1 Introduction

Since its discovery in 1772 by Joseph Priestley, nitrous oxide has had a remarkable career. First, it became a popular recreational drug among the British upper class. In the second part of the 19th century, N₂O was employed as an anesthetic by dentists. This application is less common today, but in some countries, N₂O is given as a pain relief during childbirth. Very preliminary results indicate that N₂O could be used as a drug for patients with treatment-resistant depression. More technical applications include its utilization as a whipping agent for cream or as a fuel additive for rockets and motors. But there is also a ‘dark side’ of N₂O, and that is its environmental impact. In fact, N₂O has been identified as the most potent ozone-depