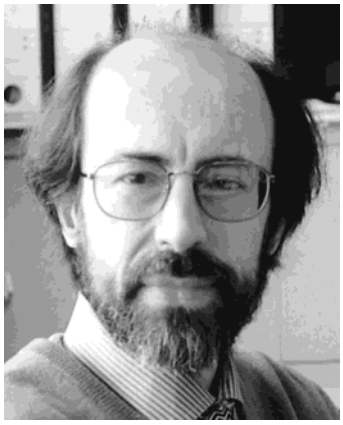
Transformations of organonitriles play an important role in both the laboratory and industry due to their well-recognized chemical versatility. In particular, in organic chemistry the addition of nucleophiles[1] or electrophiles[2] or asymmetric dipolar cycloaddition[3] to the C≡N triple bond offers an attractive route for the creation of novel C−C, C−N, C−O, and C−S bonds.

One of the main problems encountered in reactions of *nucleophilic* addition is the insufficient electrophilic activation even by very strong electron-accepting groups R at RC≡N, e.g., $Cl_3CC{\equiv}N$, to perform the addition. These difficulties, however, can be overcome with the use of metal ions—sometimes even in low oxidation-states[4,5]—as extremely strong activators toward nucleophilic attack. This activation can result in enhancement of the rate of the addition commonly in the range from 10^6 to 10^{10} and occasionally to 10^{18}.[6,7] Moreover, metal-mediated processes in many instances allow the performance of certain reactions which are not feasible without the involvement of metal ions.

The reverse form of activation (i.e., toward *electrophilic* attack) can result upon coordination of a nitrile to a low-valent electron-rich metal center with a

10.1021/cr0103266 CCC: $39.75
Published on Web 03/22/2002

Vadim Yurievich Kukushkin was born in 1956 in Leningrad (now St. Petersburg), the Russian Federation. He studied chemistry at the Lensovet Technological Institute (Technical University), where he obtained his Diploma in 1979 and doctoral degree in 1982. After two years at industrially oriented Mekhanobr Institute (Leningrad), he joined the faculty at the St. Petersburg State University (1984) as Research Associate. He obtained his D.Sc. degree (habilitation) in 1992, was promoted to Senior Research Fellow in 1994 and to full Professor in 1997, and for excellence in teaching was awarded a Soros Professorship in 2001. He was a Visiting Professor at the Institute for Molecular Science (1992) and the JSPS Visiting Professor at the Osaka City University (1996), Japan, with Professor K. Isobe, Distinguished Visiting Professor at the University of Toledo (1994) with Professor J. A. Davies, and Guest Professor at the University of Vienna (1999), Austria, with Professor B. K. Keppler. His research interests include platinum group metal chemistry, ligand reactivity, organic synthesis involving metal complexes, and catalysis. He is author of ca. 150 original papers, patents, reviews, and also four books including *Synthetic Coordination Chemistry: Principles and Practice* written under a joint Russian–American project.



Armando J. L. Pombeiro, born in Porto in 1949, did his undergraduate studies at the University of Porto and at the Instituto Superior Técnico (I.S.T., Lisbon) and obtained his D.Phil. degree at the University of Sussex (1976) under the supervision Professor R. L. Richards and Professor J. Chatt. He is Full Professor (since 1989) at the I.S.T., where his career has been developed since 1971 when he was appointed as an Assistant for Professor J. J. R. Fraústo da Silva. He is a member of the Academy of Sciences of Lisbon, Secretary-General of this Academy, and former Vice-President of the Class of Sciences. He was a member of the Physical and Engineering Science and Technology Panel and of the Advisory Panel on the Advanced Studies Institutes (ASI) program, within the NATO Science Program. He is a co-founder of the Portuguese Electrochemical Society and of the Iberoamerican Society of Electrochemistry and a former President the former society. He has published one book (and edited another one) and over 280 original papers, review articles, or book contributions. His main research interests are in the fields of activation, by transition-metal centers, of small molecules (with biological, environmental, pharmacological, or industrial significance) and molecular electrochemistry of coordination and organic compounds.

The fruitful collaboration between Kukushkin and Pombeiro and their teams (one of the most extended scientific cooperations among the two countries), started in 1994, illustrates a high standard cooperation between a former Eastern block country and the West and shows how the personal friendship and the willingness to cooperate in science might break the geographical separation, linguistic barriers, and... the lack of funding.

strong π-electron-releasing ability, leading to azavinylidene (methyleneamide) and derived species. Although this topic still remains little explored, it is of particular synthetic interest and will also be addressed in this review (see sections VIII and IX), which thus comprises a duality of behavior of organonitriles that parallels that recently reviewed for isocyanides.[8,9]

Before the 1990s the growth of metal-mediated reactions of organonitriles was summarized in a number of review articles including early surveys and textbook considerations (see ref 7). In the past decade, as a result of basic and applied interests in conversions of RCN, the number of investigations has increased to the point where the subject cannot be dealt within a single article and various excellent reviews considering *particular* aspects of such additions emerged in the literature. In most of them metal[7,10−13] and metal−enzyme (for recent reviews on the subject see refs 14−21) catalyzed hydrolysis of organonitriles was analyzed due to its superior industrial importance for the production of amides, e.g., acrylamide and nicotineamide. Some other works considered the addition of pyrazoles to ligated pseudohalides containing cyano groups,[22] the metal-promoted reactions of β-dicarbonyls with nitriles leading to carbon−carbon bond formation,[23] [2 + 3] cycloaddition of organonitriles and azides involving metal centers and giving tetrazoles (for recent reviews see refs 24−28), platinum-promoted additions,[29] and reactions at particular electron-rich binding metal centers.[30,31] The most relevant and so far the most representative (ca. 200 references) review, focused mainly toward coordination chemists, was published by Michelin and colleagues,[7] and it covers the significant reactivity patterns of ligated organonitriles known until early 1994. Such a broad coverage became possible only when processes were considered just selectively rather than comprehensively, and not surprisingly, a number of important points, e.g., application of metal-mediated reactions in organic synthesis, cycloadditions, formation of the C−C and C−P bonds, couplings with heterocycles, formation of metallacycles, were treated either briefly or omitted. Furthermore, a number of intriguing transformations, e.g., couplings with oximes, imines, or sulfimides and some cycloadditions, were discovered after the appearance of that review.[7]

Indeed, throughout the last five years, reactions of nitrile ligands have experienced a rapid growth. Recent applications of the homogeneous catalytic behavior of some metal compounds[4,12] have also sparked many new challenging directions motivated, in part, by industrial demands. In view of the emerging importance of metal-assisted additions to organonitriles for both coordination and organic chemistry, a comprehensive critical review in this area was thought to be timely.

The essential goals of this review are 3-fold: (i) to attempt, based on recent advances, to systematize and explain many diverse observations and reports and to give a general picture of reaction routes, mechanisms, and driving forces; (ii) to draw attention to the advantages which metal-mediated conversion of organonitriles gives to synthetic organic chemistry; (iii) to indicate possible metal-catalyzed routes which open up economically favorable and environmentally friendly ways for obtaining new products derived from organonitriles. We anticipate that the review will stimulate interest in this area and that further experimental studies and theoretical calculations will be performed.

II. Hydrolysis of Organonitriles Involving Metal Complexes

Hydrolysis of organonitriles involving metal complexes is treated here only briefly since up-to-date accounts on this area have been recently provided,[4,10−12] as well as on nitrile hydratases.[14−21] We now give only a short overview of experimental works which appeared in the past few years and were not included in those surveys.

The field is of a highly recognized synthetic significance in particular toward the preparation of amides, in view of their industrial applications and pharmacological interest.[1,32−35] Although most of the known synthetic transformations leading to amides are based on the reaction between an activated carboxylic acid and an amine or ammonia, an alternative preparative pathway involves hydrolysis of organonitriles. However, in the vast majority of cases a base-catalyzed reaction leads to a carboxylate salt, because the second step of the hydrolysis (conversion of amides to carboxylic acids) is often faster than the first one (conversion of nitriles to amides), and the reaction thus proceeds to the final hydration product rather than stopping at the amide stage.[32−36] Although in strong acidic solutions it can be possible to obtain amides, careful control of the temperature and of the ratio of reagents is then required in order to avoid the formation of polymers, which is promoted by the exothermic character of the hydrolysis.[32−36] Moreover, the final neutralization leads to an extensive salt formation with inconvenient product contamination and pollution effects.[4,5]

These difficulties can be overcome with the use of metal ions which can behave as extremely strong activators (see section I) of RCN toward nucleophilic attack by OH^-/H_2O. Throughout the past decade, metal-catalyzed or metal-mediated hydrolysis of nitrile ligands have experienced a rapid growth in two main directions, namely, (i) the homogeneous *catalytic* hydrolysis when the amides formed are expelled from the coordination sphere of the metal ions and (ii) the metal-*mediated* hydrolysis giving amides which remain ligated. The former direction is strongly motivated by practical applications, and the latter one gives useful information about structures, coordination modes of metal-bound amides, and stereochemistry of plausible intermediates involved in the catalytic hydration.

A. Homogeneous Catalytic Hydrolysis Involving Metal Complexes

Many metal-mediated processes for the hydration of nitriles with selective formation of metal-bound carboxamides are known from the literature,[4,7,10−12] but most of the systems are not catalytic and only a few of them are able to hydrate RCN under *homogeneous catalytic* conditions, usually exhibiting a low activity. The most active ones are based on the platinum(II) phosphinito complexes[37−40] [$PtX(R_2PO\cdots H\cdots OPR_2)(PR_2OH)$] (X = H or halide; R = alkyl or aryl), typically [$PtH(Me_2PO\cdots H\cdots OPMe_2)(PMe_2OH)$] which acts as an effective catalyst not only for the hydration of nitriles to amides but also[40] for the amidation of nitriles to *N*-substituted amides (tertiary amides). Other less active systems—apart from those few reviewed by Parkins[12,37]—include the following ones: the rhodium complex generated in situ in an aqueous solution from [$Rh(\mu\text{-}Cl)(cod)]_2$ and $P(m\text{-}C_6H_4SO_3Na)_3$[41] and various mononuclear complexes of Pd(II) with aqua, diamine, triamine, methionine methylester, etc., ligands[42] besides some hydride phosphine complexes of low-valent ruthenium[4] or iridium.[43]

Other systems are based on nitrile hydratases,[14−21] Fe- or Co-containing enzymes which catalyze the hydration of nitriles in vivo, and on complexes that mimic or are relevant to these enzymes (although so far presenting a much lower efficiency),[13,44−53] and various processes for the preparation of amides by this enzymatic route have already been the object of patents (for recent patents, see refs 54−70). In industry, nitrile hydratases have been successfully applied for more than a decade to the kiloton production of acrylamide and more recently to the smaller-scale production of nicotinic acid, *R*-(−)-mandelic acid, and *S*-(+)-ibuprofen. There is also a rapidly growing catalog of other potentially useful conversions of complex nitriles, by use of the nitrile hydratases, in which the regioselectivity of the enzyme coupled with the ability to achieve high conversion efficiencies without detriment to other sensitive functionalities is a distinct process advantage.[71,72]

Most of the above catalysts, however, are rather expensive, and their preparation and use require some particular skills, thus restricting their application. A system of higher simplicity has very recently been found,[73] and it consists of cheap and widely commercially available compounds, i.e., a zinc(II) salt (zinc nitrate) and an oxime (2-propanone oxime). It operates in air and under neutral conditions and without needing an excess of water (thus facilitating the isolation of the amide product) and has been applied to a variety of liquid organonitriles. Carboxylic acids, the full hydrolysis products, are also formed, although in low yields, and can be removed by recrystallization from the carboxamide main products.[73] The study on Zn(II)/ketoxime-catalyzed hydrolysis of nitriles[73] is relevant to the Co(II)/ketoxime-promoted conversion of RCN to amidines[74] which will be considered in section V.

Other examples are known of association of nitrile hydrolysis with different reactions in more complex metal-promoted processes that can lead to various

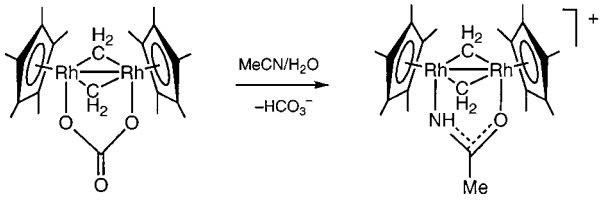
types of products distinct from carboxamides or carboxylic acids, as discussed below.

B. Metal-Mediated Hydrolysis

1. Formation of Bimetallic Metallacycles

Treatment of $[Rh_2Cp^*_2(\mu\text{-}CH_2)_2(\mu\text{-}O_2CO)]$ ($Cp^* = \eta^5\text{-}C_5Me_5$) with acetonitrile in aqueous solution followed by addition of KPF_6 affords the Rh−Rh complex $[Rh_2Cp^*_2(\mu\text{-}CH_2)_2(\mu\text{-}\eta^1{:}\eta^1\text{-}NHC(=O)Me)][PF_6]$ (Scheme 1),

Scheme 1



which is the first example of a bimetallic metallacycle where the amidato ligand $[NHC(=O)Me]^-$ links the metal−metal site.[75]

A similar amidato dimetallacycle containing a Re−Re quadruple bond has recently been prepared upon hydrolysis of 1,4-dicyanobenzene,[76] benzonitrile,[77] or acetonitrile[78,79] in the presence of $(Bu_4N)_2[Re_2Cl_8]$[76−79] or $[Re_3(\mu\text{-}Cl)_3Cl_7(H_2O)_2]^{2-}$.[80] The molybdenum-based metallacycles $Mo_2(\mu\text{-}MeCONH)$ were obtained by hydrolysis of ligated acetonitrile in $[Mo_2(MeCN)_8](BF_4)_4$[81] or $[Mo_2Cp_2(MeCN)_2(\mu\text{-}SMe)_3](BF_4)$.[82] Some other reactions occurred at multimetallic centers, e.g., involving the molecular clusters with $[Re_4]$ core,[83] dinickel(II),[84,85] or disilver(I)[86] complexes, are known. Syntheses of iridium(III) carboxamides via the *bimetallic* reaction[87] between $[Cp^*Ir(Ph)(OH)(PMe_3)]$ and $[Cp^*Ir(Ph)(NCR)(PMe_3)]^+$ and also mediated by the mononuclear complex $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{NH{=}C(OR)Me\}]^+$ [88,89] have recently been described.

2. Formation of Metallacycles Involving Hydrolytic Conversion of Nitriles

Hiraki et al.[90] reported the formation of metallacycles upon reaction of the hydridoruthenium(II) complex $[RuCl(H)(CO)(PPh_3)_3]$ with aromatic nitriles ArC≡N in the presence of water. Thus, in the case of *p*-tolunitrile, heating of the complex and the nondried nitrile in a sealed tube at 120 °C for several hours followed by addition of hexane led to the precipitation of the *N*-imidoylimidate complex **A.II** in 92% yield, depicted in Figure 1.

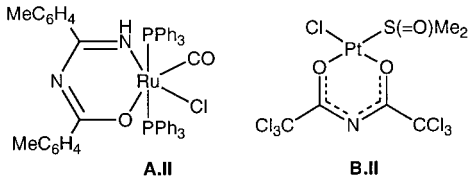


Figure 1.

The authors[90] convincingly show that *water* is essential for the occurrence of the reaction. Chemical experiments indicate that the formation of the metallacycle proceeds via initial hydrolysis of ArCN to give the carboxamide species followed by the coupling with one more molecule of the nitrile. The carboxamide formed in the reaction also serves as the hydride-abstracting reagent.

A somehow similar reaction was observed when $K[PtCl_3(Me_2SO)]$ was treated at pH ca. 7 with trichloroacetonitrile.[91] The platinum(II) complex which contains a novel metallacycle **B.II**, depicted in Figure 1, was isolated in good yield along with an insignificant amount of the expected $[PtCl_2(Cl_3CCN)(Me_2SO)]$ and the aqua complex $[PtCl_2(H_2O)(Me_2SO)]$. A plausible mechanism[91] involves the hydrolysis of carboxamide (in the amide or in the tautomeric iminol form), coupling with another Cl_3CCN molecule, and hydrolysis of the imino group formed. The ligand is stabilized by deprotonation to give the ring system, including the Pt center, with delocalized π-electron density.

3. Other Examples of Metal-Mediated Hydrolysis

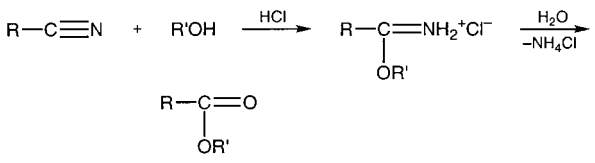
In the vast majority of cases diverse metal centers facilitate the first step of the hydrolysis of nitriles giving either free $RC(=O)NH_2$ or metal-bound carboxamides in iminol or amide forms. The second step of the metal-mediated hydrolysis, i.e., conversion to carboxylic acid and ammonia, was—to the best of our knowledge—observed extensively only in a few cases including Pt(IV),[92] Os(IV),[93] and Nb(V)[94] systems. This little explored type of reactivity of metal-activated nitriles might be relevant to the investigation of a not well-known enzyme system, *nitrilase*,[71,95] which catalyzes the direct conversion of nitriles to carboxylic acids, an important process not only for the production of organic materials but also in the detoxification of compounds contaminated with highly toxic organonitriles or inorganic cyanides.[96]

III. Metal-Mediated Alcohol–Nitrile Coupling

A. General Considerations

In organic chemistry, the Pinner reaction[97] (for recent examples see refs 98−104) is widely applicable for the preparation of imino ester hydrochlorides. Interaction between an organonitrile and an alcohol (RSH can also be used for the addition, a so-called Thio-Pinner reaction[105,106]) is typically performed in the presence of substantial amounts of hazardous hydrogen chloride and requires dried conditions. Otherwise, the iminium salts formed are subject to hydrolysis to give the corresponding carboxylic esters, Scheme 2.

Scheme 2



The reaction with an alcohol differs in one major way from that with water—the intermediate cannot tautomerize and an imino ester is obtained. The Pinner reaction for nitriles was also extended to the nitrilium salts, $RC{\equiv}N^+R''$, and the addition per-

formed in the presence of a base catalyst led to the *N*-alkylimino esters, RC(OR′)=NR″ (see, e.g., ref 107).

Probably the first *metal-mediated* addition of alcohols to organoniriles was reported by Rouschias and Wilkinson,[108] who heated the rhenium(IV) complex $[ReCl_4(MeCN)_2]$ in either methanol or ethanol and isolated the corresponding imino ester complexes $[ReCl_4\{NH=C(OR)Me\}_2]$ but failed to react the complex with phenol. Further treatment of $[ReCl_4\{NH=C(OEt)Me\}_2]$ with triphenylphosphine resulted in substitution and gave $[ReCl_4(PPh_3)_2]$ along with the liberated imino ester, i.e., NH=C(OEt)Me, which was detected by GLC. The reaction described[108] illustrates some advantages of the application of metal-bound imino esters over the hydrochlorides.

Imino esters are useful synthetic intermediates in organic chemistry,[109] but in the vast majority of cases, their utilization involves the free R′(RO)C=NH rather than its hydrochloride, R′(RO)C=NH·HCl. Careful neutralization of 1 equiv of HCl in *nonaqueous* media is sometimes a technically complicated task especially when the synthesis is performed in microscales. Moreover, products of neutralization, e.g., H_2O, can affect the condition of either the imino ester or a product of its transformation. Similarly to protonation, coordination to a metal center makes imino esters quite stable, and they can be stored in this form for a prolonged time. Their liberation in many instances is easier to perform than that of dehydrochlorination. If the replacement is carried out in nonaqueous dried solvents and the complex formed is precipitated and can be removed by filtration (see, for example, ref 110), the liberated imino esters retained in the filtrate are stable toward hydrolysis and can be used in situ for further reactions.

Attention should be drawn to the fact that imino ester metal complexes are interesting by themselves, and some of them are the subject of rapt attention. Indeed, recent interest in the chemistry of, for example, platinum complexes[111,112] with imino esters stems from the discovery of an unusual antitumor activity of some of these complexes which breaks the rule of higher antitumor activity of cis isomers of platinum(II) complexes with *N*-donor ligands as compared to the trans form.

B. Metal-Mediated ROH Additions

The organonitrile−alcohol coupling has been studied at metal centers of different characters. Inspection of these reactions shows a tendency in the formation of imino ester complexes, i.e., monodentate imino esters are, more often, formed with *soft* metal centers such as platinum or iridium where they display a high stability toward both hydrolysis and substitution. Alcoholysis also occurs at *hard* metal centers giving monodentate imino ester ligands, but it is especially effective when their additional stabilization, by chelation, is feasible. In accord with that, we divided the material on the addition of alcohol to RCN species in two conditional parts. In the first, given below in sections III.B.1−4, we consider, with small deviations, reactions at *soft* (Pt, Pd, Ir, Rh) or borderline (Ni) metal centers giving in the vast majority of cases monodentate imino esters. Alcoholysis of nitriles at *hard* metal centers giving stable metallacycles will be considered in section III.B.5.

1. Reactions at Platinum Centers

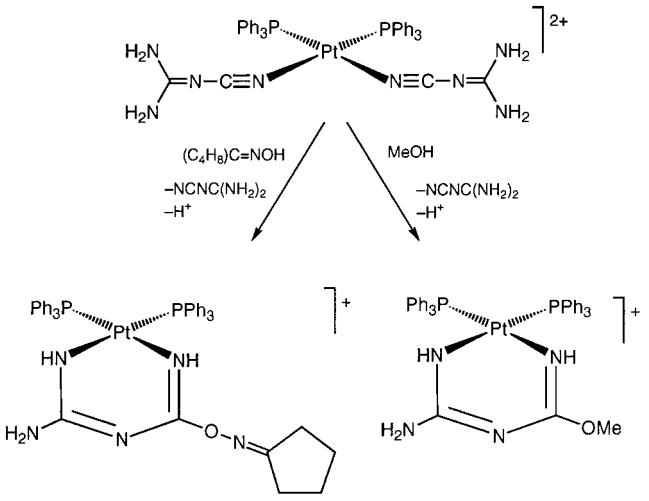
Treatment of the platinum(II) acetonitrile complex $[PtCl_2(MeCN)_2]$ with KOH (1 equiv) or KOPh (3 equiv) in anhydrous alcohols ROH (R = Me, Et, *i*-Pr) at room temperature resulted in the precipitation, in a rather good yield (50−70%), of the corresponding imino ester complexes $[PtCl_2\{NH=C(OR)Me\}_2]$ that were also converted to the platinum(IV) compounds $[PtCl_4\{NH=C(OR)Me\}_2]$ by oxidation with a so-called solid chlorine equivalent, i.e., $PhICl_2$, in chloroform.[113] The addition of ROH is considered to be base-catalyzed, and the authors report that the bases which were added to the reaction mixture to facilitate the reaction are not consumed in the course of the reaction. It is remarkable that the starting platinum(II) complex reacts selectively with the alcohols in the presence of other strong nucleophiles such as OH^- or PhO^-. In contrast to platinum(II) systems, addition of R′OH to the organonitrile platinum(IV) complexes occurs under mild conditions and does not require a base as a catalyst.[110] It is also worthwhile to mention that attempts to make the reaction catalytic failed because the imino ester species are better ligands to platinum(II) than RCN.[113] The stereochemistry of the addition of alcohols to (nitrile)-Pt(II) complexes, including $[PtCl_2(MeCN)_2]$, has been studied by Natile et al.,[114] and it is discussed in section III.E.

When 2 equiv of KOH was added to the propionitrile platinum(II) complex $[Pt(EtCN)_4][CF_3SO_3]_2$ in ethanol, the formation of the homoleptic imino ester complex $[Pt\{E\text{-}NH=C(OEt)Et\}_4][CF_3SO_3]_2$ was observed.[115] Ros et al.[116] prepared the *cationic* platinum(II) complexes $[Pt(\mu_2\text{-}C,N\text{-}CH_2C_6H_4C{\equiv}N)L_2]_2[BF_4]_2$ (L_2 = 2PPh$_3$, dppe) and studied the addition of alcohols with a variable sterical hindrance along the nitrile group. They reported that, under similar reaction conditions, the rate of the coupling decreases in accord with the bulkiness of the alkoxy group in the following order MeOH ∼ EtOH > *i*-PrOH ≫ $PhCH_2OH$, while the addition of either *t*-BuOH or PhOH does not proceed at all.

The cyanoguanidine complex *cis*-$[Pt\{N{\equiv}C-N=C(NH_2)_2\}_2(PPh_3)_2][BPh_4]_2$ readily reacts with methanol or cyclopentanone oxime to give complexes that contain an azametallacycle (Scheme 3).[117,118]

At least formally the reaction proceeds via coupling of cyclopentanone oxime (other metal-mediated oxime−nitrile couplings are given in section IV) or methanol with the electrophilically activated nitrile group of cyanoguanidine, loss of the other cyanoguanidine, and ring closure with concomitant deprotonation. On the basis of X-ray structural results, it was suggested that the six-membered ring can be described as a delocalized π-electron system.[117,118] Although a related reaction can be performed with methanol as a nucleophile at other metal centers, e.g., Cu(II)[119−121] and Zn(II),[122] the platinum(II) system[117] is the only one fully characterized starting from an individual cyanoguanidine starting material.

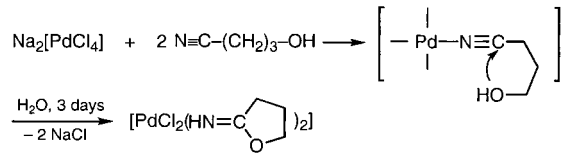
Scheme 3



2. Reactions at Palladium Centers

A kinetic study[123] of the methanolysis of dichloroacetonitrile involving palladium(II) systems will be considered in section III.E. Michelin and Angelici[124] reported the synthesis of 4-hydroxybutyronitrile, HO-$(CH_2)_3C{\equiv}N$, from the reaction of 3-bromo-1-propanol and $[Et_4N][CN]$ in CH_2Cl_2 at room temperature. Although stable and unreactive as the free ligand, the hydroxyalkanenitrile undergoes spontaneous intramolecular cyclization in the presence of $Na_2[PdCl_4]$ to afford the bis-2-iminotetrahydrofuran complex indicated in Scheme 4.

Scheme 4



The intermediate Pd(II)−nitrile complex could not be detected by IR or ^{1}H NMR spectroscopy.

The palladium hydroxo-bridged complex $[Pd_2(C_6F_5)_4(\mu\text{-}OH)_2]^{2-}$ reacted with either benzonitrile or acetonitrile in MeOH or EtOH to give the imino ester complexes $[Pd(C_6F_5)_2\{NH{=}C(OR')R\}_2]$ (R = Ph, Me, R′ = Me, Et), and the alcoholysis has been studied in a parallel way to hydrolysis of nitriles mediated by $[Pd_2(C_6F_5)_4(\mu\text{-}OH)_2]^{2-}$.[125] If bifunctional 2-cyanopyridine, $NC_5H_4(C{\equiv}N)$, or succinonitrile, $N{\equiv}CCH_2CH_2C{\equiv}N$, is employed, the reaction furnishes the palladium(II) complexes with bidentate imino ester ligands, i.e., $[Pd(C_6F_5)_2\{NC_5H_4C(OR'){=}NH\}]$ and $[Pd(C_6F_5)_2\{NH{=}C(OR')CH_2CH_2C(OR'){=}NH\}]$, in the latter case containing an unusual seven-membered chelate ring. The complexes with monodentate imine esters $[Pd(C_6F_5)_2\{NH{=}C(OR')R\}_2]$ exist in acetone-d_6 solution as equilibrium mixtures of *EE*, *EZ*, and *ZZ* isomers. The authors[125] succeeded to isolate the solid isomerically pure $[Pd(C_6F_5)_2\{E\text{-}NH{=}C(OMe)Me\}_2]$ complex and to characterize it by X-ray diffraction. They observed that this complex on dissolution in acetone-d_6 rapidly converts to the equilibrium mixture of *EE*, *EZ*, and *ZZ* isomers.

3. Reactions at Nickel Centers

Wada and Shimohigashi[126] described the reactivity of the nickel(II) complexes $[Ni(C_6Cl_5)(NCR)(phosphine)_2][ClO_4]$ toward alcohols and found some factors affecting the addition. Among them, attention should be drawn to the type of alcohol used and the electron-acceptor properties of the radical R at RCN as well as to the presence or absence of a catalyst and the sterical hindrance of other innocent ligands. Thus, both methanol and ethanol can be added to acetonitrile in $[Ni(C_6Cl_5)(NCMe)(PPhMe_2)_2][ClO_4]$, in the presence of NEt_3 as a catalyst, to give the $[Ni(C_6Cl_5)\{HN{=}C(OR)Me\}(PPhMe_2)_2][ClO_4]$ complexes in a mixture of *E*- and *Z*-forms. The benzylcyanide compounds $[Ni(C_6Cl_5)(NCCH_2Ph)(phosphine)_2][ClO_4]$ (phosphine = $PPhMe_2$ and PPh_2Me) exhibit a much higher susceptibility toward the addition, and MeOH adds along the CN triple bond even without the catalyst.[126] However, ethanol is unreactive in the latter reaction. Eventually the coupling of MeOH and benzonitrile was observed in $[Ni(C_6Cl_5)(NCPh)(phosphine)_2][ClO_4]$ where the phosphine is $PPhMe_2$ but not in the case of the more sterically hindered PPh_2Me.

The reaction of a rather complicated system that contains a mixture of $Ni(NO_3)_2$, pyrazole, and the nitrosodicyanomethanide salt $NaON{=}C(C{\equiv}N)_2$ (**A.III** in Figure 2), in aqueous methanol, gave the nickel-

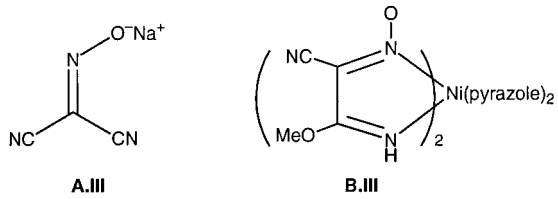


Figure 2.

(II) complex **B.III** (Figure 2), characterized by X-ray diffraction, containing ligands formed due to the addition of MeOH to the nitrile group. Unfortunately, neither information about involvement of the metal ion in that transformation was given nor a plausible mechanism was suggested.[127,128a] The same type of reactivity was observed for the process involving a copper(II) system.[129,130] Alcoholysis of pyrazinecarbonitriles[128b,c] mediated by a nickel(II) center has been studied. Two more works which deal with alcoholysis of nickel(II)-bound nitriles will be considered in section III.E.

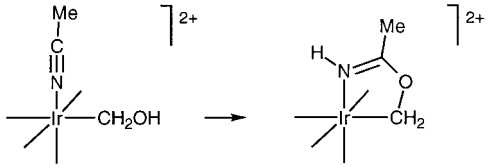
4. Reactions at Iridium and Rhodium Centers

The liberation of the imino ester from the metal has been reported only rarely, and therefore, the possibility for application in organic syntheses of the metal-mediated alcohol addition to a nitrile has not yet been developed. Nevertheless, the imino ligands NH=C(OR)Me (R = Me, Et, *i*-Pr) in $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{NH{=}C(OR)Me\}]^+$ (derived from ROH addition to the parent acetonitrile complex[88]) are displaced by PPh_3 in dry deuterated solvents. It is also established that $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)(PhC{\equiv}N)](SO_3CF_3)$ catalyzes the methanolysis of benzonitrile in the presence of Na_2CO_3 at 70 °C.[88] In this context,

it is noteworthy that the addition of ROH (R = Me, Et) to organonitriles R′CN (R′ = Me, Et) in the presence of $AuCl_3$ in chloroform gives rise to the imino ester salts $[R'C(OR)NH_2][AuCl_4]$.[131]

Intramolecular coupling of alcohol and a metal-bound organonitrile was observed by Thorn and Calbrese,[132] who discovered that the hydroxymethyl complex $[Ir(CH_2OH)(MeCN)(PMe_3)_4]^{2+}$ undergoes base-catalyzed (e.g., by pyridine or PMe_3) intramolecular attack (Scheme 5) by the oxygen atom of the hydroxymethyl group to form a metallacyclic complex which has been structurally characterized.[132]

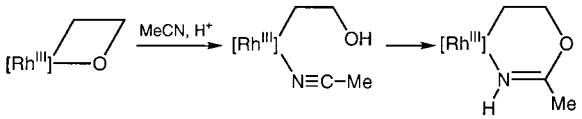
Scheme 5



The cyclization proceeds, although much slower, without addition of the base. Moreover, the coupling is suppressed by $HBF_4 \cdot Et_2O$, but the etherate also leads to the overall decomposition of $[Ir(CH_2OH)(MeCN)(PMe_3)_4]^{2+}$.

A similar, in some respects, transformation was observed by Gal and co-workers,[133] who treated the rhodaoxetane complex $[Rh(tpa)(CH_2CH_2O)]^+$ [*tpa* is the tripod-type ligand *N*,*N*,*N*-tri(2-pyridylmethyl)-amine] with NH_4PF_6 in MeCN. NMR monitoring of the progress of the reaction allowed the detection of an acetonitrile intermediate solvento complex formed on protonation and ring opening of the rhodaoxetane ring. Subsequent intramolecular cyclization led to the metallacycle depicted in Scheme 6.

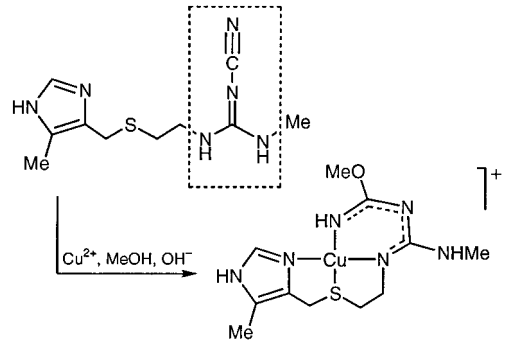
Scheme 6



5. Reactions at Other Metal Centers

Cimitidine, the potent histamine H_2-receptor antagonist, has the same structural unit as cyanoguanidine (indicated in the box in Scheme 7) and a similar reactivity in a metal-assisted reaction toward such a nucleophile as methanol. Thus, it has been reported that its reaction with copper salt in methanol in the presence of KOH at 60 °C leads to the chelate depicted in Scheme 7.[134] X-ray diffraction data show that both Cu−N bonds have essentially the same length. Moreover, the distribution of bond distances and angles in the six-membered ring proves the formation of a delocalized π-electron system in the metallacycle.

Scheme 7



Refluxing 1,2-bis(2-cyanoguanidino)ethane or 1,2-bis(2-cyanoguanidino)propane, $N{\equiv}C{-}N{=}C(NH_2)NH(CH_2)_nNHC(NH_2){=}N{-}C{\equiv}N$ (n = 2, 3) in methanol or ethanol in the presence of copper(II) salts led to the addition of two ROH molecules to each nitrile group and formation of the imino chelates **C.III** depicted in Figure 3.[135]

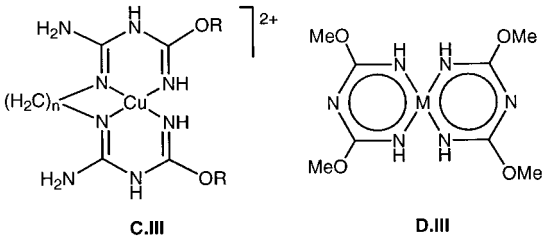


Figure 3.

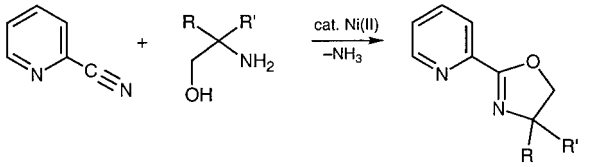
The pseudohalide dicyanamide $^-N(C{\equiv}N)_2$ also interacts with methanol in copper(II)- or zinc(II)-mediated[136,137a] processes with the addition of the alcohol to both nitrile groups to give metallacycles **D.III** (Figure 3), which are isoelectronic with the appropriate β-diketonate compounds, like $[M(acac)_2]$. Methanolysis of pyrazinecarbonitrile in the coordination sphere of copper(II) has been studied.[137b]

C. Alcoholysis of 2-Cyanopyridines and Synthesis of Oxazolines

Reaction of 2-cyanopyridine ($N{\equiv}CC_5H_4N$) with copper(II) chloride in MeOH gives, besides the simple substitution product $[CuCl_2(NCC_5H_4N)_2]$, two other complexes, i.e., $[Cu(H_2O)_2\{NH{=}C(OMe)C_5H_4N\}_2]Cl_2$ and $[CuCl_2\{NH{=}C(OMe)C_5H_4N\}]$, containing the imino ester which is derived from metal-promoted addition of the alcohol to the CN triple bond of the ligand. A similar reaction was observed with ethanol and *n*-butanol.[138] It was also found that the imino ester formed in the course of the addition can be liberated by reacting the complexes with Na_2Y (H_2Y = EDTA) and is subject to fast hydrolysis to give $O{=}C(OMe)C_5H_4N$ in good yield. The metal-assisted alcoholysis of 2-cyanopyridine was also observed in cases of Ni(II), Pd(II), Co(II), Cu(II), and Fe(III) systems.[125,138−140]

Metal-mediated addition of alcohols to 2-cyanopyridine has an interesting application for organic preparations of oxazolines[142−152] which were intensively utilized in different branches of chemistry, including asymmetric synthesis and catalysis (for reviews see refs 153−155), and these heterocycles also have some biological and insecticidal implications (for recent works see refs 156−158); the coordination chemistry of oxazolines has been reviewed.[159] The Ni(II)- or Cu(II)-catalyzed reaction of $N{\equiv}CC_5H_4N$ with bifunctional reagents,[141−147] i.e., amino alcohols, led to the oxazolines, e.g., depicted in Scheme 8.

Scheme 8

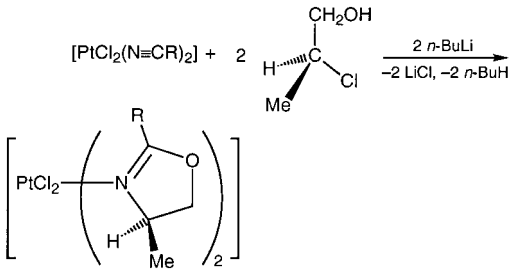


Dinitriles react likewise with amino alcohols in a zinc(II)-catalyzed process to give bis(oxazolines).[148−152] The corresponding reaction giving oxazolines is known in the so-called pure organic chemistry as a two-step procedure (diimino ester formation from 1,3-dinitriles followed by the reaction with amino alcohols[160]), but this method can only be applied to a rather restricted subclass of nitriles.

D. Reactions with Halo Alcohols and the Oxirane/Cl^- System: Synthesis of Oxazolines and Oxazines

Michelin, Angelici, and colleagues reported an elegant method for generation of oxazoline species, which is based on the platinum-mediated addition of halo alcohols to organonitriles.[161−166] Nitrile ligands in the complexes $[PtCl_2(NCR)_2]$ (R = alkyl, aryl)[161,162] or *trans*-$[Pt(R')(NCR)(PPh_3)_2]^+$ (R′ = H, CH_3, CF_3; R = alkyl, aryl)[163,164] react with the alkoxide $^-OCH_2CH_2Cl$ (which can be generated in two ways, i.e., by deprotonation of $HOCH_2CH_2Cl$ with a base or by oxirane ring opening with Cl^-) to give the oxazoline complexes $[PtCl_2\{\overline{N{=}C(R){-}OCH_2CH_2}\}_2]$ and *trans*-$[Pt(R')\{\overline{N{=}C(R){-}OCH_2CH_2}\}(PPh_3)_2]^+$, respectively. Recently some chiral oxazoline complexes were obtained by the cyclization reaction of the platinum(II) nitrile complexes with chiral halo alcohols in the presence of 2 equiv of *n*-BuLi (Scheme 9).[165]

Scheme 9

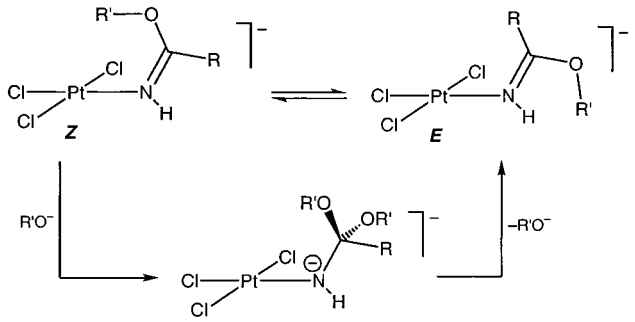


The reaction was also extended to 3-chloro-1-propanol, $HOCH_2CH_2CH_2Cl$, to give complexes that contain six-membered 1,3-oxazines $[PtCl_2\{\overline{N{=}C(R){-}OCH_2CH_2CH_2}\}_2]$. Both oxazoline and oxazine species are rather poorly bonded to the platinum(II) center and were liberated either by reaction with dppe or Cl^-.[163,166]

E. Stereochemistry and Kinetics of Alcohol Additions

To the best of our knowledge, currently there are two basic but *not coherent* reports on the stereochemistry of alcohol addition to coordinated nitriles. In the first, Natile and colleagues described the reactions of $K[PtCl_3(RCN)]$ and *cis*- and *trans*-$[PtCl_2(RCN)_2]$ (R = Me, Et, Ph, *t*-Bu) with R′OH that occur readily at ambient temperature in the presence of a catalytic amount of KOH to give the corresponding imino ester complexes with ligands in the *Z*- and *E*-configurations.[114] The progress of the KOH-catalyzed addition of methanol to $K[PtCl_3(RCN)]$ was monitored by ^1H NMR spectroscopy, and the initial formation of the *Z*-isomer, i.e., $[PtCl_3\{Z\text{-}NH{=}C(OR')R\}]^-$, corresponding to a *trans*-addition (the alkoxide and the hydrogen add to the C≡N bond from opposite sides) of the alcohol to the nitrile triple bond was detected, Scheme 10.

Scheme 10



Subsequently, under the same reaction conditions, $[PtCl_3\{Z\text{-}NH{=}C(OR')R\}]^-$ isomerizes to the *E*-form, and this transformation depends on the sterical hindrance of the radical R′ in R′OH. The transformation is complete for R′ = Me or Et, but for R = Ph an equilibrium between the two isomers was observed, while in the case R = *t*-Bu only the *Z*-form exists and does not isomerize to the *E*-form. The rate of the *Z*−*E* transformation is slow under normal conditions, but it becomes faster in the presence of a catalytic amount of MeO^-, which presumably adds reversibly to the azomethine residue of the imino ester group, thus facilitating the conversion (Scheme 10).[114]

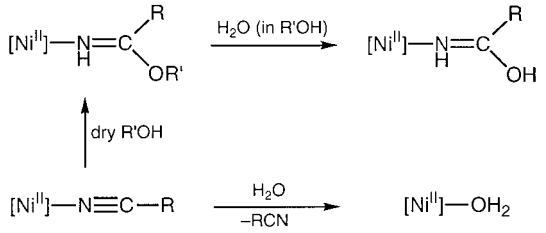
In the second work,[88] which appeared recently, the methanol or ethanol additions to coordinated acetonitrile in the iridium(III) cationic complex $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)(NCMe)](SO_3CF_3)$ proceed readily at room temperature to give mixtures of *E*- and *Z*-isomers of $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{NH{=}C(OR)Me\}]^+$ (R = Me, Et). In the presence of the appropriate ROH or Na_2CO_3, the complete *E*−*Z* isomerization occurs and this direction is *opposite* to that found[114] for the platinum(II) complexes. In the case of the more sterically hindered *i*-PrOH, the addition leads exclusively to $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{Z\text{-}NH{=}C(OPr^i)Me\}]^+$ and no evidence for the *E*-isomer was obtained. When a mixture of the *E*- and *Z*-isomers of $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{NH{=}C(OEt)Me\}]^+$ was stirred in a MeOH solution in the presence of Na_2CO_3 for 24 h at room temperature, the pure *Z*-isomer of $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)\{NH{=}C(OMe)Me\}]^+$ was obtained, and the authors argue that this observation suggests that the isomerization, likewise in the case of platinum(II) complexes,[114] is initiated by the nucleophilic attack of MeO^- to the imino carbon of the ligand, giving the amido−ketal complex followed by elimina-

tion of the ethoxy group. It is obvious that more examples of *E*/*Z* addition/transformation at different metal centers should be found to make the system predictable.

A wide series of reactions of alcohols and amines with the Ni(II) nitrile complexes $[NiL(NCR)][ClO_4]$ (L = a *S*,*N*,*N*-tridentate anion; R = Me, Et, Ph) has been reported.[167,168] The complexes react under reflux with dry alcohols R′OH (R′ = Me, Et, *n*-Pr) in the presence of excess free RCN (dimerization to give μ-OR complexes rather than the addition would otherwise be observed) to give the corresponding imino ester complexes $[NiL\{NH{=}C(OR')R\}][ClO_4]$.[167] The reaction seems to be controlled by sterical properties of both R and R′. Indeed, the rate falls off strongly with an increase in the chain length of the alcohol. Concurrently, the addition occurs smoothly with the use of MeCN and EtCN complexes, but in the case of PhCN, the reaction is very slow irrespective that the nitrile carbon in benzonitrile should be more activated toward the nucleophilic attack. It is important that the rate of the alcohol−nitrile coupling can be dramatically accelerated, e.g., by more than 4 orders of magnitude,[168] by use of sodium alkoxide as a catalyst.

If the alcohol used is wet, the product is a carboxamido complex $[NiL(NH_2COR)][ClO_4]$. The latter results upon attack of water to the imino ligand rather than direct attack at the nitrile carbon, while reaction of $[NiL(NCR)]^+$ with water led solely to the substitution of organonitrile, Scheme 11.

Scheme 11



The kinetics and mechanism of these additions with MeOH were investigated,[168] and it was suggested that the addition might occur in two stages. The first one involves direct nucleophilic attack of the alcohol to the nitrile carbon atom yielding a labile adduct which can either revert to the starting reagent (preequilibrium stage) or proceed (second stage) to the final imino ester product via a four-membered cyclic transition state ***a*** (Figure 4) (first-order rate

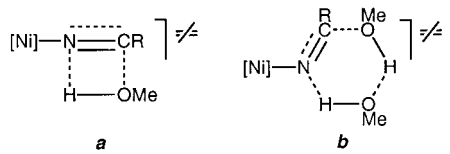


Figure 4.

dependence on MeOH concentration) and/or intermolecularly through the participation of another methanol molecule (second-order term on MeOH concentration) which behaves as a catalyst in a six-membered activation state ***b***.

The palladium(II) solvento complexes $[Pd(solv)_2\{S,S\text{-}HO(CH_2)_2S(CH_2)_2S(CH_2)_2OH\}]^{2+}$ (solv = D_2O, $(CD_3)_2CO$, CD_3OD) catalyze the methanolysis of dichloroacetonitrile to produce $Cl_2CHC(OMe){=}NH$.[123] A kinetic study showed the following: (i) in the metal-catalyzed process, the addition of methanol is 10^6 times faster than in the uncatalyzed reaction; (ii) the methanolysis has almost an identical rate constant to that of the hydration of Cl_2CHCN which is also catalyzed by the same palladium complex; (iii) the first-order reaction with respect to $[CD_3OD]$ indicates an intermolecular reaction between metal-bound dichloroacetonitrile and CD_3OD. A plausible mechanism for the methanolysis involves displacement of the *solv* ligands and coordination of the nitrile to the metal center which activates it toward the addition. The imino ester formed is expelled from the coordination sphere by substitution with *solv* ligands. Some other palladium(II) solvento complexes containing innocent bi- or tridentate ligands also display the same type of catalytic activity.[123]

F. Final Remarks

The alkoxylation of coordinated nitriles is dramatically affected by the electronic and steric properties of the substituent R in the alcohol. Indeed, the reaction proceeds smoothly with sterically unhindered alkyls, e.g., R = Me, Et, *n*-Pr, while it is less efficient with more sterically demanded alcohols, e.g., R = *i*-Pr, or does not proceed at all, e.g., *t*-Bu. Moreover, no R′CN−ROH coupling was observed with phenol or even phenolate. The nature of the substituent R′ in the nitrile also affects the addition, and the reaction proceeds smoothly with less bulky substituents. Furthermore, the coupling occurs easier with nitriles bearing acceptor groups rather than with donor ones, e.g., Ph > $PhCH_2$ > Me.

The addition strongly depends on the oxidation state of the metal. In the case of high oxidation state metal ions, the R′CN−ROH coupling does not require a base which, for a reaction promoted by low oxidation state metal ions, catalyzes the process.

Imine esters are much better ligands for *soft* metal centers than nitriles. Hence, the high stability of the imino ester complexes, which is a useful property for stoichiometric reactions, prevents, however, their usage in catalytic processes, and only one catalytic reaction of this kind has been reported. We assume that further progress in the search of catalytic processes for the metal-mediated conversion of nitriles to imino esters could well be connected with the application of *hard* metal centers, where the stability of the imino ester species formed should be lower and they could be involved in catalysis.

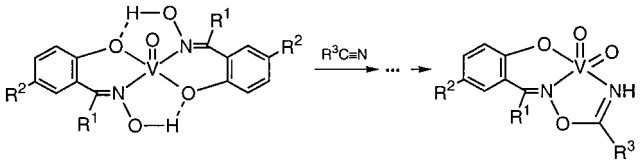
IV. Metal-Mediated Nitrile–Oxime Coupling

In organic chemistry, it is well-documented that oximes are ambidentate nucleophiles, and their reactions with electrophilic reagents, e.g., alkylation, arylation, or *acylation*, have been extensively studied and reviewed.[169−174] Similar processes involving metal complexes are also known although scarce.[175,176] Metal-mediated *iminoacylation* of oximes is even a

less explored area, and only recently have publications on this subject started to emerge in the literature.

After the first evidence on the coupling between metal-bound benzonitrile and 3,3-dimethyl-2-butanone oxime reported at a conference,[177] Grigg et al.[178] found the (formally) reverse reaction between a coordinated oxime and a nitrile. The authors[178] studied the conversions of the oxovanadium(IV) aldoxime and ketoxime complexes in solutions of various nitriles and observed the oxime−nitrile coupling, Scheme 12.

Scheme 12

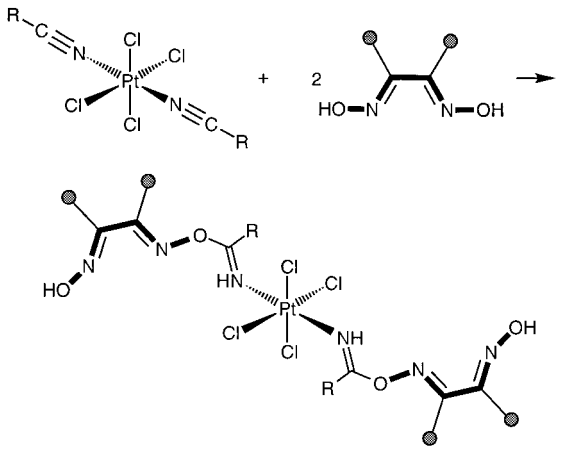


Since the novel ligand cannot be generated from a direct combination of the nitrile and the oxime, a metal-ion-assisted mechanism for this reaction was suggested. It is anticipated[178] that the mechanistic pathway of the reaction involves initial coordination of the organonitrile to the oxovanadium(IV) center, prior to oxidation followed by the loss of an oxime bidentate ligand and the addition of the oxime OH group across the C≡N bond. The nature of the oxidant for the V^{IV} center remains unelucidated. Later, Zerbib et al.[179] prepared the salicylaldoximato oxovanadium complex $[VO(OC_6H_4CH{=}NOH)_2]$ and found that its heating in MeCN gives the iminoacylation product $[VO\{OC_6H_4CH{=}NOC(Me){=}NH\}_2]$. Similarly, the salicylamide oximato complex $[VO\{OC_6H_4C(NH_2){=}NOH\}_2]$ gives $[VO\{OC_6H_4C(NH_2){=}NOC(Me){=}NH\}_2]$ in refluxing acetonitrile.

The authors of this review article recently reported on the metal-mediated iminoacylation reaction of various ketoximes, aldoximes,[180] chloroximes, and amidoximes,[181] $HON{=}CR_1R_2$, or *vic*-dioximes,[182] HON=C(R′)C(R′)C=NOH, upon treatment with the organonitrile platinum(IV) complexes *trans*-$[PtCl_4(RCN)_2]$ (R = Me, CH_2Ph, Ph) that proceeds under relatively mild conditions to give, in almost quantitative yield, the platinum(IV) complexes *trans*-$[PtCl_4\{NH{=}C(R)ON{=}CR_1R_2\}_2]$[180,181] or *trans*-$[PtCl_4\{NH{=}C(R)ON{=}C(R')C(R')C{=}NOH\}_2]$[182] with *O*-iminoacylated [or (alkylideneaminooxy)imines] ligands (see Scheme 13, reaction with *vic*-dioximes).

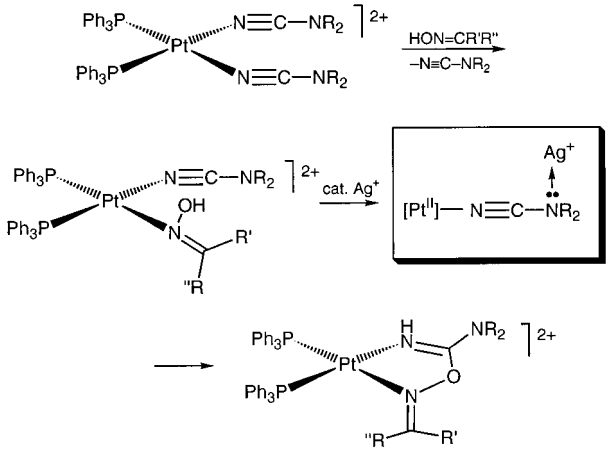
It is remarkable that the reaction of *trans*-$[PtCl_4(MeCN)_2]$ and the oximes in acetonitrile as a solvent led almost quantitatively to the metal-bound iminoacylated oximes despite the incomparably higher concentration of free MeCN. ^1H NMR experiments show that neither MeCN nor the other nitriles react with the oximes under the reaction or even more harsh conditions, and this also supports the idea of the metal-mediated reaction. It is worthwhile to mention that the metal-mediated nitrile−oxime coupling has certain parallels with the reported addition of 2-propanone oxime to nitrilium salts $[R{-}N{\equiv}C{-}R']^+$ giving the adducts $R{-}(H)N^+{=}C(R'){-}O{-}N{=}CMe_2$.[183]

Scheme 13



The platinum(IV)-mediated oxime−nitrile coupling, initially performed for $[PtCl_4(RCN)_2]$, was then extended to the other platinum(IV) complexes, i.e., $[PtCl_4(RCN)(Me_2SO)]$ and $[PtCl_5(EtCN)]^-$.[92,182] Furthermore, the reaction was proved to be efficient for rhenium(IV)[184] and rhodium(III)[185,186] systems. An unusual example of activation of a nitrile by *two metal centers* has also been reported.[187] Thus, the dialkylcyanamide complexes *cis*-$[Pt(N{\equiv}CNR_2)_2(PPh_3)_2][BF_4]_2$ react with oximes, HON=CR′R″ (R′R″ = Me_2 or C_4H_8), in the presence of a catalytic amount of $Ag[BF_4]$ or $Cu(MeCO_2)_2$ to give a novel type of azametallacycle, *cis*-$[Pt\{N,N\text{-}NH{=}C(ON{=}CR'R'')NR_2\}(PPh_3)_2][BF_4]_2$, upon coupling of the organocyanamides with oximes in a process that proceeds via the mixed oxime−organocyanamide species *cis*-$[Pt(NCNR_2)(HON{=}CR'R'')(PPh_3)_2][BF_4]_2$ (Scheme 14).[187]

Scheme 14



In contrast, in the complexes *cis*-$[Pt(N{\equiv}CR)_2(PPh_3)_2][BF_4]_2$ (R = C_6H_4OMe-4 or Et), the ligating nitriles were inactive toward the coupling even in the presence of the Lewis acids. This observation led the authors[187] to the assumption that the nucleophilic attack by the oxime was facilitated via, on one hand, ligation of the dialkylcyanamide to the platinum(II) center and, on the other hand, by interaction of the Lewis acid metal ion with the amido-*N* of the cyanamide ligand (see boxed intermediate in Scheme 14), thus enhancing the electrophilicity of the nitrile carbon. As described above (Scheme 3), for the related

cyanoguanidine Pt(II) complex *cis*-[Pt{N≡C−N=C(NH$_2$)$_2$}$_2$(PPh$_3$)$_2$][BPh$_4$]$_2$, the oxime coupling with the cyano group does not require the presence of the second Lewis acid, being assisted by ligand cyclization to yield a six-membered azametallacycle product.[117,118]

The iminoacylation of oximes was also observed, by Pavlishchuk and colleagues,[188] at a nickel(II) center. The authors[188] studied the reaction between 4,7-dithiadecane-2,9-dione dioxime (DtoxH$_2$) with 1 equiv of Ni(ClO$_4$)$_2$·6H$_2$O in 96% ethanol under reflux conditions, giving a precipitate which was then recrystallized from acetonitrile to form a product that was subject to X-ray analysis. It appears that in the course of recrystallization both OH groups of the dioxime couple with two molecules of MeCN to give a hexadentate ligand bound to the nickel(II) center via four N and two S atoms (Figure 5). The addition

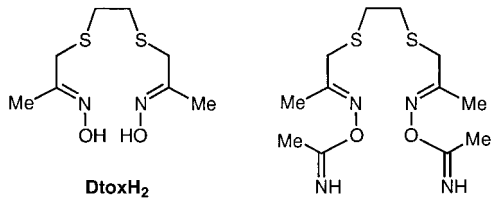


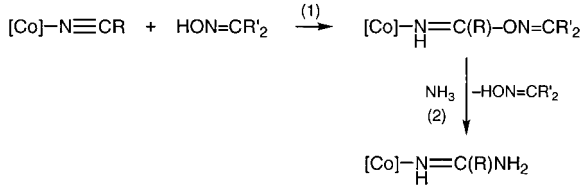
Figure 5.

is metal-mediated insofar as there was no reaction observed between 4,7-dithiadecane-2,9-dione dioxime and acetonitrile upon reflux for several days. The coupling of the dioxime and MeCN is reversible, as confirmed by the fact that the treatment of the iminoacylated complex with sodium acetate furnished [Ni$_3$(Dtox)(DtoxH)$_2$]$^{2+}$ with the regular oxime/oximato groups.

The nitrile−oxime coupling was investigated by ab initio methods for [PtCl$_5$(NCMe)]$^-$, which were also applied to the related neutral platinum(IV) [PtCl$_4$(NCMe)$_2$] and platinum(II) [PtCl$_2$(NCMe)$_2$] complexes.[92] The calculations included the geometry optimization of the starting and final complexes, location of possible transition states for the reaction discussed, and the intrinsic reaction coordinate calculations for one of the reactions. The results obtained provided an interpretation, on the basis of kinetic (activation energies) and thermodynamic (reaction energies) effects, for the order of observed reactivity [neutral Pt(IV) > anionic Pt(IV) > neutral Pt(II)] and indicated that the mechanism based on the nucleophilic addition of the protic nucleophile (undeprotonated oxime), to form a transition state with a four-membered NCOH ring, is energetically favored relative to the alternative one involving the prior deprotonation of the oxime, unless base-catalyzed conditions are operating.[92]

The iminoacylation of oximes, as modeled on kinetically inert systems (see above), has recently found an unusual application in organic synthesis involving kinetically labile metal complexes. Thus, sterically unhindered organonitriles RCN (R = Me, Et, *n*-Pr or *n*-Bu) are converted, in the presence of Co(NO$_3$)$_2$·6H$_2$O or of a nitrile Co(II) complex (nitrate salt) and the ketoxime R′$_2$C=NOH (R′$_2$ = Me$_2$ or C$_5$H$_{10}$), into the corresponding amidines, RC(=NH)NH$_2$, isolated as their nitrate salts, and carboxylic acids.[74] This process was rationalized in terms of competitive nucleophilic attacks to ligated NCR by H$_2$O (to give ammonia and carboxylic acid) and by the oxime yielding, in the latter case, an iminoacylated intermediate [Co]−NH=C(R)ON=CR′$_2$ (reaction 1, Scheme 15) which, on further reaction with ammonia,

Scheme 15



furnishes the amidine product (reaction 2, Scheme 15). The addition of water to the ligated RCN is the favorable process for the sterically hindered organonitriles which hamper the attack by the bulky ketoxime, thus preventing the formation of the amidines.[74]

The nitrile−oxime coupling is also believed to play a relevant role in another kinetically labile system, consisting of a Zn(II) salt and an oxime, which acts as an efficient catalyst for the hydrolysis of nitriles to carboxamides,[73] as described in section II.

It is also worthwhile to mention (i) that the oxime−nitrile-type coupling was extended to dialkyl and dibenzylhydroxylamines, see section V.D, and (ii) to nitrones which can be viewed as a "frozen", by alkylation, form of the other oxime tautomer, see section X.B.

V. Formation of the C–N Bond

A. Formation of Amidines

It is well known that the development of efficient and catalytic methods for the formation of the C−N amide linkage is of paramount importance due to the high synthetic utility of amides in general and amidines, RC(=NH)NR′R″, in particular and a number of their industrial applications. The organic,[189−191] medicinal,[192,193] and coordination[194,195] chemistries of amidines have been reviewed in a number of articles. Their *direct* synthesis from RCN and R′R″NH can only be achieved when the nitrile bears a strong electron-acceptor group R, e.g., CCl$_3$. A general, although more time-consuming, method for preparation of amidines is based on the Pinner reaction (see section III) and involves the reaction between RCN and R′OH (or RSH, so-called the Thio-Pinner reaction) in a nonaqueous solvent containing substantial amounts of HX (X = Cl, Br) followed by interaction of the imino ester salt RC(OR′)=NH·HX thus formed with ammonia or primary or secondary amines to give the amidines RC(NR^{1}R^2)=NH. The *metal-mediated* synthesis of amidines opens up a new route to achieve these important compounds, as described in the current and the following sections (sections V.A and V.B), the latter dealing with organic synthesis involving metal complexes.

1. Additions of Ammonia

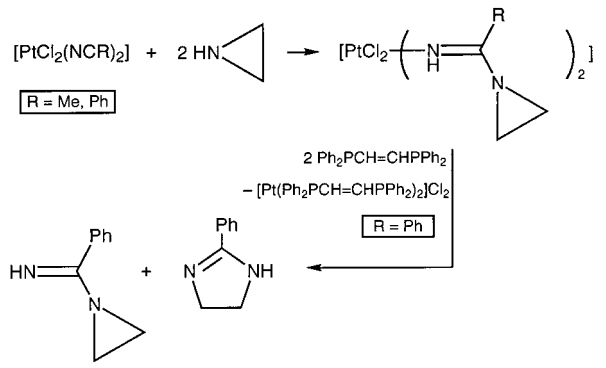
In the vast majority of cases complexes containing the $RC(NH_2)$═NH species are prepared by direct addition of the *amidine* to a complex, but metal-assisted reactions of *coordinated organonitriles* and ammonia lead to a very attractive route for the preparation of complexes containing the $RC(NH_2)$═NH ligands. This exciting chemistry is little developed, although additions of *substituted* amines to RCN ligands (see section V.A.2) are fairly well-documented. Thus, it was found[196−199] that the complexes $[PtCl_n(RCN)_2]$ (n = 2, 4) react with NH_3 to give products of both substitution of chloride ligands and addition to RCN, and the formation of amidines occurs faster in platinum(IV) complexes than in the appropriate platinum(II) compounds.

The alkyl and arylnitrile complexes of the series $[Co(NH_3)_5(NCR)]^{3+}$ were treated with liquid NH_3 at −76 °C, and after evaporation of ammonia, the corresponding amidine compounds $[Co(NH_3)_5\{NH{=}C(NH_2)R\}]^{3+}$ were isolated in quantitative yields. The cyanamide complex $[Co(NH_3)_5(N{\equiv}CNH_2)]^{3+}$ deprotonates in liquid ammonia to give the unreactive ion $[Co(NH_3)_5(N{\equiv}CNH)]^{2+}$, whereas $N{\equiv}CNMe_2$[6a,200] (at Co(III),[6a,200] Os(III),[6a] or Pt(II)[6a] centers) or $N{\equiv}CCH_2NH_2$,[201] which cannot be deprotonated in the same way, underwent the addition to give the amidine derivative.[200,201] Diffusion of ammonia into a solution of *mer*-$[RhCl_3(RCN)_3]$ (R = Me, CH_2Ph) in neat RCN at 20−25 °C for 1 day led to the addition of NH_3 across the C−N bond, giving the rhodium(III) complexes containing neutral amidine ligands *mer*-$[RhCl_3\{RC(=NH)(NH_2)\}_3]$.[202] Tungsten-mediated addition of ammonia or amines with concomitant unusual coupling with alkyne or CO ligands[203] will be considered in section XI, while a Co(II)/ketoxime-promoted conversion of RCN to amidines $RC(=NH)NH_2$ was treated in section IV.

2. Additions of Primary and Secondary Amines and of Aziridine

Aziridine, in contrast to oxirane, which is involved in the ring expansion (see section III), undergoes addition to the nitrile carbon in the platinum(II) complexes $[PtCl_2(RCN)_2]$ to afford the amidine compounds depicted in Scheme 16.[204]

Scheme 16



The newly formed ligands were liberated by reaction with 2 equiv of $Ph_2PCH{=}CHPPh_2$ at room temperature to give, along with the free amidine, 2-(phenyl)imidazoline. When the liberation is performed at 90 °C, 2-(phenyl)imidazoline is the only product from the reaction. The authors believe that only after displacement of the amidine from the coordination sphere and release of the electron pair of the amidine N does this atom start to attack intramolecularly the aziridine ring. The corresponding palladium complex $[PdCl_2(PhCN)_2]$ reacts differently with aziridine to give only the substitution product, i.e., $[PdCl_2(\overline{NHCH_2CH_2})_2]$.[204]

A study, indicating a different reactivity, i.e., addition vs substitution, was performed for tungsten and molybdenum complexes. Thus, organonitriles in the tungsten complexes $[Cp_2WX(NCR)]^+$ (X = Br, SPh; R = Me, Et, Ph) couple with secondary amines NHR'_2 to give the W-bound amidines $[Cp_2WX\{NH{=}C(R)NR'_2\}]^+$. In contrast, the molybdenum complexes $[Cp_2MoX(NCR)]^+$ react with the amines to give substitution products rather than amidines.[205] A similar observation on different reactivity of structurally similar W and Mo complexes has recently been done by McGaff et al.[78] We assume that the difference in reactivity might be explained by the difference in kinetic lability of the ligated nitrile species, giving the preference to addition for more kinetically inert compounds. Indeed, in the platinum(II) complex *trans*-$[Pt(CF_3)(NCEt)(PPh_3)_2][BF_4]$, where the CF_3 group exhibiting a high *trans*-effect should labilize the nitrile, only substitution by aziridine was observed.[204]

Complexes *cis*-$[ReCl_4\{NH{=}C(Me)NHR\}_2]$ (R = Ph, *p*-C_6H_4Me) were prepared from *cis*-$[ReCl_4(MeCN)_2]$ and aniline or *p*-toluidine.[206] Recrystallization of the piperidine adduct $AlCl_3{\cdot}2\{HN(CH_2)_5\}$ from acetonitrile resulted in the release of crystals, which were subject to an X-ray crystallographic study that showed that piperidine coupled to MeCN to form the homoleptic compound $[Al\{HN{=}C(Me)N(CH_2)_5\}_4]Cl_3{\cdot}$MeCN.[207] Reaction of $[Mo(OBu^t)_2\{(2,2'\text{-}NC_6H_4)_2(CH_2CH_2)\}]$ with *p-tert*-butylcalix[6]areneH_6 (H_6L) in refluxing toluene followed by removal of the solvent in a vacuum and extraction of the residue formed with acetonitrile affords the amidine complex $[Mo\{2\text{-}NC_6H_4CH_2CH_2C_6H_4NHC(Me){=}NH\}LH_2]$ containing an 11-membered ring which originates from intramolecular addition of the pendant amino group to MeCN activated by coordination.[208] Suspending CuI in a solution of pyrrolidine, $HN(CH_2)_4$, in acetonitrile in oxygen-free conditions leads to the iminoacylation of the amine to yield $[Cu\{NH{=}C(Me)N(CH_2)_4\}_2]I$.[209] The cyclic anhydride ligand in the tungsten complex $[W(\eta^5\text{-}C_5H_5)(CO)\{\eta^3\text{-}\overline{CHCHC(Me)C(=O)O}C(=O)\}(MeCN)]$ does not react with Me_2NH, while the coordinated acetonitrile is active toward the addition giving the amidine compound $[W(\eta^5\text{-}C_5H_5)(CO)\{\eta^3\text{-}\overline{CHCHC(Me)C(=O)O}C(=O)\}\{NH{=}C(Me)NMe_2\}]$.[210] Primary and secondary amines R_2NH [R_2 = Me_2, Me(H), *i*-Pr(H), $(CH_2)_5$] were successfully, although under rather harsh conditions, added to the acetonitrile moiety in the complex $[Cp^*Ir(\eta^3\text{-}CH_2CHCHPh)(MeC{\equiv}N)](SO_3CF_3)$ to give the amidine

compounds [Cp*Ir(η^3-$CH_2CHCHPh$){NH=$C(NR_2)Me$}](SO_3CF_3).[88] The newly formed ligands were released after the addition of triphenylphosphine in dry solvents and identified by ^1H and ^{13}C NMR spectroscopy. It was also reported that tertiary amines, e.g., NMe_3 and NEt_3, do not undergo the coupling with the coordinated MeCN.[88] Reaction of excess $NH_2CH_2CH_2OH$ with $[PtCl_2(PhCN)_2]$ gives rise to the addition of the amine and substitution of the two chloride ligands to form the amidine complex $[Pt\{NH{=}C(Ph)NHCH_2CH_2OH\}_2(NH_2CH_2CH_2OH)_2]^{2+}$. The latter was isolated as the $[PtCl_4]^{2-}$ salt.[211]

The above reactions are noncatalytic, and the metal-catalyzed additions of amines to nitriles will be considered below in section V.B.

3. Additions of Diamines

Two early works on nucleophilic additions of a diamine to the coordinated nitrile have been analyzed in a previous review.[7] Reaction of *cis*- and *trans*-$[PtCl_2(PhCN)_2]$ with 3 equiv of 1,2-diaminoethane in water leads to $[Pt\{NH{=}C(Ph)NHCH_2CH_2NH_2\}_2]^{2+}$ precipitated as the PF_6^- and SbF_6^- salts.[212] The bis-hydrate $[Pt\{NH{=}C(Ph)NHCH_2CH_2NH_2\}_2]Cl_2{\cdot}2H_2O$ was also obtained upon treatment of the platinum(IV) complex $[PtCl_4(PhCN)_2]$ with 1,2-diaminoethane under the same reaction conditions. The X-ray diffraction analysis of $[Pt\{NH{=}C(Ph)NHCH_2CH_2NH_2\}_2][SbF_6]_2$ showed that the complex ion contains two unusual seven-membered organic metallacycles comprising the same platinum(II) center.

A different reaction was obtained for the copper(I)-mediated coupling of RCN (R = Me, Ph) and $NH_2CH_2CH_2NH_2$. It was reported[213] that the reaction occurs in the presence of a stoichiometric amount of CuCl. The process performed in MeOH results in disproportionation of Cu(I) to Cu(II) and Cu(0), and the authors[213] believe that the addition is copper(II) assisted. After completion of the reaction, an inorganic material was precipitated by addition of excess aqueous NaOH, and the organic products, i.e., 2-methyl and 2-phenyl-2-imidazolines R−C=NCH_2CH_2NH, were extracted with Et_2O. Unfortunately, the mechanism of that conversion was not studied,[213] and it is unclear which advantages give the copper system over purely organic methods[214,215] based on the Thio-Pinner reaction for generation of imidazolines. A process involving titanium compounds and giving cyclic amidines, e.g., 2-imidazoline, has been patented.[216]

4. Stereochemical and Mechanistic Studies on the Addition of Amines

The reaction of *trans*-$[PtCl_2(NCMe)_2]$ with a 5-fold excess of $MeNH_2$ in dichloromethane at −10 °C yields the bis-amidine complex *trans*-$[PtCl_2\{N(H){=}C(NHMe)Me\}_2]$, where the amidine ligands assume both the *Z*-configuration corresponding to the trans addition of the amine along the nitrile triple bond.[217a] An X-ray study revealed that the *Z*-configuration of N(H)=C(NHMe)Me species is determined by the formation of strong intramolecular hydrogen bonds between each chlorine atom and the amino proton of the NHMe moiety to give a six-membered ring. Treatment of *cis*-$[PtCl_2(NCMe)_2]$ with Me_2NH gives *cis*-$[PtCl_2\{N(H){=}C(NMe_2)Me\}_2]$ with the amidine ligands in the *E*-configuration.[217b]

The kinetics and mechanism of nucleophilic attack of amines to coordinated nitriles have been studied only in a few cases. In particular, the formation of the amidino complexes *cis*-$[Pt\{o\text{-}CH_2C_6H_4C(=NH)(NHAr)\}(PPh_3)_2][BF_4]$ by reaction of the dinuclear *o*-cyanobenzyl complex $[Pt(\mu\text{-}o\text{-}CH_2C_6H_4CN)(PPh_3)_2]_2[BF_4]_2$ with primary anilines $ArNH_2$ (Ar = Ph, *p*-MeC_6H_4, *p*-$MeOC_6H_4$) in 1,2-dichloroethane occurs as a two-stage process.[218] The first stage is fast and involves displacement of the nitrile group by the amine leading to a labile mononuclear amino complex with a dangling −CN group. In the second and slower stage this intermediate reacts with the amine via external nucleophilic attack of the amine nitrogen on the nitrile carbon in a cyclic four-center transition state **I**$^{\neq}$ (Figure 6) to yield the final Pt(II)−amidino

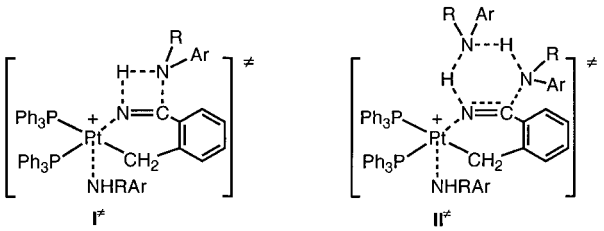


Figure 6.

species.

Related reactions of $[Pt(\mu\text{-}o\text{-}CH_2C_6H_4CN)(PPh_3)_2]_2[BF_4]_2$ with secondary anilines[219] Ar(R)NH (Ar = *p*-MeC_6H_4, *p*-$MeOC_6H_4$; R = Me, Et) comprise the same first stage, but the second step is different following a two-term rate expression of the form k[complex][Ar(R)NH] + k'[complex][Ar(R)NH]^2. The first-order dependence of the rate law on the aniline concentration corresponds to a process identical to that mentioned above, but the second-order term in aniline concentration is interpreted by considering a rapid preequilibrium formation of an aniline dimer which adds to the nitrile via a six-membered cyclic activated complex **II**$^{\neq}$ (Figure 6). This mechanism also appears to occur for the reactions of primary amines RNH_2 (R = *n*-Pr, *n*-Bu) with the dinitrile complexes $[PtCl_2(NCAr)_2]$ (Ar = Ph, *o*-, *m*-, *p*-MeC_6H_4).[7]

The reaction proceeds via two stages, and the kinetics (investigated for *n*-butylamine as the nucleophile) of the first one, which leads to *trans*-$[PtCl(NH_2R)\{HN{=}C(Ar)(NHR)\}_2]^+$, follows a second-order dependence on the amine concentration which has been rationalized on the basis of the addition of an amine dimer to the ligated nitrile. The second stage involves addition of amine to the second nitrile ligand, replacement of Cl^- by amine, and isomerization.

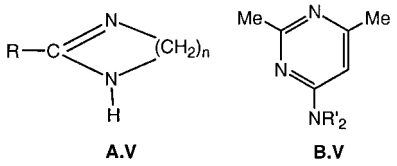
The kinetics is dependent on both electronic and steric effects,[7] following the order PhC≡N > *p*-$MeC_6H_4C{\equiv}N$ > *m*-$MeC_6H_4C{\equiv}N$ > *o*-$MeC_6H_4C{\equiv}N$. The inductive electron-donor character of the methyl group deactivates the nitrile carbon toward nucleo-

philic addition, which is further hampered by steric hindrance of that group.

B. Amidation and Hydrolytic Amidation in Metal-Mediated Organic Synthesis

It was established that unactivated organonitriles RCN, i.e., with electron-donor groups, can be activated toward the coupling with amines by application of Lewis acids such as $FeCl_3$, $AlCl_3$, $ZnCl_2$, or $MeAl(Cl)NR'R''$.[220−223] In the latter case the aluminum amidine complexes formed were decomposed in SiO_2 and extracted with MeOH to yield, after evaporation, purely organic material.[220] Similarly, reaction of (*N*-alkyl-*N*-alkoxyamine)methylaluminum chlorides, $MeAlCl_2\{NHR'(OR)\}$, with alkyl or aryl nitriles R″CN under reflux conditions followed by passage of the reaction mixture through silica gel afforded *N*-alkoxy amidine hydrochlorides, R″C(=NH)-NR′-(OR)·HCl, with moderate to excellent yields depending on the substituent R′.[224]

Other metal-based systems, e.g., $Ln(SO_3CF_3)_3$ (Ln = lanthanide)[225] or CuCl,[213] are also proved to be useful in organic synthesis for generation of amidines from nitriles and primary or secondary amines. In fact, lanthanide(III) triflates catalyze the reaction of nitriles (N≡CR) with primary amines ($R'NH_2$) and diamines [$H_2N(CH_2)_nNH_2$, $n = 2-4$] to form *N*,*N*′-disubstituted amidines RC(=NR′)NHR′ (R = Me, Et, Ph; R′ = alkyl, Ph) and cyclic amines **A.V** (Figure 7),



A.V B.V

Figure 7.

respectively, with loss of NH_3.[225]

The reaction proceeds via the intermediate formation of the corresponding *N*-substituted amidine, RC-(=NH)NHR′ or $RC(=NH)NH(CH_2)_nNH_2$. Further condensations yield heterocyclic compounds as byproducts, in particular triazines when using excess nitrile.[225] Triazines were better obtained from the direct reaction, also catalyzed by a Ln^{3+} ion, between ammonia and the nitrile or between the latter and an *N*-substituted amidine.[225]

Secondary alicyclic amines, R'_2NH, react with acetonitrile to yield pyrimidines **B.V** (Figure 7) and 2,4,6-trimethyltriazine via the corresponding amidines $MeC(=NH)NR'_2$.[225] Monosubstituted and *N*,*N*-disubstituted amidines, RC(=NH)NR′R″ (R = Me, Ph; R′, R″ = H, alkyl), are formed by copper(I)-induced addition of primary or secondary amines, respectively, to acetonitrile or benzonitrile.[213] The obtained yields are not catalytic in relation to the metal salt, CuCl or CuBr.[213] Rather recently a facile synthesis of amidines involving the intermolecular reductive coupling of nitriles with organic nitro or aza compounds induced by SmI_2,[226−228] $TiCl_4$/Sm,[229] or $TiCl_4$/Zn[230] has been reported.

It has been shown[231] that the phthalonitrile cobalt complex reacts with liquid ammonia to form the stable diiminoisoindolino complex $[(NH_3)_5Co\{-\overline{N-C(=NH)-C_6H_4-C(=NH)}\}]^{2+}$ where the newly formed ligand bonds via the deprotonated endocyclic nitrogen. Pentaammine(2,5-diiminopyrrolidino)cobalt(III), $[(NH_3)_5Co\{-\overline{N-C(=NH)(CH_2)_2C(=NH)}\}]^{2+}$, was prepared analogously starting from the succinonitrile precursor.[231]

An interesting study has been undertaken by Cobley et al.,[40] who discovered that the platinum(II) complex $[Pt(H)(POMe_2)\{P(OH)Me_2\}_2]$ in dimethoxyethane homogeneously catalyzes (0.1 mol %, autoclave, 160 °C) the *hydrolytic* amidation of unactivated nitriles with primary and secondary amines to give carboxamides RC(=O)NR′R″ along with $RC(=O)NH_2$ as the only byproduct. The mechanism of the amidation is yet unclear, but presumably it consists of either amidation of nitriles followed by hydrolysis of the amidine RC(=NH)NR′R″ formed or, vice versa, hydrolysis of the nitrile to give $RC(=O)NH_2$ followed by its amidation to produce RC(=O)NR′R″ and NH_3. A similar hydrolytic amidation of organonitriles by use of $[RuH_2(PPh_3)_4]$ as the catalyst was previously described by Murahashi et al.[4,5]

C. Addition of Hydrazines

In organic chemistry one of the most important methods for generation of amidrazones,[232] $RC(NH_2)=NNHR'$ or $RC(=NH)NR'NH_2$, is the reaction between organonitriles and hydrazine or substituted hydrazines. The addition is efficient in the case of electron-deficient nitriles, e.g., R = CF_3 or CN. When a compound with an R donor group should be obtained, activation can be achieved by two ways, i.e., application of $AlCl_3$ as a Lewis acid which binds nitriles making them more electrophilically activated and the use of hydrazides, $NHNHR'^-$, insofar as these anions are more reactive than the parent hydrazines.[232]

Reactions of coordinated organonitriles are still a little explored area, and only a few works in this direction are known. The amidrazone complexes $[M\{\eta^2-NH=C(R)N(R')NH_2\}\{P(OEt)_3\}_4][BPh_4]_2$ (M = Ru,[233] Os;[234] R = Me, *p*-tol; R′ = H, Me) were prepared and isolated in ca. 50% yield upon treatment of the appropriate nitrile precursors $[M(N\equiv CR)_2\{P(OEt)_3\}_4]^{2+}$ with an excess amount of either hydrazine or methylhydrazine in 1,2-dichloroethane followed by reflux for 3 h. The authors argued that a plausible mechanism of the coupling involves initial substitution of one organonitrile ligand giving one-end-bonded hydrazine followed by intramolecular nucleophilic attack at the nitrile carbon by the free end of the hydrazine, and the addition eventually furnishes the chelated five-membered amidrazone ligand. A relevant formation of amidrazone iron(II) compounds has been described by the same group.[235]

Formation of tungsten-ligated amidrazones was observed by Wu and co-workers,[236] who studied conversions within the system $WS_4^{2-}/P_2S_5/NH_2NH_2\cdot 2HCl$ in acetonitrile and propionitrile. Products of the reaction were subject to X-ray structural determination, and it was proved that the new compounds, i.e., $[W(=O)(S_2)_2\{RC(=NH)NHNH\}]$ (R = Me, Et), contain the amidrazone chelate ring.

It is worthwhile to mention that ligation to a metal center results in stabilization of the other amidrazone tautomer,[233−236] i.e., $RC(=NH)NHNH_2$, rather than that existing in the free state,[232] i.e., $RC(NH_2)=NNH_2$. This observation, in turn, suggests that the reactivities of the coordinated and free species could be different, a point that deserves further investigation.

D. Addition of Hydroxylamines

Although hydroxylamine is an ambidentate nucleophile and its *N*- and *O*-additions to the nitrile group are known,[237−240] in the vast majority of cases NH_2OH adds to RC≡N by its nitrogen and this reaction leads to the generation of amide oximes, $RC(NH_2)=NOH$, through the intermediate formation of RC(=NH)NHOH. Strong acceptors R in RC≡N make the nitrile carbon increasingly susceptible to nucleophilic attack by the more electronegative oxygen—rather than by the nitrogen atom—and conventional *N*-additions are accompanied by less usual *O*-additions giving, in the latter case, carboxamides $RC(=O)NH_2$ along with NH_3 and N_2.[240]

To the best of our knowledge, there is not even a single example of addition of hydroxylamine itself to organonitriles in metal-assisted reactions, but examples of metal-mediated additions of *alkylated* hydroxylamines to organonitriles are known, although scarce, and they were not analyzed in previous reviews on nitrile ligand reactivity. Weighardt and co-workers[241] reported on the reaction between $[MoO_2(MeNHO)_2]$ and acetonitrile in the presence of MeNHOH·HCl, which furnishes the complexes with ligated *N*,*O*-NH=(Me)C−N(O−)Me (M = Mo, R = Me in Figure 8). It is highly probable that the tendency

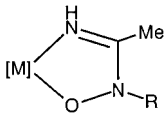


Figure 8.

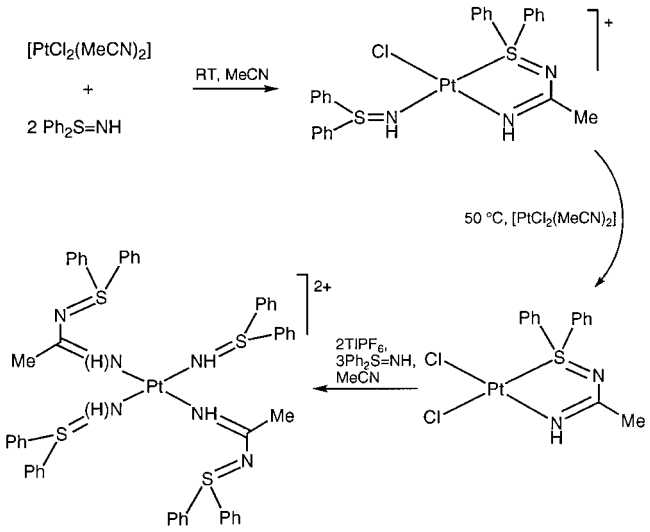
for the *N*-additions of even alkylated hydroxylamines is so strong that when WO_2Cl_2 was treated with Et_2NOH in MeCN the reaction yielded $[WO_2\{N,O\text{-}NH=(Me)C-N(Et)O\}_2]$ (M = W, R = Et in Figure 8) due to dealkylation/*N*-addition reactions.[242]

In contrast to the above-mentioned addition of Et_2NOH to acetonitrile in the tungsten-mediated system,[242] the reaction of the platinum(IV) complex $[PtCl_4(MeCN)_2]$ with R_2NOH in MeCN proceeds in an unusual direction giving the *O*-iminoacylated dialkylhydroxylamine complex *trans*-$[PtCl_4\{NH=C(Me)ONR_2\}_2]$ in good (R = CH_2Ph) to almost quantitative (R = Me or Et) yield.[240] Although attempts to carry out similar reactions with NH_2OH failed, the iminoacylated hydroxylamino species, $NH=C(R)ONH_2$, can be obtained indirectly by selective metal-mediated hydrolysis of iminoacylated oximes, e.g., in rhodium(III) complexes $[RhCl_2\{NH=C(Me)ON=CR_2\}_2]^+$ (R_2 = Me_2, $(CH_2)_4$).[186]

E. Addition of Sulfimides and Imines

Kelly and Slawin[243a] observed the addition of sulfimide $Ph_2S=NH$ to the acetonitrile ligand in the platinum(II) complex $[PtCl_2(MeCN)_2]$ to give $[PtCl(Ph_2S=NH)\{Ph_2S=N-C(Me)=NH\}]Cl$ (Scheme 17).

Scheme 17

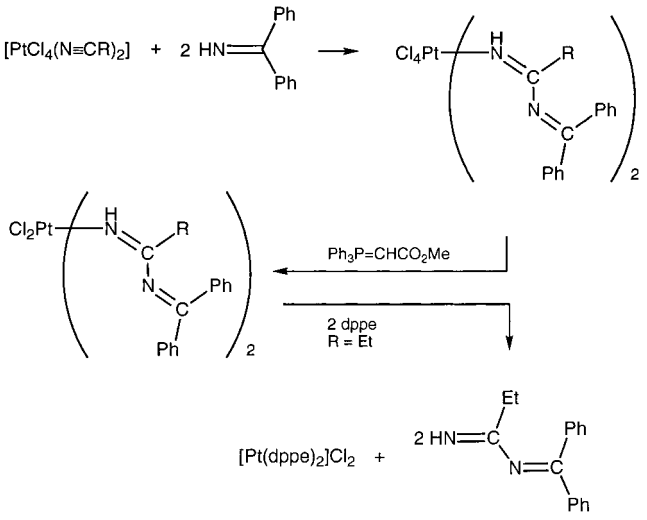


In the course of the reaction the sulfimide is added to MeCN via the N atom to form the C−N bond and the S atom of the newly formed ligand is coordinated to the platinum(II) center to give the chelate. Since it was proved that free acetonitrile does not react with sulfimide, the authors concluded that the reaction is platinum(II) assisted. Moreover, it appears that the choice of metal is significant for the performance of the addition. Thus, it was reported that the coupling does not proceed with some Pd and Co acetonitrile complexes, and only ligation of $Ph_2S=NH$ to these metal centers was observed. Though complexes of $Ph_2S=NH$ are also the primary products of reactions with Cu species, $[Cu(Ph_2S=NH)_3\{Ph_2S=N-C(Me)=NH\}][BF_4]_2$ has been shown to form as a minor product of the reaction with copper tetrafluoroborate in MeCN.[243b]

The reaction of $[PtCl(Ph_2S=NH)\{Ph_2S=N-C(Me)=NH\}]Cl$ with $[PtCl_2(MeCN)_2]$ allowed the isolation of the complex $[PtCl_2\{Ph_2S=N-C(Me)=NH\}]$. Halide abstraction with 2 equiv of $TlPF_6$ in MeCN in the presence of the sulfimide leads to $[Pt(Ph_2S=NH)_2\{Ph_2S=N\text{-}C(Me)=NH\}_2]^{2+}$, where the *N*-coordinated ligand $Ph_2S=N-C(Me)=NH$ is monodentate.[244]

The metal-mediated coupling between benzophenone imine, $Ph_2C=NH$, and coordinated organonitriles in the platinum(IV) complexes $[PtCl_4(RCN)_2]$ (R = Me, Et) proceeds rapidly under mild conditions to afford the 1,3-diaza-1,3-diene compounds $[PtCl_4\{NH=C(R)N=CPh_2\}_2]$ (Scheme 18).[245a] The addition of the imine occurs also in the platinum(II) nitrile compounds, but its selectivity is lower and $[PtCl_2\{NH=C(R)N=CPh_2\}_2]$ were more easily prepared by reduction of the corresponding (1,3-diaza-1,3-diene)-Pt(IV) complexes. Liberation of 1,3-diaza-1,3-dienes was exemplified by the reaction of $[PtCl_2\{NH=C(Et)N=CPh_2\}_2]$—which can be synthesized by reduction of the appropriate platinum(IV) complex with mild and selective reducing agents, i.e., the phosphorus ylide $Ph_3P=CHCO_2Me$[245b]—with 2 equiv of 1,2-bis(diphenylphosphino)ethane in $CHCl_3$ to give, along

Scheme 18



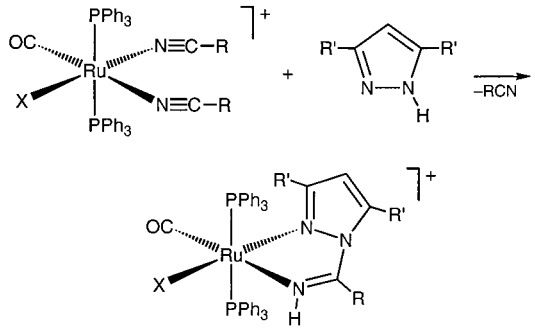
with free NH=C(Et)N=CPh$_2$ retained in solution, the solid complex [Pt(dppe)$_2$]Cl$_2$, Scheme 18.

In organic chemistry 1,3-diaza-1,3-dienes are useful for syntheses of six-membered nitrogen-containing heterocycles, and their involvement in [4 + 2] cycloadditions to give these systems has been a subject of rapt attention in the past years. The known synthetic pathways to achieve 1,3-diaza-1,3-dienes do not include direct interaction between organonitriles and imines, and therefore, the nitrile−imine coupling reaction constitutes a potential *alternative* pathway to the synthesis of such compounds.[245]

F. Metal-Mediated Iminoacylation of Heterocycles

This reaction relates to the above-mentioned addition of amines to coordinated nitriles. However, it is noteworthy to mention the significant difference between the heterocycles and the amines due to the possibility, in the former, of the involvement of their electron pair in aromatization. Despite this, the coupling can also proceed readily for some heterocycles, e.g., for pyrazoles. Thus, the addition of pyrazole and its derivatives to ruthenium-bound organonitriles was observed upon their reaction with the ruthenium hydrides and alkenyls [RuX(CO)(RCN)$_2$(PPh$_3$)$_2$]$^+$ (X = H, CH=CHR″; R = Me, CH$_2$Ph) (Scheme 19).[246] Interestingly, a selective addition

Scheme 19



of the pyrazoles was performed in methanol or ethanol, which are also good reagents for the addition (see section III) under reflux conditions.

In accord with the authors, the reaction is most likely initiated by substitution of one of the nitrile ligands by the pyrazole, followed by intramolecular nucleophilic attack of the pyrazole N atom on the adjacent nitrile.

Carmona and colleagues[274] reported that the coupling can be performed starting from a pyrazole complex but anticipated that the reaction proceeds via formation of a nitrile intermediate. Thus, abstraction of a pyrazolate ligand, as Ag(pz), from the iridium complex [(η^5-Cp*)Ir(pz)$_2$(pzH)] by AgBF$_4$ in RCN gave the solvento complex [(η^5-Cp*)Ir(pz)(pzH)(RCN)] which then, with excess Ag$^+$, is converted to the tetranuclear complex [(η^5-Cp*)Ir(μ-pz){μ-N=C(R)pz}Ag]$_2$(BF$_4$)$_2$ containing the iminoacylated pyrazole. The addition of pyrazoles to ligated pseudohalides, e.g., NCO$^-$ or NCNCN$^-$, has been reviewed.[22]

Amino-alkylated adenines R$_2$AdH (R = Me, Et) react with *cis*-[ReCl$_4$(MeCN)$_2$] to give the products of the addition of the adenines to the CN triple bond of the nitrile,[248] **C.V**, Figure 9.

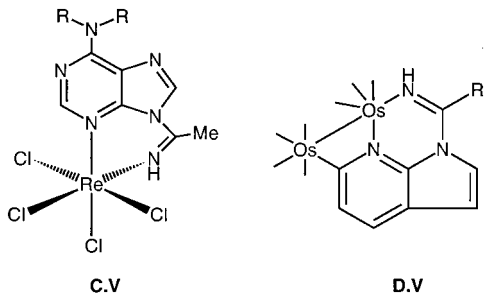


Figure 9.

The complex with R = Me was characterized by X-ray single-crystal diffractometry.[248]

Treatment of organonitrile-containing osmium clusters with 7-azaindole led to the addition of the heterocycle to RCN to generate [Os$_6$(CO)$_{14}$(μ-CO)(μ-H)(μ-η^1:η^2-C$_9$H$_8$N$_3$)] (R = Me, Et).[249] A fragment of the molecule (**D.V**) is depicted in Figure 9. Interestingly, the imino hydrogen can be deprotonated, e.g., by the strong base 1,8-diazabicyclo[5.4.0]undec-7-ene, to give the anionic cluster [Os$_6$(CO)$_{14}$(μ-CO)(μ-H)(μ-η^1:η^2-C$_9$H$_7$N$_3$)]$^-$ which converts back to the starting material upon addition of CF$_3$CO$_2$H.

G. Other Examples of the C–N Bond Formation

The titanium(IV) imido complex (H$_3$NBu^t)$_2$[TiCl$_3$(NBu^t)]$_2$ reacts with acetonitrile to give the ketimido (or amidinate) compound [TiCl$_3${N=C(Me)NHBu^t}(MeCN)$_2$], whose X-ray structure was successfully determined.[250] The authors argued that the latter is formed upon solvolysis of the starting material in MeCN to give the acetonitrile solvento complex. Further coupling of the adjacent metal-bound imido and MeCN species, activated by ligation of the latter, results in the formation of the new ketimido ligand.[250] This reaction is remarkable from at least one more viewpoint, i.e., the coupling between (H$_3$NBu^t)$_2$[TiCl$_3$(NBu^t)]$_2$ and MeCN can be, at least formally, considered as insertion of acetonitrile into the Ti−N bond. However, the observed solvolytic path suggests that the reaction proceeds via electrophilically activated,

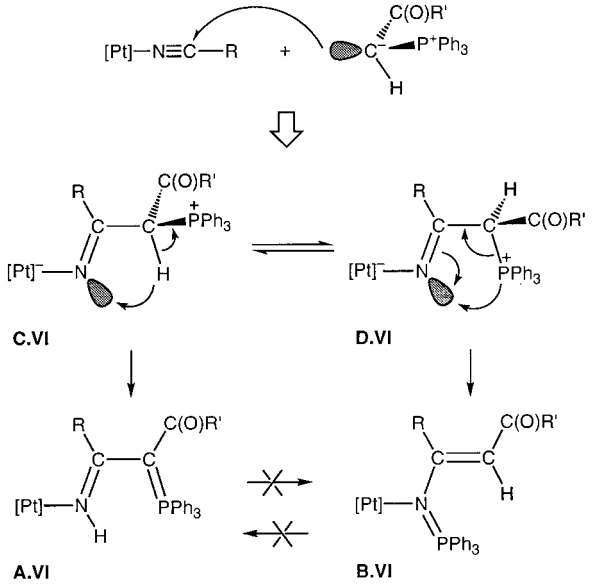
by coordination, organonitrile. Perhaps some other insertions[251,252] of RCN into M−N bonds might follow the same solvolytic route.[253] However, their mechanisms have not yet been investigated.

VI. Formation of the C–C Bond

A. Addition of Phosphorus Ylides

Vicente and colleagues[254−256] studied the iminoacylation of carbonyl-stabilized phosphorus ylides $Ph_3P{=}CHC(=O)R'$ (R′ = alkyl, alkoxyl) with the platinum(II) organonitrile complexes *trans*-$[PtCl_2(RCN)_2]$ (R = Me, Ph, C_6F_5) that give, depending on the character of R and R′, ylideimino (**A.VI**, Scheme 20), iminophosphorano (**B.VI**, Scheme 20) complexes,

Scheme 20



or compounds which contain both ylideimino and iminophosphorano species. A plausible mechanism for this intriguing transformation involves a nucleophilic attack on the nitrile carbon by the ylide C atom to give intermediate(s) **C.VI** and/or **D.VI** that differ in conformations and, at least formally, arise from the rotation around the =C−C single bond. Subsequent rearrangement to give **A.VI** and **B.VI**, which do not interconvert to each other, terminates the process.

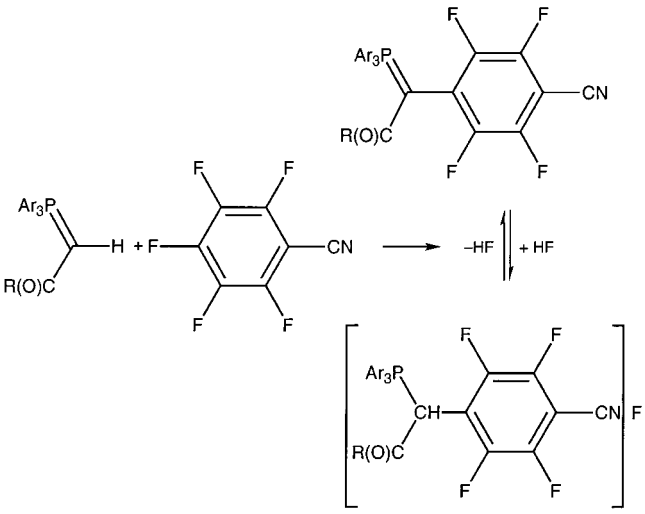
The coordination of the nitrile to platinum plays a key role in the result because the same or similar ylides $Ar_3P{=}CHC(=O)R$ (Ar = Ph, R = CO_2Me, CO_2Et, $CONMe_2$; Ar = C_6H_4Me-4, R = py-2) react with one of the above-mentioned nitriles, C_6F_5CN, giving an equilibrium mixture of ylides $Ph_3P{=}C(C_6F_4CN\text{-}4)C(O)R$ and phosphonium salts $[Ph_3P{=}CH(C_6F_4CN\text{-}4)C(=O)R]^+$ through a room-temperature C−F bond cleavage (Scheme 21).[257,258]

Lewis acid, e.g., Li^+, catalyzed reactions between aromatic nitriles and the phosphonium ylides are known from organic chemistry.[259,260]

B. Coupling of Nitriles and Compounds with Activated CH_2 Group

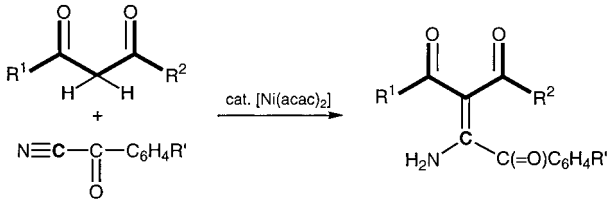
The reactions of β-dicarbonyls, β-ketoamides, β-ketophosphonates, or phosphonoacetates, exhibiting

Scheme 21



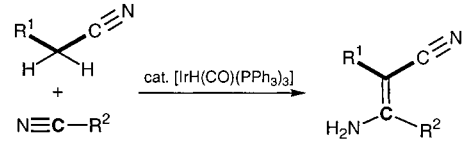
strong C−H acidity, with nitriles which are based on the use of metal(II) centers as homogeneous catalysts have already been reviewed,[23] in 1993, and later updated by additional experimental works[261−266] from the same authors, and therefore, this topic will not be treated herein. The metal-mediated reaction between β-dicarbonyls and nitriles have also been extended to acyl cyanides, and it was observed that $[Ni(acac)_2]$[267] (4 mol %) or $[Cu(acac)_2]$[268,269] (5 mol %) catalyze the addition of β-diketones to RCOCN to give, e.g., the enamino diketones[267] depicted in Scheme 22.

Scheme 22



A relevant work has been performed by Murahashi et al.,[270] who found that in the presence of $[IrH(CO)(PPh_3)_3]$ (3 mol %), activated nitriles undergo dimerization to give the corresponding cyano enamines, e.g., *Z*-$EtO_2CC(C{\equiv}N){=}C(NH_2)CH_2CO_2Et$ was obtained from $N{\equiv}CCH_2CO_2Et$. Other low-valent iridium complexes such as $[Ir(CO)_2(acac)(PR_3)]$ and $[Ir_4(CO)_{12}(PR_3)]$ and rhodium hydride complexes such as $[RhH(PPh_3)_4]$ were also effective. The reaction can be carried out with two different activated nitriles, and it is generally presented in Scheme 23.

Scheme 23

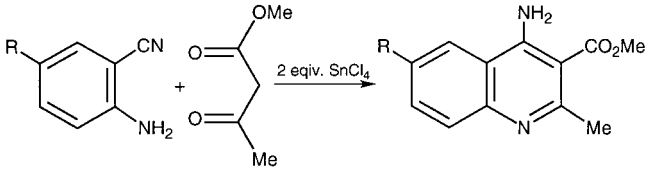


A ruthenium-catalyzed aldol condensation of nitriles with an activated CH_2 group and carbonyl compounds was also reported by the same team.[271]

Although the starting materials and the products given in Schemes 22 and 23 are similar in many respects, the reactions are catalyzed by metal centers of different nature, i.e., "electron-poor" and "electron-rich". Consequently, the two groups propose different mechanisms. The authors[267] suggest that the reaction catalyzed by [Ni(acac)$_2$] proceeds via activation, by coordination, of the acyl nitriles and this reverses a typical pattern of the chemical reactivity of RC(=O)-CN species and β-dicarbonyls, providing the attack at the cyano group instead of at the carbonyl group which would give, in the latter case, α-acylated β-dicarbonyls. The Japanese group believes that the reactions catalyzed by the Ir complex also start with the initial coordination of the nitrile to the metal center but, on the next step, oxidative addition occurs giving an H−Ir−C(R^1)(H)C≡N species which couples with one more equivalent of the nitrile (directly or via *C*-to-*N* linkage isomerization[272]) and then the newly formed ligand liberates via reductive elimination.

Tin(IV)-assisted reactions between nitriles and β-dicarbonyls, having an implication for the synthesis of pyridines and quinolines,[273] are exemplified in Scheme 24.

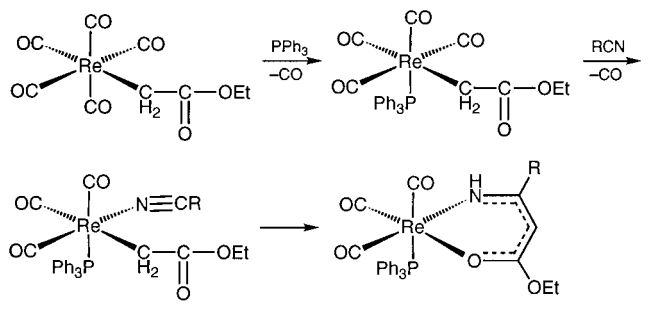
Scheme 24



Although the precise role of the metal ion has not yet been clearly understood, the authors anticipate that it might be dually expressed, on one hand, in electrophilic activation of the nitriles toward the nucleophilic attack and, on the other hand, in enhanced acidity of the CH_2 group upon ligation of the β-dicarbonyl to the metal center.

Bergman and colleagues[274] observed the coupling between the $CH_2C(=O)OEt$ ligand in the rhenium complex [Re{$CH_2C(=O)OEt$}(CO)$_5$] and organonitriles (this reaction can also be formally viewed as nitrile insertion into a transition-metal−carbon single bond) in the presence of PPh_3 giving a new C−C bond. Upon the basis of synthetic experiments supported by a kinetic study, the authors[274] suggested a mechanism for this reaction that involves the intermediate formation of a nitrile solvento complex (Scheme 25), consequent polarization of the C≡N bond, and coupling with the $CH_2C(=O)OEt$ ligand

Scheme 25



that might occur either via direct migration of the latter from the metal to the nitrile ligand or through rearrangement to an *O*-bound species followed by intramolecular nucleophilic attack of the CH_2-carbon to the ligated nitrile.

Some other examples of the insertion of nitriles into the M−C bond, occurring at Sc(III), Ti(IV), Cr(III), Th(IV), and U(IV) centers, have been summarized.[274]

C. Dimerization and Trimerization of Nitriles

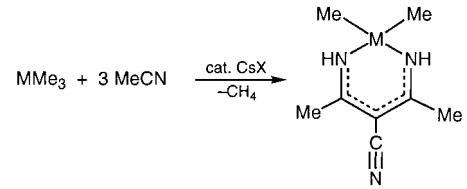
Both two-electron and four-electron reductive coupling (with C−C bond formation) of organonitriles, mediated by transition metals, to give diimino, $^{-}N{=}C(R){-}C(R){=}N^{-}$, or enediimido, $^{2-}N{-}C(R){=}C(R){-}N^{2-}$, ligands, respectively, have been reported. Hence, reaction of the W(II) complex [Tp′WBr(CO)$_3$] (Tp′ = hydrotris(3,5-dimethylpyrazolyl)borate) with NaS^{i}Pr in refluxing acetonitrile led to the formation of the dinuclear W(II) compound [{Tp′W(CO)$_2$}$_2${μ-NC(Me)C-(Me)N-*N*:*N*′}], which is proposed to involve an initial W(II) → W(I) reduction by the thiolate (one-electron reductant) followed by a two-electron reductive nitrile coupling to give the bridging diimino ligand, each metal behaving as a single-electron reducing agent.[275] The isolation from the reaction solution of an η^2-NCMe complex was considered as indirect support for the involvement of monomeric acetonitrile complexes in the process.[275]

A four-electron reductive coupling of acetonitrile has resulted from its reaction with [TiCl$_2$(TMEDA)] (TMEDA = *N*,*N*,*N*′,*N*′-tetramethylethylenediamine) to yield the dinuclear Ti(IV) complex [{TiCl$_4$-(TMEDA)}$_2${μ-NC(Me)=C(Me)N}] with an enediimido bridge.[276]

Deprotonation from one of the two molybdenum-bound acetonitriles in [Mo$_2$(η^5-Cp)(μ-SMe)$_3$(MeCN)$_2$]-[BF$_4$] with butyllithium in THF initiates its intramolecular coupling with the second ligated acetonitrile giving the novel μ-η^1-azavinylidene complex [Mo$_2$(η^5-Cp)(μ-SMe)$_3${μ-η^1-*N*=C(Me)CH$_2$C≡N}].[277]

Neumüller and colleagues reported[278,279] that MMe_3 (M = Al, Ga, In) reacts with acetonitrile to give the solvento complexes [MMe_3(MeCN)]. If MMe_3 is refluxed in MeCN for 70 h in the presence of a catalytic amount of CsX (X = F, Cl, Br), trimerization of acetonitrile to give the metallacycle [Me$_2$M{(NH=CMe)$_2$C(C≡N)}] (depicted in Scheme 26) is ob-

Scheme 26



served.[278] The newly formed ligand in this complex was liberated, in an NMR experiment, by acidification with HCl.

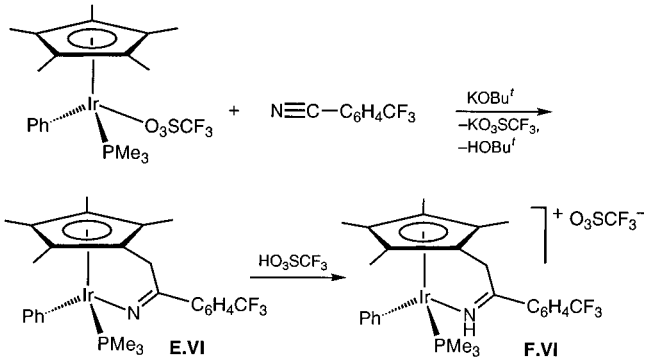
Although the mechanism of the reaction was not studied, the authors[278,279] believe that in the initial stage of the reaction MMe_3 forms anionic halide complexes, e.g., [Me$_3$MX]$^-$ or [(Me$_3$M)$_2$(μ-X)]$^-$, with weaker M−C bonds than that in the starting methyl

compounds. This makes the intermediates better methyl donors, and they can deprotonate the CH_3 group in acetonitrile. The latter, in turn, reacts with two more nitrile species activated by coordination to a metal center. The reaction is metal-mediated insofar as it is known that acid or base, i.e., metal-free, induced trimerizations of nitriles usually furnishes 1,3,5-triazines.[280]

D. Coupling of Nitriles with Other Carbon Groups

Bergman and colleagues[87] reported on the C−C bond formation occurring when the iridium(III) complex [Cp*IrPh(SO_3CF_3)(PMe_3)] is treated with an excess of *p*-trifluorotolunitrile in THF followed by addition of KOBu^t, Scheme 27.

Scheme 27



A postulated mechanism of this coupling involves formation of the solvento complex [Cp*IrPh(N≡$CC_6H_4CF_3$)(PMe_3)]$^+$. The base deprotonates the Cp* methyl group, and the resulting carbanion attacks the metal-bound nitrile to generate the final cyclometalated product **E.VI**, which can be easily protonated to achieve the cationic complex **F.VI**. A relevant coupling with the methyl group of Cp* has been observed recently when the early−late heterobimetallic complex $Cp_2Zr(\mu\text{-}N^tBu)IrCp^*$ was treated with various organonitriles.[281]

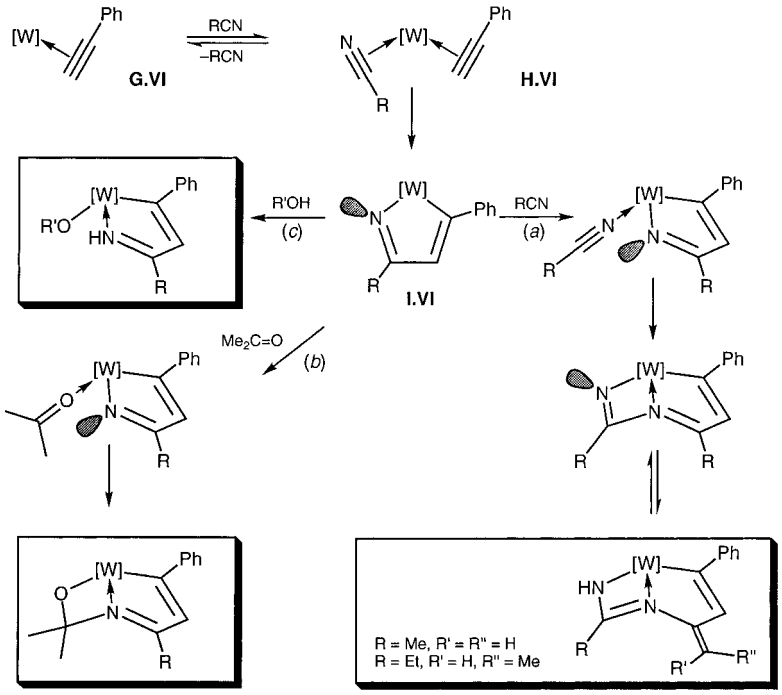
Legzdins and co-workers[282,283] observed an intriguing stepwise incorporation of small molecules, including organonitriles, into a tungsten vinyl fragment. It was reported that thermolysis of the vinyl complex [Cp*W(NO)(CH_2SiMe_3)(CPh=CH_2)] in nitriles or in the nitriles in the presence of either acetone or an alcohol gives metallacyclic products. Their formation is consistent with the intermediacy of the acetylene complex [Cp*W(NO)(η^2-CPh≡CH)] (**G.VI** in Scheme 28) formed in situ due to the reductive elimination of $SiMe_4$ from [Cp*W(NO)(CH_2SiMe_3)(CPh=CH_2)]. The former reacts further with RCN to give **H.VI**, whereupon the acetylene and the nitrile undergo reductive coupling on the metal template to furnish the metallacycle **I.VI**, which then traps one more molecule of the nitrile (route *a*), acetone (route *b*), or alcohol (route *c*) to give the boxed products with new C−C bonds.

Early works on additions of the α-phosphino carbanions $[Ph_2PCHR]^-$ (R = CO_2Et, CN) and also of cyanide ion to metal-activated organonitriles were considered in ref 7, and to the best of our knowledge, no further accounts on these reactions were published up to the year 2001.

VII. Formation of the C–P Bond

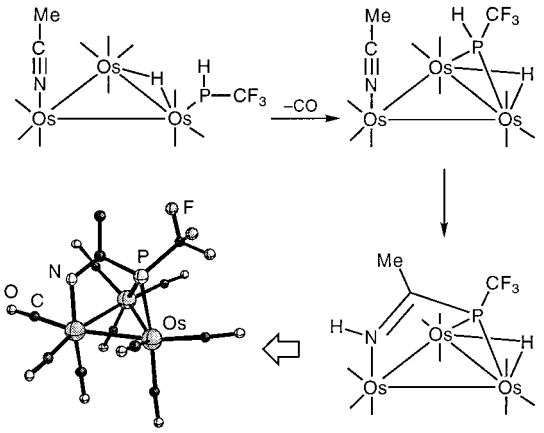
Additions to organonitriles giving, in metal-mediated processes, the C−P bond are very scarce, and only a few examples of such reactions are known from the literature. Thus, the reaction between the phosphine $(CF_3)_2(HO)CPH(CF_3)$ and the trisosmium bisacetonitrile cluster $[Os_3(CO)_{11}(MeCN)_2]$ performed in dichloromethane at room temperature afforded a crystalline product that was analyzed by X-ray single-crystal diffractometry (the hydride was not

Scheme 28



found but verified in ^{1}H NMR experiments), and it has been shown that it contains a novel type of ligand due to coupling between MeCN and μ-PH(CF_3) which is presumably formed as an intermediate (Scheme 29).[284]

Scheme 29



Interestingly, both primary, $(CF_3)_2(HO)CPH_2$, and tertiary, $P(CF_3)_3$, phosphines react with the $[Os_3(CO)_{11}(MeCN)_2]$ cluster to give only substitution products.

Cotton and colleagues[285] prepared a molybdenum dinuclear complex that contains a $[Mo_2]^{4+}$ core, i.e., $[Mo_2(MeCN)_8(ax\text{-}MeCN)_2][BF_4]_4$, and investigated its treatment with 1,2-bis(diphenylphosphino)ethane. The reaction proceeds in carefully dried MeCN at room temperature and brings about a facile nitrile–dppe coupling to produce the complex $[Mo_2(\mu,\eta^2\text{-}MeCN)\{\mu\text{-}N{=}C(Me)PPh_2CH_2CH_2PPh_2\}(MeCN)_7][BF_4]_4$ which contains the newly formed seven-membered chelating ligand **A.VII** (comprising a bridging azavinylidene-type ending moiety) indicated in Figure 10.

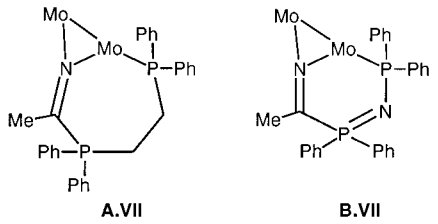


Figure 10.

This metallacycle differs from the six-membered chelated ring **B.VII** obtained in the course of the reaction between $[Mo_2(MeCN)_8][BF_4]_4$ and bis(diphenylphosphino)amine, $Ph_2PNHPPh_2$, where the addition to acetonitrile is concerted with deprotonation of the phosphine and the reaction proceeds in accord with eq 1[286]

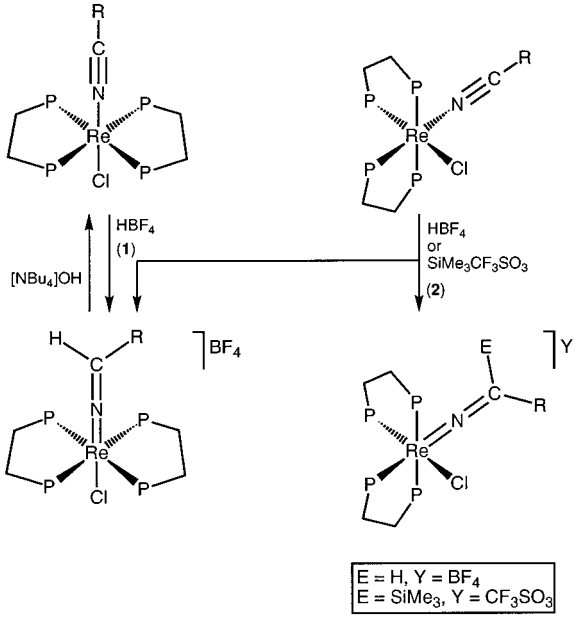
$$[Mo_2(MeCN)_8][BF_4]_4 + 2Ph_2PNHPPh_2 \rightarrow [Mo_2(\mu,\eta^2\text{-}MeCN)\{\mu\text{-}N{=}C(Me)P(Ph_2)NP(Ph_2)\}(Ph_2PNHPPh_2)(MeCN)_5][BF_4]_3 + HBF_4 + MeCN$$

VIII. Electrophilic Additions

The rich coordination chemistry of nitriles, as discussed in the previous sections, has been typically developed at metal centers in high or medium oxidation states which often can activate them toward nucleophilic additions at the unsaturated carbon atom. However, when ligating (η^1-mode) an electron-rich metal center, with the metal in a low oxidation state and with a strong π-electron releasing ability, a nitrile can be activated to electrophilic attack which also occurs at the unsaturated *C*-atom to afford a methyleneamide (also called alkylideneamide or azavinylidene) species (NCHR in the case of protic addition). Following the first reported example,[287] the latter type of reaction has been developed for series of nitrile complexes with the dinitrogen-binding d^6 metal centers of the types $\{ReCl(dppe)_2\}$ (dppe = $Ph_2PCH_2CH_2PPh_2$)[287–289] or $\{M(N_2)(dppe)_2\}$ (M = Mo or W)[290–292] and extends to nitriles the mode of reactivity known for isocyanides,[8,293–297] vinylidenes,[298,299] alkyne-derived allenes,[300,301] and even dinitrogen (for reviews see refs 302–306) which, when binding such sites (or related ones), also undergo β-protonation.

Hence, the aromatic nitriles at the complexes *trans*- or *cis*-$[ReCl(NCR)(dppe)_2]$ (R = Ph or a *para*-substituted derivative, e.g., $C_6H_4NEt_2$-4, C_6H_4OMe-4, C_6H_4-Me-4, C_6H_4F-4, C_6H_4Cl-4), which can be derived from N_2 displacement by the nitrile at *trans*-$[ReCl(N_2)(dppe)_2]$,[31,289,307,308] undergo stereoselective β-protonation (by HBF_4) or β-silylation (by $SiMe_3CF_3SO_3$) to afford (reactions 1 and 2, Scheme 30) the correspond-

Scheme 30



ing methyleneamide complexes *trans*- or *cis*-$[ReCl(NCER)(dppe)_2]Y$ (E = H, Y = BF_4; E = $SiMe_3$, Y = CF_3SO_3).[287–289] The trans isomers were formerly formulated[288,309] as hydride complexes, but recently the methyleneamide formulation was unambiguously established.[289] The protonation reaction is reversible, and the methyleneamide compounds revert to the nitrile complexes (trans isomers) on treatment with a base like $[NBu_4]OH$.[289]

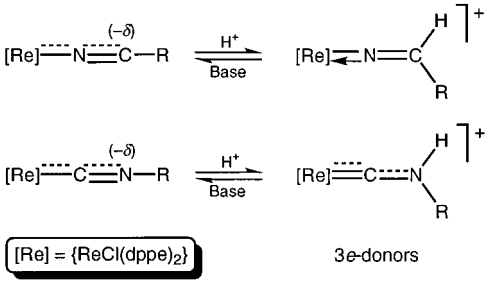
The mechanism of the protonation reaction of the *cis*-$[ReCl(NCR)(dppe)_2]$ complexes, as indicated by

stopped-flow kinetic studies,[288] involves, as the first step, a fast β-proton addition to the nitrile to form the *cis*-methyleneamide species which upon isomerization or further protonation/deprotonation steps with rearrangement can lead to the corresponding trans isomers.

The activation of η^1-coordinated nitrile ligands toward electrophilic attack is interpreted by considering the effective π-electron back-donation from the metal center, as accounted for by (i) the low IR ν(N≡C) vibrations of those ligands which appear at significantly lower wavenumbers than in the free state (coordination shift from −20 to −140 cm^{-1})[31,289,307] and (ii) the unusually short Re−N bond, 1.978(5) Å, exhibited[31] by the acetonitrile complex *trans*-[ReCl(NCMe)(dppe)$_2$].

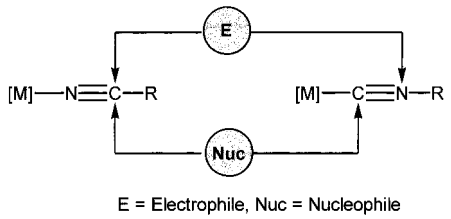
The linear coordination mode of the methyleneamide ligand has been established by the X-ray diffraction analysis of *trans*-[ReCl(NCHR)(dppe)$_2$][BF_4] (R = C_6H_4F-4), which also shows a short Re−N distance, 1.831(8) Å, consistent with a significant double-bond character.[289] The structural data indicate that the methyleneamide ligand behaves both as a three-electron donor (conferring the closed-shell electronic configuration to the complex) and an effective π-electron acceptor, thus resembling (Scheme 31) the aminocarbyne CNHR ligands derived[293−297]

Scheme 31



from protonation (which also occurs exclusively at the β-position) of isocyanides (CNR) when binding the same metal center. Therefore, nitriles can follow a general pattern of reactivity comparable with that displayed by isocyanides[9,293−297] (Scheme 32), being

Scheme 32

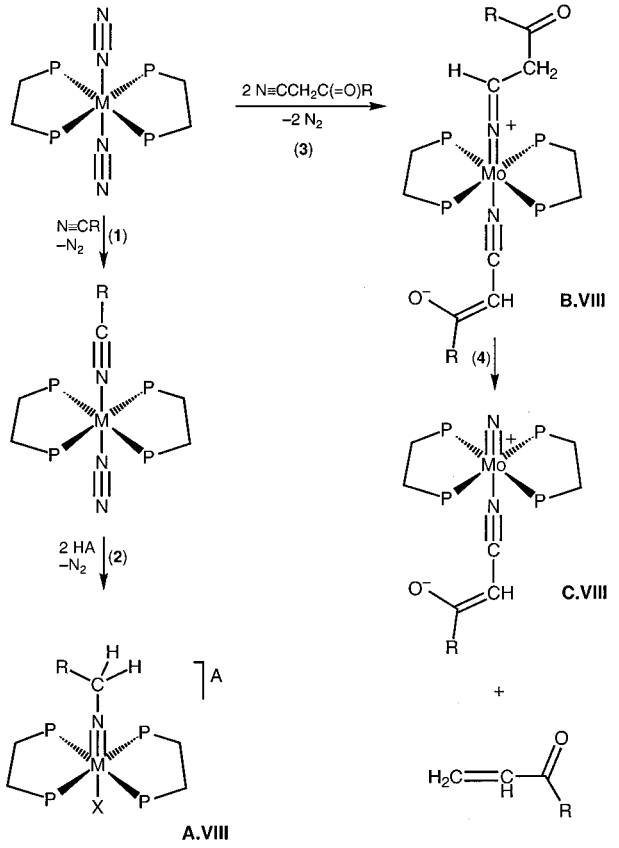


susceptible to activation toward either β-electrophilic attack when ligated to a suitable π-electron-releasing metal center or nucleophilic addition if, in contrast, the binding metal site is behaving as a strong Lewis acid without a considerable π-back-donation ability.

Another example of β-protonation of a nitrile at a rhenium center has been proposed[310] in the metal-mediated conversion of organonitriles into imido ligands in the complexes [Re(NCH$_2$R)X$_3$(dppbe)] [R = alkyl; X = Cl, Br; dppbe = 1,2-bis(disphenylphosphino)benzene]. The reaction has recently been extended to the {M(dppe)$_2$} (M = Mo or W) centers[290−292] at which the derived methyleneamide ligand can undergo further protonation to form imido or nitrido species, the latter upon complete N≡C bond rupture.

Hence, the mixed dinitrogen−organonitrile complexes *trans*-[M(N$_2$)(NCR)(dppe)$_2$] (M = Mo, W; R = Ph, C_6H_4Me-4, C_6H_4OMe-4, or Me), normally obtained by N_2 displacement from *trans*-[M(N$_2$)$_2$(dppe)$_2$], react with acid (HA = HCl, HBr or HBF_4) to afford the corresponding cationic imido complexes *trans*-[MX(NCH$_2$R)(dppe)$_2$]$^+$ (**A.VIII**; X = Cl,[290] Br,[290] or F[290,292]) (reactions 1 and 2, Scheme 33), as authen-

Scheme 33



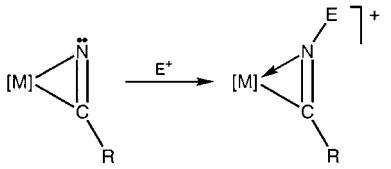
ticated by the X-ray analyses of *trans*-[WX(NCH$_2$Me)(dppe)$_2$]A [X = Cl, A = PF_6;[290] X = F, A = BF_4[292]].

Conversion of the imido into the nitrido ligand upon complete cleavage of the unsaturated NC bond occurs in the case of β-ketonitriles, in particular N≡C−CH$_2$COR (R = Ph, C_6H_4OMe-4, C_6H_4Me-4, C_6H_4-Cl-4, C_6H_4COOMe-4, 2-C_4H_3O, 2-C_4H_3S, Pr^i), with acidic CH hydrogens and which on reaction with *trans*-[Mo(N$_2$)$_2$(dppe)$_2$] form the corresponding (nitrido)(nitrile−enolate) species *trans*-[Mo(N)(NCCHCOR)(dppe)$_2$] **C.VIII** (reactions 3 and 4, Scheme 33) with concomitant elimination of a vinyl ketone, CH$_2$=CHCOR.[290,291] The reaction proceeds via the formation of the (alkylideneamido)(nitrile−enolato) complexes *trans*-[Mo(NCHCH$_2$COR)(NCCHCOR)(dppe)$_2$] **B.VIII**, which is believed[290,291] to involve substitution of a dinitrogen ligand, at the parent bis(dinitrogen complex), with a β-ketonitrile to yield the mixed dinitrogen−nitrile intermediate *trans*-[Mo(N$_2$)(NCCH$_2$COR)(dppe)$_2$] in which the β-ketonitrile ligand is

protonated by a second nitrile molecule with replacement of the second N_2 ligand by the enolate anion of the nitrile. A postulated[290,291] prototropic shift from the α- to the β-position (relative to the carbonyl group) in the ligated alkylideneamide in **B** with elimination of the vinyl ketone from the derived imido ligand gives the final nitrido complex **C** [reaction 4 (Scheme 33) whose rate constant correlates[291] with the Hammett σ_p or σ_a constants for the aroyl substituents, thus increasing with the acidity of the methylene moiety in the $-CH_2COR$ group]. The reaction also occurs for other β-ketonitriles such as $(N{\equiv}C)_2CHCOR$ (R = Me, Ph), and the nitrido product *trans*-[Mo(N){NCC(CN)COMe}(dppe)$_2$] was analyzed by X-rays.[291]

We have been discussing the electrophilic addition reactions to η^1-coordinated nitriles when activated by a sufficiently effective π-electron-releasing metal center. However, when coordinated in the uncommon edge-on (η^2) fashion, nitriles are expected to exhibit an enhanced nucleophilic character in view of the localization at the N atom of an electron lone pair that is not involved in bonding to the metal, and in fact, they can then undergo electrophilic attack at this atom, in particular to give an iminoacyl derivative (Scheme 34). Thus, alkylation has been recently

Scheme 34

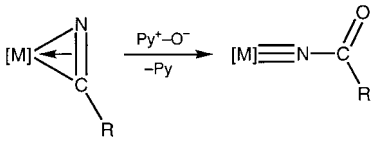


achieved[311] on reaction of [(η^5-$C_5H_4Bu^t$)$_2$Mo(η^2-N≡CMe)] with RI (R = Me, Et) to afford the corresponding iminoacyl complexes [(η^5-$C_5H_4Bu^t$)$_2$Mo(η^2-MeC=NR)]I (the molecular structure of the ethylated one has been determined by X-rays), and the reaction is suggested to occur via direct nucleophilic addition to the N atom.

Rare examples of double electrophilic attack at an η^2-bonded nitrile are known[7] for dicyclopentadienylmolybdenum species, when using a protic acid as the electrophile, to give imino, NH=CHR (R = Me), or possibly iminium, $C(R){=}NH_2$ (R = CF_3), derivatives.

Another case of electrophilic addition to a side-on-bonded nitrile is provided by the reaction of [Tp′WI(η^2-NCR)(CO)] (R = Me, Et, Ph), in which the nitrile behaves as a four-electron donor ligand, with an oxygen-transfer reagent, pyridine *N*-oxide, to give (Scheme 35) the alkylimido complexes [Tp′WI{NC-

Scheme 35



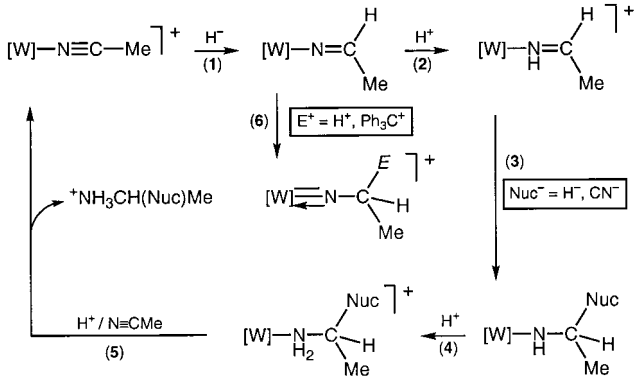
(O)R}(CO)][312,313] whose thiolate analogue [Tp′W(SPh){NC(O)R}(CO)] (R = Me), derived via methathesis with NaSPh, has been structurally characterized.[313] The direct attack of the *N*-oxide to the side-on-coordinated nitrile has not been ascertained, and the generality of this type of oxyfunctionalization of nitrile ligands has yet to be achieved.

The activation of nitriles to electrophilic additions, either by η^1-coordination to an electron-rich π-electron-releasing metal center or by η^2-coordination, as discussed above, opened new preparative routes for methyleneamide, imide, acetylimide, nitride, iminoacyl, imine, and, possibly, iminium ligands, species of synthetic significance. Moreover, the involvement of β-protonation can be postulated in the nitrogenase reduction of nitriles to ammonia and alkanes,[31] similar to what has been proposed for the enzymatic reduction of dinitrogen[302−304] and isocyanides.[8,293,314,315] Hence, a promising emergence of a novel coordination chemistry of nitriles, based on their activation toward electrophiles, can be expected.

IX. Stepwise Nucleophilic–Electrophilic Additions

Although the reduction of organonitriles to amines is a well-known reaction, intermediates in the metal-mediated processes have commonly been elusive to characterization. However, stepwise reduction of a coordinated nitrile to an amine has been achieved by sequential nucleophilic and electrophilic addition reactions in an elegant work reported by Templeton et al.[316] which allowed the isolation and characterization of a series of intermediates (Scheme 36).

Scheme 36



Hence, the nitrile ligand in [Tp′W(CO)(MeC≡CR)(NCMe)][BF_4] (R = Me, Ph) undergoes nucleophilic attack by $LiHBEt_3$ to give (step 1) the azavinylidene N=CHMe species which is subject to protonation, by HBF_4, at nitrogen to form (step 2) the imine NH=CHMe. Further nucleophilic addition [$Nuc^- = H^-$, CN^-] followed by protonation affords the amide NHC(Nuc)HMe (step 3) and the amine $NH_2CH(Nuc)HMe$ (step 4) ligands, the latter being liberated (in the form of the ammonium salt) on acidification in the presence of NCMe (step 5), with regeneration of the starting acetonitrile complex. The nucleophilic addition to the imine complex (step 3), with the chiral {Tp′W(CO)(MeC≡CPh)} moiety, is stereoselective.

The electronic flexibility of the alkyne ligand, which can behave either as a four- or a three-electron donor, is believed to play a key role in the process, and its replacement by a carbonyl results in a distinct reactivity. In fact, although in the related complexes [Tp′W$(CO)_3$(NCR)][BF_4] (R = Me, Ph) the nitrile also

undergoes β-nucleophilic addition (by $NaBH_4$, EtMgBr, or NaOMe) to yield the corresponding azavinylidene complexes [Tp′W(CO)$_2${N=C(Nuc)R}] (Nuc = H, Et, MeO), which alternatively can be formed (for $Nuc^- = H^-$) by photolytic NCR insertion in the W−H bond of [Tp′WH(CO)$_3$], the subsequent electrophilic attack (by HBF_4 or [Ph_3C][PF_6]) occurs again at the β-position (C-atom) to produce a nitrene (or imido) product (step 6),[317] in contrast with the above case in which an α-electrophilic addition (step 2) has occurred. For the non-acetylenic complexes [Tp′W(CO)$_2$(N=CHR)], the lone pair at nitrogen of the azavinylidene ligand is involved in a π-bond to the metal, thus not being available to an electrophilic reagent, and the imine carbon becomes the site of electrophilic addition.[317] A different type of organonitrile conversion into imido (acylimido) species, obtained by an oxygen atom transfer reaction, is described in section VIII.

Other sequential nucleophilic−electrophilic additions have been reported in the reactions of [W(PhC≡CPh)$_3$(NCMe)] or [W(η^4-C_4Ph_4)(PhC≡CPh)$_2$(NCMe)] with PhLi, MeLi, or $LiHBEt_3$ and subsequent hydrolysis to produce the corresponding imine NHC=C(R)Me (R = Me, Ph) or amine NH_2CH_2Me (R = H) complexes.[318] No intermediates were characterized, but experiments with deuterated reagents suggest that although the formation of the imine species could be accounted for by sequential β-nucleophilic and α-electrophilic additions, in the case of the $LiHBEt_3$ reaction the alternative formation of a postulated intermediate nitrene species, NCH_2Me, by double H^- addition to the nitrile carbon followed by *N*-protonation could be involved.[318]

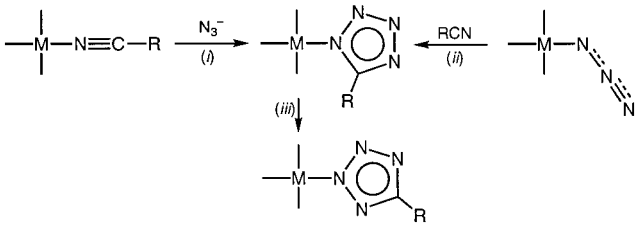
X. Cycloadditions

The triple bond in nitriles RCN exhibits only moderate dipolarophilicity[3,319] which, however, can be enhanced by introducing strong acceptor groups R to the nitrile carbon[320] or affecting the nitrile through the opposite end, i.e., via the N atom—by alkylation of RCN to give nitrilium salts, R−C≡N$^+$R′,[2,321] application of Lewis acid catalysts,[322,323] or coordination of the nitrile to a metal center. The latter route is the least explored, and it involves reaction of a ligated nitrile with dipoles often giving new species which persist in the coordination state but can be liberated by further reactions, e.g., substitution. The cycloadditions of metal-activated organonitriles with dipolar species will be considered in this section.

A. [2 + 3] Cycloaddition of Nitriles and Azides: Synthesis of Tetrazoles

The progress in the chemistry of tetrazoles[24−28] in the past decade is mostly associated with the widescale employment of these heterocycles in medicine, although other applications, e.g., for production of explosives, sweeteners, fuels, photographic processing chemicals, and agricultural agents, are known. One of the main synthetic routes to achieve tetrazole systems is the [2 + 3] cycloaddition between organonitriles and azide salts such as, for instance, NaN_3 and also silyl, aliphatic, or aromatic azides RN_3. Beck and colleagues in their fundamental works[7,324] and, later, other workers[7,325−346] have demonstrated that the involvement of metal ions in the addition of the azides to nitriles allows the reactivity to be greatly enhanced and the [2 + 3] cycloaddition to be performed under mild conditions. In particular, it was established that the cycloaddition can be carried out starting either from organonitrile (route *i* in Scheme 37) or azide (route *ii* in Scheme 37) metal complexes.

Scheme 37



Two groups[325,346] have studied the reaction between cobalt(III)-bound nitriles and azide ion in aqueous solutions and observed the fast cycloaddition giving a tetrazolato complex (*i* in Scheme 37) followed by slow linkage isomerization (*iii* in Scheme 37) when the N_1-bonded ligand changes the coordination site to the N_2-position. This isomerization is anticipated to be driven by the steric congestion between the substituent R in the heterocycle and the four cis ammines ligated to the Co center.[325]

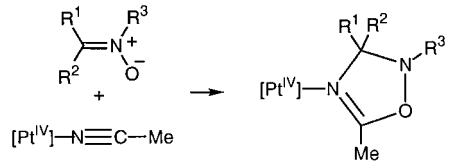
Currently, the majority of the reactions have been reported for platinum(II) and palladium(II) systems. However, other metal centers, i.e., rhodium(I), iridium(I), gold(I), copper(I), manganese(I), nickel(II), mercury(II), lead(II), indium(III), cobalt(III), iron(III), gold(III), germanium(IV), and tin(IV), have also been successfully employed. In some instances the ligated tetrazoles formed were liberated along the metal-mediated reaction as in the case of the reaction with Me_3SiN_3 catalyzed by $Pd(PPh_3)_4$ (5 mol %),[344] suggesting an alternative way for the preparation of this type of heterocycles. A general mechanism of the [2 + 3] cycloaddition, including the *metal-mediated* cycloaddition,[345,346] has been suggested, i.e., a concerted mechanism involving one cyclic transition state. In conclusion, it is noteworthy to mention that the [2 + 3] cycloaddition of organoazides to metal-bound nitriles is relevant to (i) the cycloaddition of organoazides to nitrilium salts, i.e., R−C≡N$^+$R′ − a process which leads to the trisubstituted tetrazolium salts[347] and (ii) the metal-mediated cycloaddition of azides to isocyanides, RNC, to give a *C*-coordinated tetrazolato ligand (for recent works see refs 348,349).

B. [2 + 3] Cycloaddition of Metal-Bound Nitriles and Nitrones: Synthesis of Oxadiazolines

Δ^4-1,2,4-Oxadiazolines represent a class of compounds that, although known, is rather limited in the number of heterocycles synthesized. Known methods of their preparation include [2 + 3] cycloadditions of *electron-deficient* organonitriles, e.g., Cl_3CCN or $NCCH_2CN$, or aryl cyanates, ROCN, and nitrones.[350]

Another route for their preparation is based upon the reaction of highly dipolarophilic nitrilium salts and nitrones.[351] Concurrently, organonitriles bearing donor groups are inactive in the reaction. Recently it was observed that the [2 + 3] cycloaddition between acetonitrile ligands, containing an *electron-donor* alkyl, in the platinum(IV) complex $[PtCl_4(MeCN)_2]$ and various nitrones $^-O^+N(R^3)=C(R^1)(R^2)$ proceeds under mild conditions and gives the first examples of Δ^4-1,2,4-oxadiazoline complexes depicted in Scheme 38 as a 1:1 mixture of two diastereoisomers in 70−

Scheme 38



90% yields.[350,352]

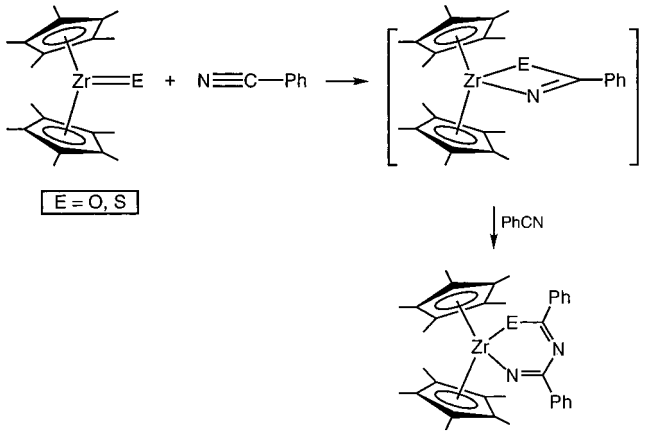
The heterocycles formed in the course of the metal-mediated reaction were liberated almost quantitatively by reaction of the complexes with pyridine in chloroform giving free Δ^4-1,2,4-oxadiazolines, which were isolated, and *trans*-$[PtCl_4(pyridine)_2]$. These two reactions, i.e., the cycloaddition and substitution, open up a general route to Δ^4-1,2,4-oxadiazoline heterocyclic species whose synthesis and further chemistry are still little explored.[350]

Later the role of the metal oxidation state on the control of the reactivity and/or the effect of substituents R at the [Pt]−NCR center have been verified.[352] It has been found that for the highly reactive platinum(IV) complexes $[PtCl_4(RCN)_2]$ the cycloaddition can be performed under mild conditions, starting even from a very unreactive organonitrile bearing an electron-donor substituent, e.g., R = Me, while for the much less reactive organonitriles in the platinum(II) complexes $[PtCl_2(RCN)_2]$ the cycloaddition occurs only in the case of the organonitrile with an electron-acceptor substituent, i.e., R = Ph. Thus, the ligated benzonitriles in the platinum(II) complex $[PtCl_2(PhCN)_2]$ undergo metal-mediated [2 + 3] cycloaddition with the nitrones $^-ON^+(R^3)=C(R^1)(R^2)$ to give the oxadiazoline complexes $[PtCl_2\{N=C(Ph)O-N(R^3)-C(R^1)(R^2)\}_2]$ in good yields, while $[PtCl_2(MeCN)_2]$ is inactive toward the addition. However, a strong activation of acetonitrile was reached by application of the platinum(IV) complex $[PtCl_4(MeCN)_2]$, and both $[PtCl_4(RCN)_2]$ (R = Me, Ph) react smoothly with various nitrones to give $[PtCl_4\{N=C(R)O-N(R^3)-C(R^1)(R^2)\}_2]$.

C. Other Cycloaddition Reactions

Bergman and colleagues[353,354] investigated reactions between highly reactive zirconium species $Cp^*_2Z=E$ (E = O or S) and substrates bearing triple and double bonds, e.g., benzonitrile. The authors isolated and structurally characterized the six-membered metallacycles shown in Scheme 39. These two compounds are formed upon [2 + 2] cycloaddition, giving an unstable four-membered ring which,

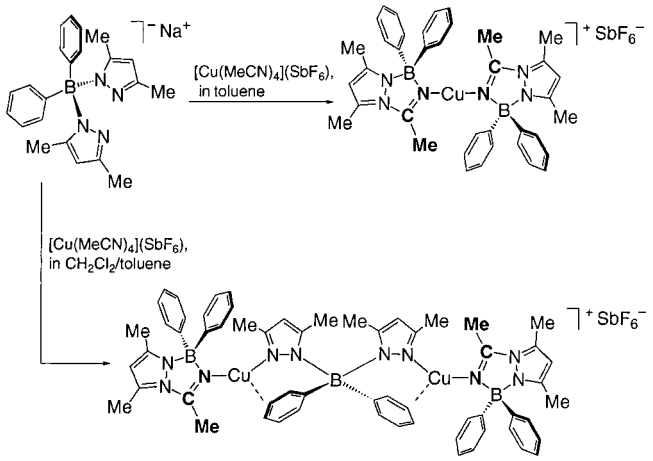
Scheme 39



however, is stable in the case of the [2 + 2] cycloaddition with $R_1C{\equiv}CR_2$. Addition of one more molecule of PhC≡N terminates the process. A relevant formal [2 + 2] cycloaddition occurred between nitriles and the methylidene complex $Cp_2Ti=CH_2$ formed in situ, and other formal cycloadditions involving nitrile insertion reactions into metal−carbon bonds have been reported for other titanocene derivatives.[355−360]

An unusual example of copper-mediated addition to acetonitrile has recently been reported by Tolman and colleagues.[361] When the homoleptic copper(I) solvento complex $[Cu(MeCN)_4](SbF_6)$ was treated with the potentially bidentate bis(pyrazolyl)borate ligand $Na[Ph_2B(pz^{Me,Me})_2]$ (Scheme 40), the formation

Scheme 40

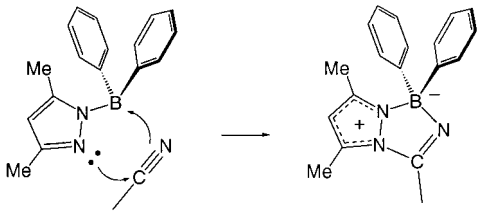


of mononuclear or binuclear, depending on the solvent used, copper complexes containing new heterocyclic ligands with the $BNCN_2$ ring was observed.

Although mechanistic aspects of the reaction have not yet been investigated, the authors[361] argued that such ligands can be formed due to the fragmentation of $Na[Ph_2B(pz^{Me,Me})_2]$ (similar to that described in section V) to give $Ph_2B(pz^{Me,Me})$ followed by the [2 + 3] cycloaddition with acetonitrile (Scheme 41).

Special attention was drawn to the fact that the reaction between $Na[Ph_2B(pz^{Me,Me})_2]$ and MeCN does not proceed in the absence of the metal center, thus giving an indication in favor of a metal-mediated process.

Scheme 41

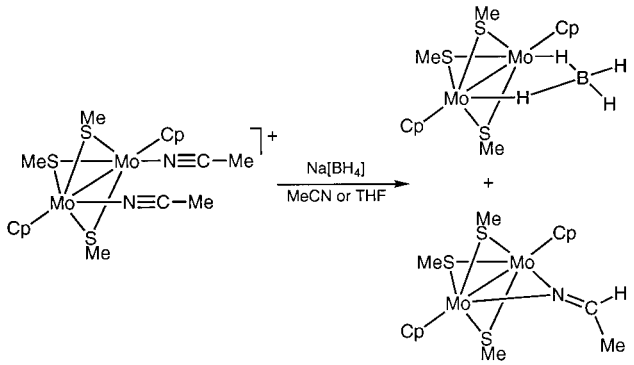


XI. Miscellaneous

In this section we have compiled material which does not belong to the categories described above.

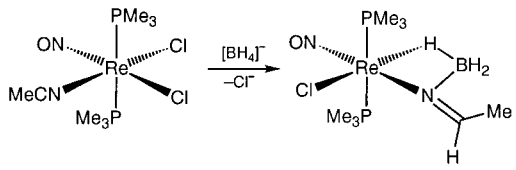
The reduction of nitriles by the nucleophilic attack of hydride-transfer reagents has been widely investigated and is a process with significant synthetic potential. However, intermediates formed in the reduction have been trapped only in a few cases, and examples (involving also other nucleophiles) with a subsequent electrophilic addition have been given in section IX. The reaction of $Na[BH_4]$ and the dinuclear bis-acetonitrile complex $[Mo_2(\eta^5\text{-}Cp)(\mu\text{-}SMe)_3(NCMe)_2][BF_4]$ in either MeCN or THF gives two products, i.e., a bridging azavinylidene species due to addition of hydride to coordinated MeCN and a tetrahydroborate compound upon substitution of ligated acetonitriles.[362] The formation of the azavinylidene product (Scheme 42) is more favorable in THF.

Scheme 42



Treatment of $[ReCl_2(MeCN)(NO)(PMe_3)_2]$ with $[BH_4]^-$ in THF results in conversion of the ligated acetonitrile giving the four-membered chelate ring depicted in Scheme 43.[363]

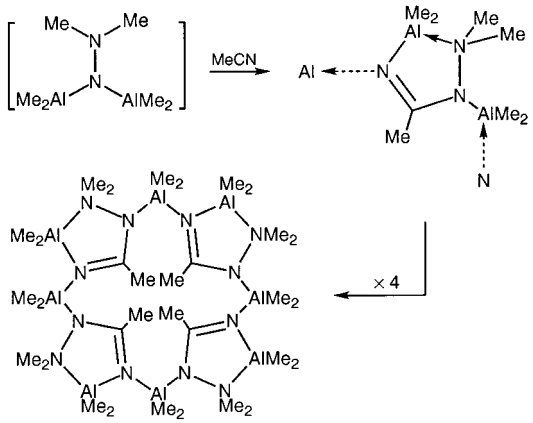
Scheme 43



The reaction can be viewed as a nucleophilic addition of hydride to the nitrile carbon and concomitant addition of BH_3 to the nitrogen.[363] The final complex represents a rare case of the trapped intermediate in reductions of the coordinated organonitriles by boron hydrides—the reaction that usually gives azavinylidene, imino, or amino complexes.

Addition of $AlMe_3$ to 1,1-dimethylhydrazine in toluene followed by removal of the solvent and redissolution of the residue in acetonitrile gave crystals of a new compound that was subject to X-ray crystallographic study.[364] The latter revealed formation of a novel aluminum-containing 16-membered ring system which is a structural analogue of calix[4]pyrrole. The authors suggested a plausible mechanism for the ring formation (Scheme 44) that

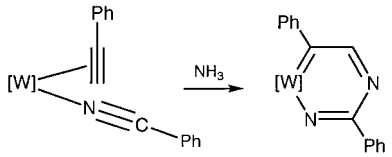
Scheme 44



involves the bridged hydrazido(2−) intermediate $[(Me_2Al)_2(\mu\text{-}\eta^1\text{-}N-NMe_2)]$ which reacts with acetonitrile, giving, after tetramerization, the ring system.[364]

In accord with the data considered in section V.A, treatment of the nitrile complex $[Tp'(CO)(PhC{\equiv}CR'')W(N{\equiv}CR)][BF_4]$ with amines NH_2R' (R = Me; R′ = H, Ph; R″ = Me, H) leads to the amidine complexes $[Tp'(CO)(PhC{\equiv}CR'')W\{NH{=}C(R)NHR'\}][BF_4]$.[203a] The alkyne PhC≡CR″ in the nitrile or the amidine complexes can undergo an intramolecular coupling to give metallacycles depicted in Scheme 45

Scheme 45

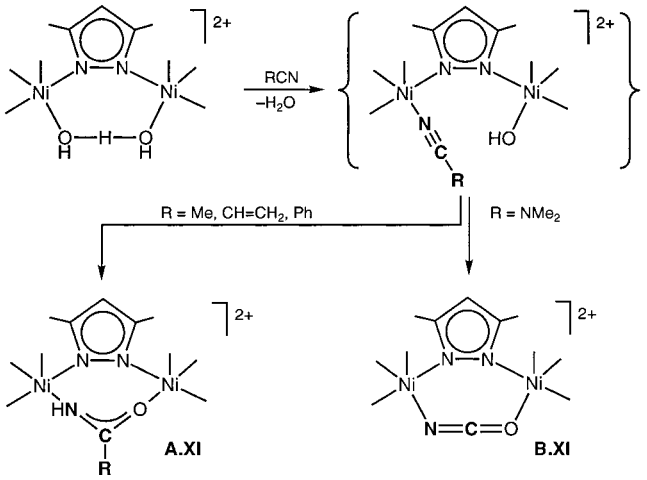


(R′ = H).

The plausible mechanism[203a] involves the initial formation of the amidine derivative $W-NH{=}C(Ph)-NH_2$ followed by deprotonation of the amide group, attack of a nitrogen lone pair to couple with the alkyne terminal site, and subsequent H_2 loss. A coupling with a carbonyl ligand has also been described[203b] in the reactions of $[Tp'(CO)_3W(N{\equiv}CMe)][BF_4]$ with ammonia or *n*-butylamine to form the metallacycles $[Tp'(CO)_2W\{C,N\text{-}C(=O)N(R)C(Me){=}NH\}]$ (R = H, *n*-butyl) which undergo protonation at the acyl oxygen atom to afford cationic metallacycle hydroxycarbene derivatives.

An unusual conversion of metal-bound dialkylcyanamide has been observed by Meyer and colleagues[84,85] upon investigation of the nitrile hydrolysis that occurred at a dinickel(II) complex. The authors treated the complex with the $\{H_3O_2\}Ni_2$ core, schematically depicted in Scheme 46, with different nitriles.

Scheme 46



In the case of acetonitrile, acrylonitrile, or benzonitrile, the reaction led to the expected (see section II.B.1) hydrolytic conversion furnishing the bridging amidato complex **A.XI** presumably via the intermediate formation of a solvento complex. The reaction went to another, unconventional, direction when dimethylcyanamide ($N{\equiv}CNMe_2$) was employed and the formation of the cyanato-bridged compound **B.XI** was found. It is believed that **B.XI** is formed via coordination of $N{\equiv}CNMe_2$ to one nickel(II) ion, followed by the addition of OH^- to give an *N*,*O*-bridging dimethylureate (type **A.XI** with $R = NMe_2$), and eventually the loss of dimethylamine terminates the process.

Addition of thiols, RSH, to metal-activated organonitriles has been studied only scarcely, and only one example of such addition, occurring at a platinum(II) center, was considered in the review by Michelin and colleagues.[7] Another example has later been reported for the rhodium(III) complex $[RhCl_3(MeCN)_3]$, which was treated with *i*-PrSH in MeCN to give the thioimino ester compound $[RhCl_3\{NH{=}C(Me)SPr\text{-}i\}(H_2O)_2]$.[365]

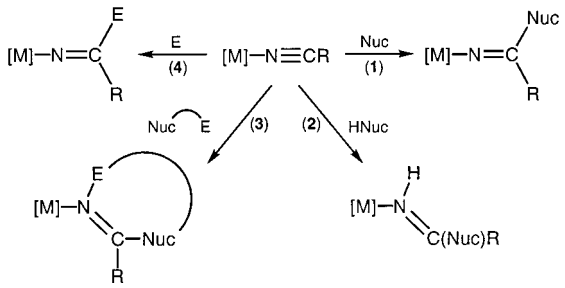
Some low-valent transition-metal complexes were found to catalyze the Michael and the aldol reactions of $RCH_2C{\equiv}N$ (R = strong acceptor) compounds having the reactive methylene group (e.g., see refs 366−369). Coordination of the nitrile N atom to the metal center enabled the nitriles to generate the enolate intermediate which then reacted with electrophiles.

XII. Conclusions

Organonitrile complexes have been extensively used as convenient starting materials in coordination chemistry, in view of the common lability of the NCR ligands which usually do not behave either as strong σ-donors or effective π-electron acceptors, as indicated by their values of the electrochemical P_L and E_L parameters (which constitute a measure of the net π-electron acceptor minus σ-donor character of a ligand)[370−372] which lie between those of stronger electron donors (e.g., hydroxide, hydride, halide, cyanate, cyanide, or ammonia) and those of the more effective π-electron acceptors (such as isocyanides, arylphosphines, dinitrogen, carbon monoxide, or carbyne ligands).

Nevertheless, despite their moderate coordination ability, organonitriles can be effectively activated by coordination to a metal center, undergoing a wide variety of reactions toward the formation of a diversity of nitrogen- and/or carbon-containing species of valuable synthetic value. The activation by the metal binding site [M] commonly results in an enhancement of the electrophilicity of the unsaturated nitrile carbon atom, thus promoting the β-addition (at least formally) of a *nucleophile* which can be of any of the following types. (i) Aprotic [e.g., Nuc = H^-, R^-, or MeO^- (section IX); organophosphine or deprotonated acidic phosphine (section VII)] to produce (reaction 1, Scheme 47) an azavinyledene species, [M]−N=

Scheme 47



C(Nuc)R, upon C−H, C−C, C−O, or C−P bond formation, respectively. (ii) Protic [HNuc = alcohol (section III) or thiol (section XI); hydroxide (water) (sections II and XI); ammonia, primary or secondary amines (section V); heterocyclic amine such as aziridine, pyrazole, adenine, or indole derivatives (section V); organohydrazine, hydroxylamine, imine, or sulfimide (section V); phosphorus ylide (section VI); etc.] to yield (reaction 2, Scheme 47) the corresponding imino derivatives, [M]−NH=C(Nuc)R, on C−O (or C−S), C−N, or C−C bond formation. (iii) Aprotic but bearing an active electrophilic center [E, in a few cases, e.g., for halo alcohols (section III.D), generated along the reaction] that can remain attached to the nucleophile-containing moiety, i.e., without cleavage along the reaction (Nuc⁀E), and add to the nitrile nitrogen atom to produce a cyclic imino species (reaction 3, Scheme 47).

Examples of Nuc⁀E reagents include 1,3-dipolar species, typically an azide or a nitrone (sections X.A and X.B), to yield, via [2 + 3] cycloaddition reactions, a tetrazole or an oxadiazoline product, in additions that involve the formation of C−N and N−N or of C−O and N−C bonds, respectively; a pyrazolylboron derivative (section X.C) leading to a ring formation with a C−N and a N−B bond has also been described.

The opposite type of nitrile activation, i.e., toward *electrophilic attack*, has also been achieved, although in quite a restricted number of cases, by using an electron-rich binding metal site with a high π-electron releasing ability. For end-on (η^1) coordinated nitriles, the electrophile (E) adds to the unsaturated nitrile carbon (β-electrophilic addition, reaction 4, Scheme 47) to produce azavinylidene [M]−N=C(E)R ($E = H^+$, $SiMe_3^+$) (via C−H or C−Si bond formation) or derived imido $[M]{\equiv}N{-}CH_2R$ species (upon double nitrile protonation) (section VIII). The unusual and much less studied side-on (η^2) coordination can also

induce nucleophilicity at the nitrile ligand, but the electrophile (E = Me^+, Et^+) normally adds to the *N*-atom to form an iminoacyl derivative [M]{η^2-N(E)=CR} upon N−C bond formation (alkylation), which can undergo a further protonation, although an electrophilic oxygen-transfer reaction to the nitrile *C*-atom to produce (C−O bond formation) an alkylimido species, [M]≡NC(=O)R, has been reported in a case when the η^2-nitrile is behaving us a four-electron donor (section VIII).

Variations of those general types of reactions, their sequencing and coupling with other types (such as nitrile insertion reactions), rearrangements, chelation, use of bifunctional reagents (nitriles and/or nucleophiles) or of di- or polynuclear complexes, ligand bridging ([M] can then denote a dinuclear binding site), etc., are often encountered, affording numerous types of products which in some cases can be liberated, being formed according to more convenient methods than conventional nonmetal-involving processes. However, a catalytic behavior has been achieved only in a limited number of cases, but the development of catalytic systems constitutes a subject of current interest with a prospective success.

Hence, the metal-catalyzed hydrolysis of nitriles (section II) is of particular significance toward the preparation of carboxamides $RC(=O)NH_2$ in environmentally friendly conditions (which contrast with those required in the strong acidic or basic media, in the absence of an activating metal center), and the search for cheaper and more effective catalysts is a current challenge. A better knowledge of the reaction as well as of the complete nitrile hydrolysis to carboxylic acids can result in the establishment of mimetic systems of nitrile hydratase and nitrilase, respectively, as well as in a better understanding of the action of these enzymes, at the molecular level. Carboxamides can also be prepared by metal-assisted alcoholysis followed by hydrolysis (section III.B) or by hydrolytic amidation (section V.B), but only scarce examples have been reported.

Among other useful products with various applications (namely, in pharmacology, synthesis, etc.) derived from metal activation of nitriles, which have been liberated from the binding metal centers, we can refer the following ones: heterocyclic species such as oxadiazolines and tetrazoles (with pharmacological and other applications) from [2 + 3] cycloadditions of nitrones and azides, respectively, to nitriles (section X), and oxazolines and oxazines from reactions of halo or amino alcohols with nitriles (sections III.C and III.D); amidines, cyclic amines, triazines, imidazolines, etc., from nitrile−amine coupling reactions (section V) or, rarely, amidines from nitrile reactions with oximes and hydrolysis (section IV); 1,3-diaza-1,3-dienes from nitrile−imine coupling (a single example) (section V.E); various enamines upon nitrile coupling with compounds containing an activated methylene group (section VI.B); vinyl ketones from multiple electrophilic additions to β-ketonitriles (section VIII); and amines from stepwise nucleophilic−electrophilic additions (section IX). Some of those products can be chiral [e.g., oxazolines and oxadiazolines (sections III.C and X.B), apart from a cyano−amine species (section IX)], but the field of asymmetric synthesis has still been little explored.

A diversity of nitrile-derived ligands has been achieved and undoubtedly will continue to expand. Apart from their significance toward further syntheses and/or the elucidation of reaction processes, in a few cases they can constitute valuable species with pharmacological interest, namely, in some platinum(II) imino ester complexes (derived from nitrile-alcohol addition, section III) whose trans isomers exhibit a higher antitumor activity than the cis ones, constituting sources for potential unconventional drugs. Metal-mediated reactions of nitriles can also be a source of a variety of metallacycles, and the study of their still undeveloped chemistry constitutes a promising field of research.

The mechanisms of the addition reactions have been investigated in detail only in few cases, using certain alcohols or amines as the nucleophiles, and interpretative theoretical studies have been performed also very rarely. Although kinetic evidence has been gained for the involvement of four- or six-membered cyclic transition states with one or two molecules of the protic nucleophile (sections III.E and V.A.4) and ab initio studies also support the addition of the nucleophile (oxime) in the protic form (section IV), unless base-catalyzed conditions are operating, the generality of these behaviors has still to be established. Concerted mechanisms also involving a cyclic transition state have been proposed (section IX) for the addition of some 1,3-dipolar reagents, and moreover, some addition reactions can occur via insertion of nitriles into metal−ligand bonds. Theoretical studies on the oxime−nitrile coupling (section IV) also indicate that the reactivity could not be interpreted on the basis of simple charge- or frontier-orbital-control arguments.

Hence, the above discussion illustrates the rich coordination chemistry of nitriles as versatile reagents susceptible to be activated toward a diversity of addition reactions which, however, in some cases are still quite rare and not always defined clearly with unknown mechanisms. Usually the detailed factors that drive the reactions are still elusive. Systematic studies, at both the experimental and the theoretical levels, are normally still lacking and deserve further attention, aiming to provide a better understanding of the factors that control the metal activation and the reactivity of nitriles and to recognize and interpret relationships between the electronic/structural features of the binding metal sites and the types of reactions they induce. The metal activation of nitriles is thus a promising field of research, has gained a considerable development within the past few years, and remains open to expansion in various directions with recognized significance not only in coordination chemistry, but also in organic chemistry, biochemistry, catalysis, pharmacology, and environmental chemistry.

XIII. Acknowledgements

We are indebted to our former and current coworkers, postdoctoral fellows, and students who shared with us the fascination of this area of chem-

istry and whose contributions are acknowledged through their coauthorship of the papers cited. The authors express deepest gratitude to Profs./Drs. G. Albertin, W. Beck, A. Hiller, A. Hughes, P. F. Kelly, G. I. Koldobskii, F. Meyer, R. Michelin, T. Naota, B. Neumüller, W. B. Tolman, and J. Vicente for valuable discussions and comments on different parts of the review. We also wish to thank Profs./Drs. M. Basato, C. S. Chin, K. M. Doxsee, M. Dunaj-Jurco, J. L. Eglin, W. Fehlhammer, M. Hvastijová, J. Jochims, R. W. McGaff, K. C. Molloy, S.-I. Murahashi, A. Nazarov, and F. Y. Pétillon for useful references and reprints relevant to this topic.

We are very much obliged to the FCT (Foundation for Science and Technology), PRAXIS XXI program (Portugal), and INTAS for financial support. V.Yu.K. additionally thanks the International Science Foundation for Soros Professorship and the Royal Society of Chemistry for the Grant for International Authors.

XIV. Abbreviations

Me	methyl
Et	ethyl
Pr	propyl
Bu	butyl
Ph	phenyl
Ar	aryl
Cp	cyclopentadienyl
Cp*	pentamethylcyclopentadienyl
cod	1,5-cyclooctadiene
PzH	pyrazole
acac	acetylacetonate
dppe	1,2-bis(diphenylphosphino)ethane
THF	tetrahydrofurane
Tp′	hydrotris(3,5-dimethylpyrazolyl)borate
TMEDA	*N*,*N*,*N*′,*N*′-tetramethylethylenediamine

XV. References

(1) Boyd, G. V. *The Chemistry of Amidines and Imidates*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, 1991; Vol. 2, p 339.
(2) Gridnev, I. D.; Gridneva, N. A. *Usp. Khim. (Russ. Chem. Rev.)* **1995**, *64*, 1091.
(3) For recent reviews on 1,3-dipolar cycloaddition, see: (a) Karlsson, S.; Hogberg, H.-E. *Org. Prep. Proced. Int.* **2001**, *33*, 103. (b) Raimondi, L.; Benaglia, M. *Eur. J. Org. Chem.* **2001**, 1033. (c) De March, P.; Figueredo, M.; Font, J. *Heterocycles* **1999**, *50*, 1213. (d) Gothelf, K. V.; Jørgensen, K. A. *Chem. Commun.* **2000**, 1449. (e) Gothelf, K. V.; Jensen, K. B.; Jørgensen, K. A. *Sci. Prog.* **1999**, *82*, 327. (f) Gothelf, K. V.; Jørgensen, K. A. *Chem. Rev.* **1998**, *98*, 863.
(4) Murahashi, S.-I.; Takaya, H. *Acc. Chem. Res.* **2000**, *33*, 225.
(5) (a) Murahashi, S.-I.; Naota, T. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1805. (b) Murahashi, S.-I.; Naota, T. *Chemtracts-Org. Chem.* **1994**, *7*, 281.
(6) (a) Fairlie, D. P.; Jackson, W. G.; Skelton, B. W.; Wen, H.; White, A. H.; Wickramasinghe, W. A.; Woon, T. C.; Taube, H. *Inorg. Chem.* **1997**, *36*, 1020. (b) Hay, R. W.; McLaren, F. M. *Transition Met. Chem.* **1999**, *24*, 398 and references in these works.
(7) Michelin, R. A.; Mozzon, M.; Bertani, R. *Coord. Chem. Rev.* **1996**, *147*, 299 and references therein.
(8) Pombeiro, A. J. L.; Guedes da Silva, M. F. C.; Michelin, R. A. *Coord. Chem. Rev.* **2001**, *218*, 43.
(9) Michelin, R. A.; Pombeiro, A. J. L.; Guedes da Silva, M. F. C. *Coord. Chem. Rev.* **2001**, *218*, 75.
(10) Eglin, J. L. *Comments Inorg. Chem.* **2001**, in press.
(11) da Rocha, Z. N.; Chiericato, G., Jr.; Tfouni, E. *Adv. Chem. Ser.* **1997**, 297.
(12) Parkins, A. W. *Platinum Met. Rev.* **1996**, *40*, 169.
(13) Chin, J. *Acc. Chem. Res.* **1991**, *24*, 145.
(14) Endo, I.; Nojiri, M.; Tsujimura, M.; Nakasako, M.; Nagashima, S.; Yohda, M.; Odaka, M. *J. Inorg. Biochem.* **2001**, *83*, 247.
(15) Endo, I.; Odaka, M. *J. Mol. Catal. B: Enzym.* **2000**, *10*, 81.
(16) Kobayashi, M.; Shimizu, S. *Curr. Opin. Chem. Biol.* **2000**, *4*, 95.
(17) Artaud, I.; Chatel, S.; Chauvin, A. S.; Bonnet, D.; Kopf, M. A.; Leduc, P. *Coord. Chem. Rev.* **1999**, *190*−*192*, 577.
(18) Claiborne, A.; Yeh, J. I.; Mallett, T. C.; Luba, J.; Crane, E. J., III; Charrier, V.; Parsonage, D. *Biochemistry* **1999**, *38*, 15407.
(19) Bianchi, D.; Bosetti, A.; Battistel, E. *Chim. Ind. (Milan)* **1999**, *81*, 1305.
(20) Shimizu, S. *Bitamin* **1999**, *73*, 713.
(21) Endo, I.; Odaka, M.; Yohda, M. *Trends Biotechnol.* **1999**, *17*, 244.
(22) Hvastijova, M.; Kohout, J.; Buchler, J. W.; Boca, R.; Kozisek, J.; Jäger, L. *Coord. Chem. Rev.* **1998**, *175*, 17.
(23) Corain, B.; Basato, M.; Veronese, A. C. *J. Mol. Catal.* **1993**, *81*, 133.
(24) Butler, R. N. *Comprehensive Heterocyclic Chemistry*, 2nd ed.; Katritzky, A., Ed.; Pergamon Press: 1996; Vol. 4, p 621.
(25) Zubarev, V. Yu.; Ostrovskii, V. A. *Chem. Heterocycl. Compd. (N.Y.)* **2001** (Volume Date 2000), *36*, 759−774; *Chem. Abstr.* **2001**, *134*, 147507.
(26) Ostrovskii, V. A.; Pevzner, M. S.; Kofman, T. P.; Shcherbinin, M. B.; Tselinskii, I. V. *Targets Heterocycl. Syst.* **1999**, 467.
(27) Ostrovskii, V. A.; Koren, A. O. *Heterocycles* **2000**, *53*, 1421.
(28) Koldobskii, G. I.; Ostrovskii, V. A. *Russ. Chem. Rev.* **1994**, *63*, 797.
(29) Kukushkin, Yu. N. *Russ. J. Coord. Chem.* **1998**, *24*, 173.
(30) Pombeiro, A. J. L. *Inorg. Chim. Acta* **1992**, *198*−*200*, 179.
(31) Pombeiro, A. J. L. *New J. Chem.* **1994**, *18*, 163.
(32) Stenske, A. *Schweiz. Lab.-Z.* **2000**, *57*, 112; *Chem. Abstr.* **2000**, *133*, 104574.
(33) Albericio, F.; Kates, S. A. *Solid-Phase Synthesis*; Kates, S. A., Albericio, F., Eds.; Marcel Dekker: New York, 2000; p 275.
(34) North, M. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2209.
(35) Lange, U. E. W.; Schäfer, B.; Baucke, D.; Buschmann, E.; Mack, H. *Tetrahedron Lett.* **1999**, *40*, 7067 and references therein.
(36) Brown, B. R. *The Organic Chemistry of Aliphatic Nitrogen Compounds*; Oxford University Press: Oxford, 1994.
(37) Ghaffar, T.; Parkins, A. W. *J. Mol. Catal. A: Chem.* **2000**, *160*, 249 and references therein.
(38) Ghaffar, T.; Parkins, A. W. *Tetrahedron Lett.* **1995**, *36*, 8657.
(39) Parkins, A. W.; Ghaffar, T. US Patent 6,133,478, 2000.
(40) Cobley, C. J.; van den Heuvel, M.; Abbadi, A.; De Vries, J. G. *Tetrahedron Lett.* **2000**, *41*, 2467.
(41) Djoman, M. C. K.-B.; Ajjou, A. N. *Tetrahedron Lett.* **2000**, *41*, 4845.
(42) Kaminskaia, M. V.; Kostic, N. M. *J. Chem. Soc., Dalton Trans.* **1996**, 3677.
(43) Chin, C. S.; Kim, S. Y.; Joo, K.-S.; Won, G.; Chong, D. *Bull. Korean Chem. Soc.* **1999**, *20*, 535; *Chem. Abstr.* **1999**, *131*, 144179.
(44) Marlin, D. S.; Mascharak, P. K. *Chem. Soc. Rev.* **2000**, *29*, 69.
(45) Noveron, J. C.; Olmstead, M. M.; Mascharak, P. K. *J. Am. Chem. Soc.* **2001**, *123*, 3247.
(46) (a) Tyler, L. A.; Noveron, J. C.; Olmstead, M. M.; Mascharak, P. K. *Inorg. Chem.* **2000**, *39*, 357. (b) Tyler, L. A.; Olmstead, M. M.; Mascharak, P. K. *Inorg. Chim. Acta* **2001**, *321*, 135.
(47) Noveron, J. C.; Olmstead, M. M.; Mascharak, P. K. *J. Am. Chem. Soc.* **1999**, *121*, 3553.
(48) Noveron, J. C.; Olmstead, M. M.; Mascharak, P. K. *Inorg. Chem.* **1998**, *37*, 1138.
(49) Chatel, S.; Rat, M.; Dijols, S.; Leduc, P.; Tuchagues, J. P.; Mansuy, D.; Artaud, I. *J. Inorg. Biochem.* **2000**, *80*, 239.
(50) Kung, I.; Schweitzer, D.; Shearer, J.; Taylor, W. D.; Jackson, H. L.; Lovell, S.; Kovacs, J. A. *J. Am. Chem. Soc.* **2000**, *122*, 8299.
(51) Shearer, J.; Kung, I. Y.; Lovell, S.; Kaminsky, W.; Kovacs, J. A. *J. Am. Chem. Soc.* **2001**, *123*, 463.
(52) Heinrich, L.; Li, Y.; Vaissermann, J.; Chottard, G.; Chottard, J.-C. *Angew. Chem., Int. Ed.* **1999**, *38*, 3526.
(53) Heinrich, L.; Li, Y.; Provost, K.; Michalowicz, A.; Vaissermann, J.; Chottard, J.-C. *Inorg. Chim. Acta* **2001**, *318*, 117.
(54) Aoki, H.; Kamachi, H. PCT Int. Appl. WO 01 30,994, 2001 (JP Appl. 107,855, 2000); *Chem. Abstr.* **2001**, *134*, 321627.
(55) Kamachi, H.; Aoki, H. JP 69,978, 2001; *Chem. Abstr.* **2001**, *134*, 218041.
(56) Shimizu, A.; Kobayashi, T. JP 245,494, 2000; *Chem. Abstr.* **2000**, *133*, 221870.
(57) Kawabe, M. JP 342,292, 2000; *Chem. Abstr.* **2001**, *134*, 28533.
(58) Oriel, P. J.; Padmakumar, R.; Kim, S. H. PCT Int. Appl. 1999, WO 99 55,719; *Chem. Abstr.* **1999**, *131*, 335938.
(59) Ito, K.; Tsuruoka, M.; Suzuki, T.; Nikumaru, S.; Nakamura, T. Jpn. Kokai Tokkyo Koho 1999, JP 11 253,168; *Chem. Abstr.* **1999**, *131*, 239734.
(60) Ishii, K.; Murao, K. Jpn. Kokai Tokkyo Koho 1999, JP 11 123,-098; *Chem. Abstr.* **1999**, *130*, 324408.
(61) Ito, K.; Nikumaru, S.; Abe, T.; Suzuki, T.; Nakamura, T. Jpn. Kokai Tokkyo Koho 1999, JP 11 089,575; *Chem. Abstr.* **1999**, *130*, 295628.
(62) Enomoto, K.; Ozaki, E. Jpn. Kokai Tokkyo Koho 1999, JP 11 080,103; *Chem. Abstr.* **1999**, *130*, 280928.
(63) Robins, K. T.; Nagasawa, T. PCT Int. Appl. WO 99 05,306, 1999; *Chem. Abstr.* **1999**, *130*, 167239.

(64) Fallon, R. D.; Nelson, M. J.; Payne, M. S. US Patent 5,811,286, 1998; *Chem. Abstr.* **1998**, *129*, 256000.
(65) Burlingame, R. P.; Millis, J. R.; Sanchez-Riera, F.; Blackburn, T. F.; Grund, A. D. PCT Int. Appl. WO 98 32,872, 1998; *Chem. Abstr.* **1998**, *129*, 135265.
(66) Kuz'mitskii, G. E.; Fedchenko, N. N.; Alikin, V. N.; Fedchenko, V. N.; Voronin, S. P. Russ. Patent 2,112,804, 1998; *Chem. Abstr.* **2000**, *132*, 346717.
(67) Hughes, J.; Moran, P. J.; Weir, S. PCT Int. Appl. WO 9858072, 1998; *Chem. Abstr.* **1999**, *130*, 63368.
(68) Burlingame, R. P.; Millis, J. R.; Sanchez-Riera, F.; Blackburn, T. F.; Grund, A. D. PCT Int. Appl. WO 98 32,872, 1998; *Chem. Abstr.* **1998**, *129*, 135265.
(69) Matsuoka, K.; Matsuyama, A. Jpn. Kokai Tokkyo Koho JP 10 179,183, 1998; *Chem. Abstr.* **1998**, *129*, 121724.
(70) DiCosimo, R.; Stieglitz, B.; Fallon, R. D. US Patent 5,728,556, 1998; *Chem. Abstr.* **1998**, *128*, 229433.
(71) Cowan, D.; Cramp, R.; Pereira, R.; Graham, D.; Almatawah, Q. *Extremophiles* **1998**, *2*, 207.
(72) (a) Ramakrishna, C.; Dave, H.; Ravindranathan, M. *J. Sci. Ind. Res.* **1999**, *58*, 925. (b) Shimizu, S. *Bitamin* **1999**, *73*, 713. (c) Yamada, H.; Koboyashi, M. *Biosci. Biotechnol. Biochem.* **1996**, *60*, 1391.
(73) Kopylovich, M. N.; Kukushkin, V. Yu.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. Unpublished results, 2002 (patent pending).
(74) Kopylovich, M. N.; Kukushkin, V. Yu.; Guedes da Silva, M. F. C.; Haukka, M.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1569.
(75) Kukushkin, V. Yu.; Nishioka, T.; Nakamura, S.; Kinoshita, I.; Isobe, K. *Chem. Lett.* **1997**, 189.
(76) Nelson, K. J.; McGraff, R. W.; Powell, D. R. *Inorg. Chim. Acta* **2000**, *304*, 130.
(77) Bauer, C. B.; Concolino, T. E.; Eglin, J. L.; Rogers, R. D.; Staples, R. J. *J. Chem. Soc., Dalton Trans.* **1998**, 2813.
(78) McGaff, R. W.; Dopke, N. C.; Hayashi, R. K.; Powell, D. R.; Treichel, P. M. *Polyhedron* **2000**, *19*, 1245.
(79) Concolino, T. E.; Eglin, J. L.; Staples, R. J. *Polyhedron* **1999**, *18*, 915.
(80) Neumann, D.; Paraskevopoulou, P.; Psaroudakis, N.; Mertis, K.; Staples, R. J.; Stavropoulos, P. *Inorg. Chem.* **2000**, *39*, 5530.
(81) Cotton, F. A.; Daniels, L. M.; Haefner, S. C.; Kühn, F. E. *Inorg. Chim. Acta* **1999**, *287*, 159.
(82) Schollhammer, P.; Le Hénanf, M.; Le Roy-Le Floch, C.; Pétillon, F. Y.; Talarmin, J.; Muir, K. W. *J. Chem. Soc., Dalton Trans.* **2001**, 1573.
(83) Mironov, Y. V. *Eur. J. Inorg. Chem.* **1999**, 997.
(84) Meyer, F.; Kaifer, E.; Kircher, P.; Heinze, K.; Pritzkow, H. *Chem. Eur. J.* **1999**, *5*, 1617.
(85) Meyer, F.; Hyla-Kryspin, I.; Kaifer, E.; Kircher, P. *Eur. J. Inorg. Chem.* **2000**, 771.
(86) Luo, R.-S.; Mao, X.-A.; Pan, Z.-Q.; Luo, Q.-H. *Spectrochim. Acta, Part A* **2000**, *56*, 1675.
(87) Tellers, D. M.; Ritter, J. C. M.; Bergman, R. G. *Inorg. Chem.* **1999**, *38*, 4810.
(88) Chin, C. S.; Chong, D.; Lee, B.; Jeong, H.; Won, G.; Do, Y.; Park, Y. J. *Organometallics* **2000**, *19*, 638.
(89) Chin, C. S.; Chong, D.; Lee, B.; Park, Y. J. *Organometallics* **2000**, *19*, 4043.
(90) Hiraki, K.; Kinoshita, Y.; Kinoshita-Kawashima, J.; Kawano, H. *J. Chem. Soc., Dalton Trans.* **1996**, 291.
(91) Rochon, F. D.; Kong, P. C.; Melanson, R. *Inorg. Chem.* **1990**, *29*, 2708.
(92) Kuznetsov, M. L.; Bokach, N. A.; Kukushkin, V. Yu.; Pakkanen, T.; Wagner, G.; Pombeiro, A. J. L. *J. Chem. Soc., Dalton Trans.* **2000**, 4683.
(93) Bennett, B. K.; Lovell, S.; Mayer, J. M. *J. Am. Chem. Soc.* **2001**, *123*, 4336.
(94) Lee, G. R.; Crayston, J. A. *Polyhedron* **1996**, *15*, 1817.
(95) Wieser, M.; Nagasawa, T. *Stereoselective Biocatalysis*; Patel, R. N., Ed.; Marcel Dekker: New York, 2000; p 461; *Chem. Abstr.* **2000**, *134*, 82520.
(96) Desai, J. D.; Ramakrishna, C. *J. Sci. Ind. Res.* **1998**, *57*, 441.
(97) Dunn, P. J. In *Comprehensive Organic Functional Group Transformations*; Katrizky, A. R., Meth-Cohn, O., Rees, C. W., Eds.; Elsevier: Oxford, 1995; Vol. 5, p 741.
(98) Thimann, W.; Geffken, D. *Z. Naturforsch., B: Chem. Sci.* **2001**, *56*, 547.
(99) Sharma, S. K.; Tandon, M.; Lown, J. W. *J. Org. Chem.* **2001**, *66*, 1030.
(100) Obst, U.; Betschmann, P.; Lerner, C.; Seiler, P.; Diederich, F.; Gramlich, V.; Weber, L.; Banner, D. W.; Schonholzer, P. *Helv. Chim. Acta* **2000**, *83*, 855.
(101) Shishkin, V. E.; Mednikov, E. V.; Anishchenko, O. V.; No, B. I. *Russ. J. Gen. Chem.* **1999**, *69*, 1673.
(102) Gaupp, S.; Effenberger, F. *Tetrahedron: Asymmetry* **1999**, *10*, 1777.
(103) Zhang, L.-H.; Chung, J. C.; Costello, T. D.; Valvis, I.; Ma, P.; Kauffman, S.; Ward, R. *J. Org. Chem.* **1997**, *62*, 2466.
(104) Neugebauer, W.; Pinet, E.; Kim, M.; Carey, P. R. *Can. J. Chem.* **1996**, *74*, 341.
(105) Lange, U. E. W.; Schäfer, B.; Baucke, D.; Buschmann, E.; Mack, H. *Tetrahedron Lett.* **1999**, 7067 and references therein.
(106) Ehrler, J.; Farooq, S. *Synlett* **1994**, 702.
(107) Hegedus, L. S.; Mulhern, T. A.; Asada, H. *J. Am. Chem. Soc.* **1986**, *108*, 6224.
(108) Rouschias, G.; Wilkinson, G. *J. Chem. Soc. A* **1968**, 489.
(109) On application of imino esters in organic synthesis, see: (a) Palomo, C.; Aizpurua, J. M.; Ganboa, I.; Oiarbide, M. *Eur. J. Org. Chem.* **1999**, 3223. (b) Kelarev, V. I.; Koshelev, V. N. *Usp. Khim. (Russ. Chem. Rev.)* **1995**, *64*, 339.
(110) Bokach, N. A.; Kukushkin, V. Yu.; Kuznetsov, M. L.; Garnovskii, D. A.; Natile, G.; Pombeiro, A. J. L. *Inorg. Chem.* **2002**, accepted for publication.
(111) (a) Natile, G.; Coluccia, M. *Coord. Chem. Rev.* **2001**, *216*−*217*, 383. (b) Liu, Y.; Pacifico, C.; Natile, G.; Sletten, E. *Angew. Chem., Int. Ed.* **2001**, *40*, 1226.
(112) (a) Liu, Y.; Sivo, M. F.; Natile, G.; Sletten, E. *Met.-Based Drugs* **2000**, *7*, 169. (b) Leng, M.; Locker, D.; Giraud-Panis, M.-J.; Schwartz, A.; Intini, F. P.; Natile, G.; Pisano, C.; Boccarelli, A.; Giordano, D.; Coluccia, M. *Mol. Pharmacol.* **2000**, *58*, 1525. (c) Andersen, B.; Margiotta, N.; Coluccia, M.; Natile, G.; Sletten, E. *Met.-Based Drugs* **2000**, *7*, 23. (d) Intini, P. F.; Natile, G.; Boccarelli, A.; Coluccia, M. Eur. Pat. Appl. EP 974,597, 2000; *Chem. Abstr.* **2000**, *132*, 102832. (e) Coluccia, M.; Nassi, A.; Boccarelli, A.; Giordano, D.; Cardellicchio, N.; Locker, D.; Leng, M.; Sivo, M.; Intini, F. P.; Natile, G. *J. Inorg. Biochem.* **1999**, *77*, 31. (f) Coluccia, M.; Nassi, A.; Boccarelli, A.; Giordano, D.; Cardellicchio, N.; Intini, F. Paolo; Natile, G.; Barletta, A.; Paradiso, A. *Int. J. Oncol.* **1999**, *15*, 1039. (h) Boccarelli, A.; Coluccia, M.; Intini, F. P.; Natile, G.; Locker, D.; Leng, M. *Anti-Cancer Drug Des.* **1999**, *14*, 253.
(113) Casas, J. M.; Chisholm, M. H.; Sicilia, M. V.; Streib, W. E. *Polyhedron* **1991**, *10*, 1573.
(114) (a) Gonzalez, A. M.; Cini, R.; Intini, F. P.; Pacifico, C.; Natile, G. *Inorg. Chem.* **2002**, *41*, 470. (b) Cini, R.; Caputo, P. A.; Intini, F. P.; Natile, G. *Inorg. Chem.* **1995**, *34*, 1130 and references therein.
(115) Prenzler, P. D.; Hockless, D. C. R.; Heath, G. A. *Inorg. Chem.* **1997**, *36*, 5845.
(116) Ros, R.; Renaud, J.; Roulet, R. *J. Organomet. Chem.* **1976**, *104*, 271 and references therein.
(117) Guedes da Silva, M. F. C.; Ferreira, C. M. P.; Branco, E. M. P. R. P.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Michelin, R. A.; Belluco, U.; Bertani, R.; Mozzon, M.; Bombieri, G.; Benetollo, F.; Kukushkin, V. Yu. *Inorg. Chim. Acta (Topical Volume on Platinum Chemistry)* **1997**, *265*, 267.
(118) (a) Ferreira, C. M. P.; Pombeiro, A. J. L.; Guedes da Silva, M. F. C.; Kukushkin, V. Yu. Unpublished results, 2001. (b) Ferreira, C. M. P. Ph.D. Thesis, Instituto Superior Técnico, Lisbon, Portugal, 2001.
(119) Das, B. C.; Dey, I.; Biswas, G.; Banerjee, R.; Iitaka, Y.; Banerjee, A. *J. Cryst. Spectrosc. Res.* **1993**, *23*, 509.
(120) Begley, M. J.; Hubberstey, P.; Moore, C. H. M. *J. Chem. Res.* **1991**, 334.
(121) Pickardt, J.; Kühn, B. *Z. Kristallogr.* **1996**, *211*, 728.
(122) Pickardt, J.; Kühn, B. *Z. Naturforsch., Teil B* **1996**, *51*, 1469.
(123) Kaminskaia, N. V.; Guzei, I. A.; Kostic, N. M. *J. Chem. Soc., Dalton Trans.* **1998**, 3879.
(124) Bertani, R.; Gotti, M.; Michelin, R. A.; Mozzon, M.; Bandoli, G.; Angelici, R. J. *Organometallics* **1996**, *15*, 1236.
(125) (a) Ruiz, J.; Cutillas, N.; Rodríguez, V.; Sampedro, J.; López, G.; Chaloner, P. A.; Hitchcock, P. B. *J. Chem. Soc., Dalton Trans.* **1999**, 2939. (b) Ruiz, J.; Rodriguez, V.; Lopez, G.; Casabo, J.; Molins, E.; Miravitlles, C. *Organometallics* **1999**, *18*, 1177. (c) Sanchez, G.; Serrano, J. L.; Ramirez de Arellano, M. C.; Perez, J.; Lopez, G. *Polyhedron* **2000**, *19*, 1395.
(126) Wada, M.; Shimohigashi, T. *Inorg. Chem.* **1976**, *15*, 954.
(127) Hvastijová, M.; Kozisek, J.; Kohout, J.; Díaz, J. G. *Inorg. Chim. Acta* **1995**, *236*, 163.
(128) (a) Hvastijová, M.; Kozisek, J.; Kohout, J.; Jäger, L. *J. Coord. Chem.* **1995**, *36*, 195. (b) Segl'a, P.; Palicova, M. *Synth. React. Inorg. Metal-Org. Chem.* **1999**, *29*, 1843. (c) Bu, X.-H.; Du, M.; Tanaka, K.; Shionoya, M.; Shiro, M. *Inorg. Chem. Commun.* **2001**, *4*, 150.
(129) Dunaj-Jurco, M.; Miklos, D.; Potocnak, I.; Jäger, L. *Acta Crystallogr.* **1998**, *C54*, 1763.
(130) Dunaj-Jurco, M.; Potocnak, I.; Miklos, D.; Klement, R. *Collect. Czech. Chem. Commun.* **1999**, *64*, 600 and references therein.
(131) Potts, R. A.; Gaj, D. L.; Schneider, W. F.; Dean, N. S.; Kampf, J. W.; Oliver, J. P. *Polyhedron* **1991**, *10*, 1631.
(132) Thorn, D. L.; Calabrese, J. C. *J. Organomet. Chem.* **1984**, *272*, 283.
(133) de Bruin, B.; Boerakker, M. J.; de Gelder, R.; Smits, J. M. M.; Gal, A. W. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 219.

(134) Bianucci, A. M.; Demartin, F.; Manassero, M.; Masciocchi, N.; Ganadu, M. L.; Naldini, L.; Panzanelli, A. *Inorg. Chim. Acta* **1991**, *182*, 197 and references therein.
(135) Blake, A. J.; Hubberstey, P.; Suksangpanya, U.; Wilson, C. L. *J. Chem. Soc., Dalton Trans.* **2000**, 3873.
(136) Boca, R.; Hvastijová, M.; Kozisek, J.; Valko, M. *Inorg. Chem.* **1996**, *35*, 4794.
(137) (a) Boca, R.; Hvastijová, M.; Kozisek, J. *J. Chem. Soc., Dalton Trans.* **1995**, 1921. (b) Segl'a, P.; Palicova, M.; Koman, M.; Glowiak, T. *J. Coord. Chem.* **2000**, *51*, 101.
(138) Byers, P.; Drew, M. G. B.; Hudson, M. J.; Isaacs, N. S.; Upadhaya, A.; Madic, C. *Polyhedron* **1994**, *13*, 345 and references therein.
(139) Jamnicky, M.; Segl'a, P.; Koman, M. *Polyhedron* **1995**, *14*, 1837 and references therein.
(140) El-Shazely, R. M.; Shallaby, A. M.; Mostafa, M. M. *Synth. React. Inorg. Met.-Org. Chem.* **1990**, *20*, 283.
(141) (a) Segl'a, P.; Jamnicky, M.; Koman, M.; Miklos, D.; Sima, J. *Monogr. Ser. Int. Conf. Coord. Chem.* **1999**, *4* (*Coordination Chemistry at the Turn of the Century*), 177; *Chem. Abstr.* **1999**, *131*, 222407. (b) Segl'a, P.; Miklos, D.; Jamnicky, M.; Purdekova, M. *Monogr. Ser. Int. Conf. Coord. Chem.* **1997**, *3 (Progress in Coordination and Organometallic Chemistry)*, 165; *Chem. Abstr.* **1997**, *127*, 314144.
(142) Miklos, D.; Segl'a, P.; Glowiak, T. *Inorg. Chem. Commun.* **2001**, *4*, 66.
(143) Segl'a, P.; Koman, M.; Glowiak, T. *J. Coord. Chem.* **2000**, *50*, 105.
(144) Segl'a, P.; Miklos, D.; Jamnicky, M.; Sima, J. *J. Coord. Chem.* **1999**, *48*, 15.
(145) Segl'a, P.; Jamnicky, M.; Koman, M.; Glowiak, T. *Polyhedron* **1998**, *17*, 2765.
(146) Segl'a, P.; Jamnicky, M.; Koman, M.; Sima, J.; Glowiak, T. *Polyhedron* **1998**, *17*, 4525.
(147) Segl'a, P.; Jamnicky, M. *Inorg. Chim. Acta* **1993**, *205*, 221.
(148) Stark, M. A.; Jones, G.; Richards, C. J. *Organometallics* **2000**, *19*, 1282.
(149) Scaffaro, R.; Carianni, G.; La Mantia, F. P.; Zerroukhi, A.; Mignard, N.; Granger, R.; Arsac, A.; Guillet, J. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 1795.
(150) Ikehira, H.; Yanagawa, M. JP 08,134,048, 1996; *Chem. Abstr.* **1996**, *125*, 142712.
(151) (a) Koch, G.; Lloyd-Jones, G. C.; Loiseleur, O.; Pfaltz, A.; Pretot, R.; Schaffner, S.; Schnider, P.; von Matt, P. *Recl. Trav. Chim. Pays-Bas* **1995**, *114*, 206. (b) Allen, J. V.; Dawson, G. J.; Frost, C. G.; Williams, J. M. J.; Coote, S. J. *Tetrahedron* **1994**, *50*, 799. (c) Bolm, C.; Weickhardt, K.; Zehnder, M.; Ranff, T. *Chem. Ber.* **1991**, *124*, 1173. (d) Witte, H.; Seeliger, W. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 287.
(152) Kimura, Y.; Tsutsumi, T.; Myata, H. JP 06,271,555, 1994; *Chem. Abstr.* **1995**, *122*, 81360.
(153) Guiry, P. J.; McCarthy, M.; Lacey, P. M.; Saunders, C. P.; Kelly, S.; Connolly, D. J. *Curr. Org. Chem.* **2000**, *4*, 821.
(154) Meyers, A. I. *J. Heterocycl. Chem.* **1998**, *35*, 991.
(155) Langlois, Y. *Curr. Org. Chem.* **1998**, *2*, 1.
(156) Beaufour, M.; Cherton, J.-C.; Carlin-Sinclair, A.; Hamm, S. *J. Chromatogr., B: Biomed. Sci. Appl.* **2001**, *761*, 35.
(157) Bosc, J. J.; Jarry, C.; Martinez, B.; Molimard, M. *J. Pharm. Pharmacol.* **2001**, *53*, 923.
(158) (a) Wong, W. C.; Sun, W.; Cui, W.; Chen, Y.; Forray, C.; Vaysse, P. J.-J.; Branchek, T. A.; Gluchowski, C. *J. Med. Chem.* **2000**, *43*, 1699. (b) Pehourcq, F.; Thomas, J.; Jarry, C. *J. Liq. Chromatogr. Relat. Technol.* **2000**, *23*, 443.
(159) Gómez, M.; Muller, G.; Rocamora, M. *Coord. Chem. Rev.* **1999**, *193−195*, 101.
(160) For reviews on methods for preparation of oxazolines, see: Kronek, J.; Luston, J.; Bohme, F. *Chem. Listy* **1998**, *92*, 175.
(161) Michelin, R. A.; Bertani, R.; Mozzon, M.; Bombieri, G.; Benetollo, F.; Angelici, R. J. *Organometallics* **1991**, *10*, 1751.
(162) Michelin, R. A.; Bertani, R.; Mozzon, M.; Bombieri, G.; Benetollo, F.; Angelici, R. J. *J. Chem. Soc., Dalton Trans.* **1993**, 959.
(163) Michelin, R. A.; Mozzon, M.; Berin, P.; Bertani, R.; Benetollo, F.; Bombieri, G.; Angelici, R. J. *Organometallics* **1994**, *13*, 1341.
(164) Campardo, L.; Gobbo, M.; Rocchi, R.; Bertani, R.; Mozzon, M.; Michelin, R. A. *Inorg. Chim. Acta* **1996**, *245*, 269.
(165) Belucco, U.; Bertani, R.; Meneghetti, F.; Michelin, R. A.; Mozzon, M.; Bandoli, G.; Dolmella, A. *Inorg. Chim. Acta* **2000**, *300*, 912.
(166) Michelin, R. A.; Belluco, U.; Mozzon, M.; Berin, P.; Bertani, R.; Benetollo, F.; Bombieri, G.; Angelici, R. J. *Inorg. Chim. Acta* **1994**, *220*, 21.
(167) Paul, P.; Nag, K. *Inorg. Chem.* **1987**, *26*, 1586.
(168) Paul, P.; Nag, K. *J. Chem. Soc., Dalton Trans.* **1988**, 2373.
(169) Abele, E.; Lukevics, E. *Org. Prep. Proced. Int.* **2000**, *32*, 235.
(170) Abele, E.; Lukevics, E. *Heterocycles* **2000**, *53*, 2285.
(171) (a) Adams, J. P. *J. Chem. Soc., Perkin 1* **2000**, 125. (b) Adams, J. P. *Contemp. Org. Synth.* **1997**, *4*, 517.
(172) Kurbanov, S.; Sirit, A.; Sen, N. *Org. Prep. Proced. Int.* **1999**, *31*, 681.
(173) Guler, E.; Sen, N.; Sirit, A.; Kurbanov, S.; Mirzaoglu, R. *Org. Prep. Proced. Int.* **1998**, *30*, 195.
(174) Tsay, S.-C.; Patel, H. V.; Hwu, J. R. *Synlett* **1998**, 939.
(175) Kukushkin, V. Yu.; Pombeiro, A. J. L. *Coord. Chem. Rev.* **1999**, *181*, 147.
(176) Kukushkin, V. Yu.; Tudela, D.; Pombeiro, A. J. L. *Coord. Chem. Rev.* **1996**, *156*, 333.
(177) Caglioti, L.; Galli, B.; Gasparrini, F.; Natile, G. In *Congresso Interdivisionale della Societa Chimica Italiana*, 1990, San Benedetto del Tronto, Atti, p 521.
(178) Grigg, J.; Collison, D.; Garner, C. D.; Helliwell, M.; Tasker, P. A.; Thorpe, J. M. *Chem. Commun.* **1993**, 1807.
(179) Zerbib, V.; Robert, F.; Gouzerh, P. *Chem. Commun.* **1994**, 2179.
(180) Kukushkin, V. Yu.; Pakhomova, T. B.; Kukushkin, Yu. N.; Herrmann, R.; Wagner, G.; Pombeiro, A. J. L. *Inorg. Chem.* **1998**, *37*, 6511.
(181) Garnovskii, D. A.; Guedes da Silva, M. F. C.; Pakhomova, T. B.; Wagner, G.; Duarte, M. T.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Kukushkin, V. Yu. *Inorg. Chim. Acta* **2000**, *300−302*, 499.
(182) Kukushkin, V. Yu.; Pakhomova, T. B.; Bokach, N. A.; Wagner, G.; Kuznetsov, M. L.; Galanski, M.; Pombeiro, A. J. L. *Inorg. Chem.* **2000**, *39*, 216.
(183) Glocker, M. O.; Shrestha-Davadi, P. B.; Küchler-Krischun, J.; Hofmann, J.; Fischer, H.; Jochims, J. J. *Chem. Ber.* **1993**, *136*, 1859.
(184) Wagner, G.; Pombeiro, A. J. L.; Bokach, N. A.; Kukushkin, V. Yu. *J. Chem. Soc., Dalton Trans.* **1999**, 4083.
(185) Kukushkin, V. Yu.; Ilichev, I. V.; Wagner, G.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. *J. Chem. Soc., Dalton Trans.* **1999**, 3047.
(186) Kukushkin, V. Yu.; Ilichev, I. V.; Zhdanova, M. A.; Wagner, G.; Pombeiro, A. J. L. *J. Chem. Soc., Dalton Trans.* **2000**, 1567.
(187) Ferreira, C. M. P.; Guedes da Silva, M. F. C.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Kukushkin, V. Yu.; Michelin, R. A. *Inorg. Chem.* **2001**, *40*, 1134.
(188) Pavlishchuk, V. V.; Kolotilov, S. V.; Addison, A. W.; Prushan, M. J.; Butcher, R. J.; Thompson, L. K. *Inorg. Chem.* **1999**, *38*, 1759.
(189) Oshovsky, G. V.; Pinchuk, A. M. *Russ. Chem. Rev.* **2000**, *69*, 845.
(190) Raczynska, E. D.; Gawinecki, R. *Trends Org. Chem.* **1998**, *7*, 85.
(191) Liu, Y.; Zhang, J. *Huaxue Tongbao* **1996**, *11*, 1; *Chem. Abstr.* **1997**, *126*, 89091.
(192) Greenhill, J. V.; Lue, P. *Prog. Med. Chem.* **1993**, *30*, 203.
(193) Richter, P. H.; Wunderlich, I.; Schleuder, H.; Keckeis, A. *Pharmazie* **1993**, *48*, 163.
(194) Baker, J.; Kilner, M. *Coord. Chem. Rev.* **1994**, *133*, 219.
(195) Wang, H.-X.; Ding, L.; Wu, Y.-J. *Youji Huaxue* **2000**, *20*, 44; *Chem. Abstr.* **2000**, *132*, 166256.
(196) Kukushkin, Yu. N.; Aleksandrova, E. A.; Pakhomova, T. B. *Zh. Obstch. Khim.* **1994**, *64*, 151.
(197) Kukushkin, Yu. N.; Aleksandrova, E. A.; Pakhomova, T. B.; Vlasova, R. A. *Zh. Obstch. Khim.* **1994**, *64*, 705.
(198) Kukushkin, Yu. N.; Pakhomova, T. B. *Zh. Obstch. Khim.* **1995**, *65*, 330.
(199) Kukushkin, V. Yu.; Aleksandrova, E. A.; Kukushkin, Yu. N. *Zh. Obsch. Khim.* **1995**, *65*, 1937.
(200) Fairlie, D. P.; Jackson, W. G. *Inorg. Chem.* **1990**, *29*, 140.
(201) Angus, P. M.; Jackson, W. G.; Sargeson, A. M. *Inorg. Chem.* **1993**, *32*, 5285.
(202) (a) Kukushkin, V. Yu.; Ilichev, I. V.; Wagner, G.; Revenco, M. D.; Kravtsov, V. H.; Suwinska, K. *Eur. J. Inorg. Chem.* **2000**, 1315. (b) Kukushkin, Yu. N.; Krylov, V. K.; Larionova, Yu. E.; Bavina, M. V. *Zh. Obshch. Khim.* **1994**, *64*, 342.
(203) (a) Feng, S. G.; White, P. S.; Templeton, J. L. *Organometallics* **1993**, *12*, 1765. (b) Feng, S. G.; White, P. S.; Templeton, J. L. *Organometallics* **1994**, *13*, 1214.
(204) Michelin, R. A.; Mozzon, M.; Bertani, R.; Benetollo, F.; Bombieri, G.; Angelici, R. J. *Inorg. Chim. Acta* **1994**, *222*, 327.
(205) Carrondo, M. A. A. F. de C. T.; Félix, V. *Acta Crystallogr.* **1991**, *C47*, 2451 and references therein.
(206) Engelhardt, L. M.; Figgis, B. N.; Sobolev, A. N.; Reynolds, P. A. *Aust. J. Chem.* **1996**, *49*, 489.
(207) Engelhardt, L. M.; Junk, P. C.; Raston, C. L.; Skelton, B. W.; White, A. H. *J. Chem. Soc., Dalton Trans.* **1996**, 3297.
(208) Redshaw, C.; Elsegood, M. R. J. *Polyhedron* **2000**, *19*, 2657.
(209) Xiaohua, B.; Holt, E. M. *Acta Crystallogr.* **1992**, *C48*, 1655.
(210) Lee, L.; Chen, D.-J.; Lin, Y.-C.; Lo, Y.-H.; Lin, C. H.; Lee, G.-H.; Wang, Y. *Organometallics* **1997**, *16*, 4636.
(211) Kukushkin, Yu. N.; Kiseleva, N. P.; Aleksandrova, E. A. *Russ. J. Coord. Chem.* **2000**, *26*, 32.
(212) Kukushkin, Yu. N.; Kiseleva, N. P.; Zangrando, E.; Kukushkin, V. Yu. *Inorg. Chim. Acta* **1999**, *285*, 203.
(213) Rousselet, G.; Capdevielle, P.; Maumy, M. *Tetrahedron Lett.* **1993**, *34*, 6395.
(214) Spychala, J. *Tetrahedron Lett.* **1999**, *40*, 2841.
(215) Hintermaier, H.; Poschner, U. Ger. Offen. DE 4,024,259, 1992; *Chem. Abstr.* **1992**, *116*, 194315.

(216) Noda, S.; Tsuji, T. JP 07,206,827, 1995; *Chem. Abstr.* **1996**, *124*, 8817.
(217) (a) Bertani, R.; Catanese, D.; Michelin, R. A.; Mozzon, M.; Bandoli, G.; Dolmella, A. *Inorg. Chem. Commun.* **2000**, *3*, 16. (b) Michelin, R. A.; Bertani, R.; Mozzon, M.; Sassi, A.; Benetollo, F.; Bombieri, G.; Pombeiro, A. J. L. *Inorg. Chem. Commun.* **2001**, *4*, 275.
(218) Uguagliati, P.; Belluco, U.; Michelin, R. A.; Guerriero, P. *Inorg. Chim. Acta* **1984**, *81*, 61.
(219) Calligaro, L.; Michelin, R. A.; Uguagliati, P. *Inorg. Chim. Acta* **1983**, *76*, L83.
(220) Garigipati, R. S. *Tetrahedron Lett.* **1990**, *31*, 1969.
(221) Kirby, J. P.; van Duntzig, N. A.; Chang, C. K.; Nocera, D. G. *Tetrahedron Lett.* **1995**, *36*, 3477.
(222) Moss, R. A.; Ma, W.; Merrer, D. C.; Xue, S. *Tetrahedron Lett.* **1995**, 8761.
(223) Towle, M. J.; Lee, A.; Maduakor, E. C.; Swartz, C. E.; Bridges, A. J.; Littlefield, B. A. *Cancer Res.* **1993**, *53*, 2553.
(224) Singh, S.; Nicholas, K. M. *Synth. Commun.* **1997**, *27*, 4021.
(225) Forsberg, J. H.; Spaziano, V. T.; Balasubramanian, T. M.; Liu, G. K.; Kinsley, S. A.; Duckworth, C. A.; Poteruca, J. J.; Brown, P. S.; Miller, J. L. *J. Org. Chem.* **1987**, *52*, 1017.
(226) Zhou, L.; Zhang, Y. *J. Chem. Res. (S)* **1998**, 596.
(227) Zhou, L.; Zhang, Y. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2899.
(228) Li, Z. F.; Lu, P.; Zhang, Y. *Chin. Chem. Lett.* **2000**, *11*, 495.
(229) Zhou, L.; Zhang, Y. *Synth. Commun.* **1998**, *28*, 3249.
(230) Chen, J.; Chai, W.; Zhu, J.; Gao, J.; Chen, W.; Kao, T. *Synthesis* **1993**, 87.
(231) Angus, P. M.; Jackson, W. G. *Inorg. Chem.* **1996**, *35*, 7196.
(232) For recent reviews on amidrazones, see: (a) Dobosz, M.; Pitucha, M. *Ann. Univ. Mariae Curie-Sklodowska, Sect. AA: Chem.* **2000**, 54−55 and 421−436; *Chem. Abstr.* **2000**, *134*, 115870. (b) El Ashry, E. S. H.; Rashed, N.; Shobier, A. H. S. *Pharmazie* **2000**, *55*, 403.
(233) Albertin, G.; Antoniutti, S.; Bacchi, A.; Bordignon, E.; Dolcetti, P. M.; Pelizzi, G. *J. Chem. Soc., Dalton Trans.* **1997**, 4435.
(234) Albertin, G.; Antoniutti, S.; Bacchi, A.; Bergamo, M.; Bordignon, E.; Pelizzi, G. *Inorg. Chem.* **1998**, *37*, 479.
(235) Albertin, G.; Antoniutti, S.; Bordignon, E.; Pattaro, S. *J. Chem. Soc., Dalton Trans.* **1997**, 4445.
(236) Du, S.; Zhu, N.; Wu, X. *Polyhedron* **1994**, *13*, 301.
(237) Arulsamy, N.; Bohle, D. S. *J. Org. Chem.* **2000**, *65*, 1139.
(238) Judkins, B. D.; Allen, D. G.; Cook, T. A.; Evans, B.; Sardharwala, T. E. *Synth. Commun.* **1996**, *26*, 4351.
(239) Piskunova, I. P.; Eremeev, A. V.; Mishrev, A. F.; Vosekalna, I. A. *Tetrahedron* **1993**, *49*, 4671.
(240) Wagner, G.; Pombeiro, A. J. L.; Kukushkin, Yu. N.; Pakhomova, T. B.; Ryabov, A. D.; Kukushkin, V. Yu. *Inorg. Chim. Acta* **1999**, *292*, 272 and references therein.
(241) Weighardt, K.; Holzbach, W.; Hoffer, E.; Weiss, J. *Chem. Ber.* **1981**, *114*, 2700.
(242) McDonell, A. C.; Vasudevan, S. G.; O'Connor, M. J.; Wedd, A. G. *Aust. J. Chem.* **1985**, *38*, 1017.
(243) (a) Kelly, P. F.; Slawin, A. M. Z. *Chem. Commun.* **1999**, 1081. (b) Kelly, P. F.; Holmes, K. E. Personal communication, 2002.
(244) Kelly, P. F.; Slawin, A. M. Z. *Eur. J. Inorg. Chem.* **2001**, 263.
(245) (a) Garnovskii, D. A.; Kukushkin, V. Yu.; Haukka, M.; Wagner, G.; Pombeiro, A. J. L. *J. Chem. Soc., Dalton Trans.* **2001**, 560. (b) Wagner, G.; Pakhomova, T. B.; Bokach, N. A.; Fraústo da Silva, J. J. R.; Vicente, J.; Pombeiro, A. J. L.; Kukushkin, V. Yu. *Inorg. Chem.* **2001**, *40*, 1683.
(246) Lopez, J.; Santos, A.; Romero, A.; Echavarren, A. M. *J. Organomet. Chem.* **1993**, *443*, 221.
(247) Carmona, D.; Ferrer, J.; Lahoz, F. J.; Oro, L. A.; Lamata, M. P. *Organometallics* **1996**, *15*, 5175.
(248) Pearson, C.; Beauchamp, A. L. *Inorg. Chem.* **1998**, *37*, 1242.
(249) Leung, K. S.-Y.; Wong, W.-T. *J. Chem. Soc., Dalton Trans.* **1998**, 1939.
(250) Mommertz, A.; Leo, R.; Massa, W.; Dehnicke, K. *Z. Naturforsch., Teil B* **1998**, *53*, 887.
(251) Broder, C. K.; Goeta, A. E.; Howard, J. A. K.; Hughes, A. K.; Johnson, A. L.; Malget, J. M.; Wade, K. *J. Chem. Soc., Dalton Trans.* **2000**, 3526 and references therein.
(252) Batsanov, A. S.; Goeta, A. E.; Howard, J. A. K.; Hughes, A. K.; Johnson, A. L.; Wade, K. *J. Chem. Soc., Dalton Trans.* **2001**, 1210.
(253) Hughes, A. K. Personal communication, 2001.
(254) Vicente, J.; Chicote, M. T.; Beswick, M. A.; Ramirez de Arellano, M. C. *Inorg. Chem.* **1996**, *35*, 6592.
(255) Vicente, J.; Chicote, M. T.; Lagunas, M. C.; Jones, P. G. *Inorg. Chem.* **1995**, *34*, 5441.
(256) Vicente, J.; Chicote, M. T.; Fernández-Baeza, J.; Lahoz, F. *Inorg. Chem.* **1991**, *30*, 3617.
(257) Vicente, J.; Chicote, M. T.; Fernández-Baeza, J.; Fernández-Baeza, A.; Jones, P. G. *J. Am. Chem. Soc.* **1993**, *115*, 794.
(258) Vicente, J.; Chicote, M. T.; Fernández-Baeza, J.; Fernández-Baeza, A. *New J. Chem.* **1994**, *18*, 263.
(259) Camuzat-Dedenis, B.; Provot, O.; Moskowitz, H.; Mayrargue, J. *Synthesis* **1999**, 1558 [Erratrum: Camuzat-Dedenis, B.; Provot, O.; Moskowitz, H.; Mayrargue, J. *Synthesis* **1999**, 2000].
(260) Hamzaoui, M.; Provot, O.; Camuzat-Dedenis, B.; Moskowitz, H.; Mayrargue, J.; Ciceron, L.; Gay, F. *Tetrahedron Lett.* **1998**, *39*, 4029.
(261) Basato, M.; Detomi, N.; Meneghetti, M.; Veronese, A. C.; Callegari, R. *J. Mol. Catal. A: Chem.* **1999**, *139*, 121.
(262) Veronese, A. C.; Callegari, R.; Morelli, C. F.; Basato, M. *J. Mol. Catal. A: Chem.* **1999**, *142*, 373.
(263) Basato, M.; Detomi, N.; Meneghetti, M.; Valle, G.; Veronese, A. C. *Inorg. Chim. Acta* **1999**, *285*, 18.
(264) Basato, M.; Vettori, U.; Veronese, A. C.; Grassi, A.; Valle, G. *Inorg. Chem.* **1998**, *37*, 6737.
(265) (a) Veronese, A. C.; Morelli, C. F.; Callegari, R.; Basato, M. *J. Mol. Catal. A: Chem.* **1997**, *124*, 99. (b) Basato, M.; Favero, G.; Veronese, A. C.; Grassi, A. *Inorg. Chem.* **1993**, *32*, 763.
(266) De Risi, C.; Pollini, G.; Veronese, A. C.; Bertolasi, V. *Tetrahedron Lett.* **1999**, *40*, 6995.
(267) Veronese, A. C.; Callegari, R.; Basato, M.; Valle, G. *J. Chem. Soc., Perkin Trans. 1* **1994**, 1779.
(268) Veronese, A. C.; Morelli, C. F. *Tetrahedron Lett.* **1998**, *39*, 3853.
(269) Morelli, C. F.; Manferdini, M.; Veronese, A. C. *Tetrahedron* **1999**, *55*, 10803.
(270) Takaya, H.; Naota, T.; Murahashi, S.-I. *J. Am. Chem. Soc.* **1998**, *120*, 4244.
(271) Murahashi, S.-I.; Naota, T.; Taki, H.; Mizuno, M.; Takaya, H.; Komiya, S.; Mizuho, Y.; Oyasato, N.; Hiraoka, M.; Hirano, M.; Fukuoka, A. *J. Am. Chem. Soc.* **1995**, *117*, 12436.
(272) Naota, T.; Tannna, A.; Murahashi, S.-I. *J. Am. Chem. Soc.* **2000**, *122*, 2960.
(273) Veronese, A. C.; Callegari, R.; Morelli, C. F. *Tetrahedron* **1995**, *51*, 12277.
(274) Stack, J. G.; Doney, J. J.; Bergman, R. G.; Heathcock, C. H. *Organometallics* **1990**, *9*, 453.
(275) Young, C. G.; Phillip, C. C.; White, P. S.; Templeton, J. L. *Inorg. Chem.* **1995**, *34*, 6412.
(276) Duchateau, R.; Williams, A. J.; Gambarotta, S.; Chiang, M. Y. *Inorg. Chem.* **1991**, *30*, 4863.
(277) Schollhammer, P.; Pichon, M.; Muir, K. W.; Pétillon, F. Y.; Pichon, R.; Talarmin, J. *Eur. J. Inorg. Chem.* **1999**, 221.
(278) (a) Kopp, M. R.; Neumüller, B. *Z. Anorg. Allg. Chem.* **1999**, *625*, 739. (b) Kopp, M. R.; Neumüller, B. *Z. Anorg. Allg. Chem.* **1999**, *625*, 1246. (c) Kopp, M. R.; Kraeuter, T.; Dashti-Mommertz, A.; Neumüller, B. *Organometallics* **1998**, *17*, 4226.
(279) Neumüller, B. Private communication, 2001.
(280) (a) Armstrong, D. R.; Henderson, K. W.; MacGregor, M.; Mulvey, R. E.; Ross, M. J.; Clegg, W.; O'Neil, P. A. *J. Organomet. Chem.* **1995**, *486*, 79. (b) Redina, T. N.; Zharov, A. A.; Yarosh, A. A.; Ponomarenko, V. A. *Izv. Akad. Nauk, Ser. Khim.* **1995**, 1814. (c) Zhang, W. M.; Zhang, L.; Liao, S. J.; Xu, Y.; Yu, D. R. *Chin. Chem. Lett.* **1995**, *6*, 839; *Chem. Abstr.* **1995**, *124*, 117246. (d) Morita, S. JP 10 237,130, 1998; *Chem. Abstr.* **1998**, *129*, 245662.
(281) Fulton, J. R.; Hanna, T. A.; Bergman, R. G. *Organometallics* **2000**, *19*, 602.
(282) Legzdins, P.; Lumb, S. A.; Young, V. G., Jr. *Organometallics* **1998**, *17*, 854.
(283) Legzdins, P.; Lumb, S. A. *Organometallics* **1997**, *16*, 1825.
(284) Ang, H.-G.; Koh, C.-H.; Koh, L.-L.; Kwik, W.-L.; Leong, W.-K.; Leong, W.-Y. *J. Chem. Soc., Dalton Trans.* **1993**, 847.
(285) Cotton, F. A.; Daniels, L. M.; Murillo, C. A.; Wang, X. *Polyhedron* **1998**, *17*, 2781.
(286) Cotton, F. A.; Kühn, F. E. *J. Am. Chem. Soc.* **1996**, *118*, 5826.
(287) Pombeiro, A. J. L.; Hughes, D. L.; Richards, R. L. *Chem. Commun.* **1988**, 1052.
(288) Fraústo da Silva, J. J. R.; Guedes da Silva, M. F. C.; Henderson, R. A.; Pombeiro, A. J. L.; Richards, R. L. *J. Organomet. Chem.* **1993**, *461*, 141.
(289) Guedes da Silva, M. F. C.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. *Inorg. Chem.* **2001**, in press.
(290) Seino, H.; Tanabe, Y.; Ishii, Y.; Hidai, M. *Inorg. Chim. Acta* **1998**, *280*, 163.
(291) Tanabe, Y.; Seino, H.; Ishii, Y.; Hidai, M. *J. Am. Chem. Soc.* **2000**, *122*, 1690.
(292) Field, L. D.; Jones, N. G.; Turner, P. *Organometallics* **1998**, *17*, 2394.
(293) For recent reviews, see: Pombeiro, A. J. L.; Guedes da Silva, M. F. C. *J. Organomet. Chem.* **2001**, *617−618*, 65 and ref 8 in this article.
(294) Guedes da Silva, M. F. C.; Lemos, M. A. N. D. A.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Pellinghelli, M. A.; Tiripicchio, A. *J. Chem. Soc., Dalton Trans.* **2000**, 373.
(295) Guedes da Silva, M. F. C.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Pellinghelli, M. A.; Tiripicchio, A. *J. Chem. Soc., Dalton Trans.* **1996**, 2763.
(296) Henderson, R. A.; Pombeiro, A. J. L.; Richards, R. L.; Fraústo da Silva, J. J. R.; Wang, Y. *J. Chem. Soc., Dalton Trans.* **1995**, 1193.

(297) Wang, Y.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Pellinghelli, M. A.; Tiripichio, A.; Henderson, R. A.; Richards, R. L. *J. Chem. Soc., Dalton Trans.* **1995**, 1183.
(298) Almeida, S. S. P. R.; Pombeiro, A. J. L. *Organometallics* **1997**, *16*, 4469.
(299) Carvalho, M. F. N. N.; Almeida, S. S. P. R.; Pombeiro, A. J. L.; Henderson, R. A. *Organometallics* **1997**, *16*, 5441.
(300) Kuznetsov, M.; Pombeiro, A. J. L.; Dement'ev, A. I. *J. Chem. Soc., Dalton Trans.* **2000**, 4413.
(301) Henderson, R. A.; Pombeiro, A. J. L.; Richards, R. L.; Wang, Y. *J. Organomet.Chem.* **1993**, *447*, C11.
(302) Richards, R. L. *Coord. Chem. Rev.* **1996**, *154*, 83.
(303) Hidai, M.; Mizobe, Y. *Chem. Rev.* **1995**, *95*, 1115.
(304) Eady, R. R.; Leigh, G. J. *J. Chem. Soc., Dalton Trans.* **1994**, 2739.
(305) Bazhenova, T. A.; Shilov, A. E. *Coord. Chem. Rev.* **1995**, *144*, 69.
(306) Fryzuk, M. D.; Johnson, S. A. *Coord. Chem. Rev.* **2000**, *200−202*, 379.
(307) Guedes da Silva, M. F. C.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. *J. Chem. Soc., Dalton Trans.* **1994**, 3299.
(308) Guedes da Silva, M. F. C.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Amatore, C.; Verpeaux, J.-N. *Organometallics* **1994**, *13*, 3943.
(309) Amatore, C.; Fraústo da Silva, J. J. R.; Guedes da Silva, M. F. C.; Pombeiro, A. J. L.; Verpeaux, J.-N. *Chem. Commun.* **1992**, 1289.
(310) Esjornson, D.; Bakir, M.; Fanwick, P. E.; Jones, K. S.; Walton, R. A. *Inorg. Chem.* **1990**, *29*, 2055.
(311) Shin, J. H.; Savage, W.; Murphy, V. J.; Bonanno, J. B.; Churchill, D. G.; Parkin, G. *J. Chem. Soc., Dalton Trans.* **2001**, 1732 (*corrigenda*: *J. Chem. Soc., Dalton Trans.* **2001**, 2539).
(312) Thomas, S.; Young, C. G.; Tieknik, E. R. T. *Organometallics* **1998**, *17*, 182.
(313) Thomas, S.; Lim, P. J.; Gable, R. W.; Young, C. G. *Inorg. Chem.* **1998**, *37*, 590.
(314) Pombeiro, A. J. L.; Richards, R. L. *Coord. Chem. Rev.* **1990**, *104*, 13.
(315) Pombeiro, A. J. L.; Richards, R. L. In *Trends in Organometallic Chemistry*, Council of Scientific Research Integration, Research Trends, Trivandrum, India, 1994, *1*, 263.
(316) Feng, S. G.; Templeton, J. L. *Organometallics* **1992**, *11*, 1295.
(317) Feng, S. G.; White, P. S.; Templeton, J. L. *J. Am. Chem. Soc.* **1994**, *116*, 8613.
(318) Yeh, W.-Y.; Ting, C.-S.; Peng, S.-M.; Lee, G.-H. *Organometallics* **1995**, *14*, 1417.
(319) Huisgen, R. *Adventure Playground of Mechanisms and Novel Reactions*; American Chemical Society: Washington, DC, 1994; p 279.
(320) Mloston, G.; Langhals, E.; Huisgen, R. *Tetrahedron Lett.* **1989**, *30*, 5373 and references therein.
(321) For selected works on cycloaddition to nitrilium salts, see: (a) Moustafa, A. H.; Wirschun, W.; Freyhardt, C. C.; Johims, J. C.; Abu-El-Halawa, R. *J. Prakt. Chem.* **1997**, *339*, 515. (b) Al-Talib, M.; Jochims, J. C.; Hamed, A.; Wang, Q.; Ismail, A. E. *Synthesis* **1992**, 697. (c) Abu-El-Halawa, R.; Shrestha-Dawadi, P. B.; Jochims, J. C. *Chem. Ber.* **1993**, *126*, 109.
(322) Jacobsen, H.; Berke, H.; Doering, S.; Kehr, G.; Erker, G.; Froehlich, R.; Meyer, O. *Organometallics* **1999**, *18*, 1724.
(323) Hoti, R.; Mihalic, Z.; Vancik, H. *Croat. Chem. Acta* **1995**, *68*, 359.
(324) (a) Geisenberger, J.; Erbe, J.; Heidrich, J.; Nagel, U.; Beck, W. *Z. Naturforsch.* **1987**, *B42*, 55 and references therein. (b) Beck, W.; Fehlhammer, W. P. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 169.
(325) Hall, J. H.; De La Vega, R. L.; Purcell, W. L. *Inorg. Chim. Acta* **1985**, *102*, 157 and references therein.
(326) Guilard, R.; Perrot, I.; Tabard, A.; Richard, P.; Lecomte, C.; Liu, Y. H.; Kadish, K. M. *J. Am. Chem. Soc.* **1991**, *30*, 27.
(327) Guilard, R.; Jagerovic, N.; Tabard, A.; Richard, P.; Courthaudon, L.; Louati, A.; Lecomte, C.; Kadish, K. M. *J. Am. Chem. Soc.* **1991**, *30*, 16.
(328) Becker, T. M.; Krause-Bauer, J. A.; Homrighausen, C. L.; Orchin, M. *Polyhedron* **1999**, *18*, 2563.
(329) Paul, P.; Chakladar, S.; Nag, K. *Inorg. Chim. Acta* **1990**, *170*, 27.
(330) Curran, D. P.; Hadida, S.; Kim, S.-Y. *Tetrahedron* **1999**, *55*, 8997.
(331) Bhandari, S.; Frost, C. G.; Hague, C. E.; Mahon, M. F.; Molloy, K. C. *J. Chem. Soc., Dalton Trans.* **2000**, 663.
(332) Bhandari, S.; Mahon, M. F.; Molloy, K. C.; Palmer, J. S.; Sayers, S. F. *J. Chem. Soc., Dalton Trans.* **2000**, 1053.
(333) Bethel, P. A.; Hill, M. S.; Mahon, M. F.; Molloy, K. C. *J. Chem. Soc., Perkin 1* **1999**, 3507.
(334) Bhandari, S.; Mahon, M. F.; Molloy, K. C. *J. Chem. Soc., Dalton Trans.* **1999**, 1951.
(335) Bhandari, S.; Mahon, M. F.; McGinley, J. G.; Molloy, K. C.; Roper, C. E. E. *J. Chem. Soc., Dalton Trans.* **1998**, 3425.
(336) Hill, M.; Mahon, M. F.; Molloy, K. C. *J. Chem. Soc., Dalton Trans.* **1996**, 1857.
(337) Goodger, A.; Hill, M.; Mahon, M. F.; McGinley, J.; Molloy, K. C. *J. Chem. Soc., Dalton Trans.* **1996**, 847.
(338) Hill, M.; Mahon, M. F.; McGinley, J.; Molloy, K. C. *J. Chem. Soc., Dalton Trans.* **1996**, 835.
(339) Blunden, S. J.; Mahon, M. F.; Molloy, K. C.; Waterfield, P. C. *J. Chem. Soc., Dalton Trans.* **1994**, 2135.
(340) McMurray, J. S.; Khabashesku, O.; Birtwistle, J. S.; Wang, W. *Tetrahedron Lett.* **2000**, *41*, 6555.
(341) Bovy, P. R.; Reitz, D. B.; Collins, J. T.; Chamberlain, T. S.; Olins, J. M.; Corpus, V. M.; McMahon, E. G.; Palomo, M. A.; Koepke, J. P.; Smits, G. J.; McGrow, D. E.; Gaw, J. F. *J. Med. Chem.* **1993**, *36*, 101.
(342) Itoh, F.; Yoshioku, Y.; Yukishigi, K.; Yoshida, S.; Wazima, M.; Ootsu, K.; Akimoto, H. *Chem. Pharm. Bull.* **1996**, *44*, 1498.
(343) Itoh, F.; Yukishige, K.; Wajima, M.; Ootsu, K.; Akimoto, H. *Chem. Pharm. Bull.* **1995**, *43*, 230.
(344) Gyoung, Y. S.; Shim, J.-G.; Yamamoto, Y. *Tetrahedron Lett.* **2000**, *41*, 4193.
(345) Paul, P.; Nag, K. *Inorg. Chem.* **1987**, *26*, 2969 and references therein.
(346) Hay, R. W.; McLaren, F. M. *Transition Met. Chem.* **1999**, *24*, 398.
(347) (a) Quast, H.; Hergenroether, T. *Liebigs Ann. Chem.* **1992**, 581. (c) Amer, M. I. K.; Booth, B. L. *J. Chem. Res., Synop.* **1993**, 4.
(348) Wehlan, M.; Thiel, R.; Fuchs, J.; Beck, W.; Fehlhammer, W. P. *J. Organomet. Chem.* **2000**, *613*, 159.
(349) Kim, Y.-J.; Kwak, Y.-S.; Lee, S.-W. *J. Organomet. Chem.* **2000**, *603*, 152.
(350) Wagner, G.; Pombeiro, A. J. L.; Kukushkin, V. Yu. *J. Am. Chem. Soc.* **2000**, *122*, 3106 and references therein.
(351) Hitzler, M. G.; Freyhardt, C. C.; Jochims, J. C. *Chem. Ber.* **1996**, *338*, 243.
(352) Wagner, G.; Haukka, M.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L.; Kukushkin, V. Yu. *Inorg. Chem.* **2001**, *40*, 264.
(353) Carney, M. J.; Walsh, P. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1990**, *112*, 6426.
(354) Carney, M. J.; Walsh, P. J.; Hollander, F. J.; Bergman, R. G. *Organometallics* **1992**, *11*, 761.
(355) Doxsee, K. M.; Farahi, J. B. *Chem. Commun.* **1990**, 1542.
(356) Doxsee, K. M.; Farahi, J. B.; Hope, H. *J. Am. Chem. Soc.* **1991**, *113*, 8889.
(357) Avarvari, N.; Le Floch, P.; Ricard, L.; Mathey, F. *Organometallics* **1997**, *16*, 4089.
(358) For personal review see: Doxsee, K. M.; Farahi, J. B.; Mouser, J. K. M. *Synlett* **1992**, 13.
(359) Doxsee, K. M.; Garner, L. C.; Juliette, J. J. J.; Mouser, J. K. M.; Weakly, T. J. R.; Hope, H. *Tetrahedron* **1995**, *51*, 4321.
(360) Doxsee, K. M.; Mouser, J. K. M. *Organometallics* **1990**, *9*, 3012.
(361) Schneider, J. L.; Young, V. G.; Tolman, W. B. *Inorg. Chem.* **2001**, *40*, 165.
(362) Schollhammer, P.; Cabon, N.; Pétillon, F. Y.; Talarmin, J.; Muir, K. W. *Chem. Commun.* **2000**, 2137.
(363) (a) Hiller, A. C.; Fox, T.; Schmalle, H.; Berke, H. *34th International Conference on Coordination Chemistry*, Edinburgh, Scotland, July 9−14th, 2000, Book of Abstracts, P0383. (b) Hiller, A. C. Personal communication, 2000.
(364) Gibson, V. C.; Redshaw, C.; White, A. J. P.; Williams, D. J. *Angew. Chem., Int. Ed.* **1999**, *38*, 961.
(365) Kukushkin, Yu. N.; Larionova, Yu. E. *Zh. Obshch. Khim.* **1994**, *64*, 1409.
(366) Naota, T.; Tannna, A.; Murahashi, S.-I. *Chem. Commun.* **2001**, 63.
(367) Murahashi, S.-I.; Take, K.; Naota, T.; Takaya, H. *Synlett* **2000**, *7*, 1016.
(368) Murahashi, S.-I.; Naota, T.; Taki, H.; Mizuno, M.; Takaya, H.; Komiya, S.; Mizuho, Y.; Oyasato, M.; Hiraoka, M.; Hirano, M.; Fukuoka, A. *J. Am. Chem. Soc.* **1995**, *117*, 12436.
(369) Kuwano, R.; Miyazaki, H.; Ito, Y. *J. Organomet. Chem.* **2000**, *603*, 18.
(370) Lever, A. B. P.; Dodsworth, E. S. In *Inorganic Electronic Structure and Spectroscopy*; Solomon, E. I., Lever, A. B. P., Eds.; Wiley: New York, 1999; Vol. 2 and references therein.
(371) Pombeiro, A. J. L. *New J. Chem.* **1997**, *21*, 649 and references therein.
(372) Guedes da Silva, M. F. C. G.; Martins, L. M. D. R. S.; Fraústo da Silva, J. J. R.; Pombeiro, A. J. L. *Collect. Czech. Chem. Commun.* **2001**, *66*, 139.

CR0103266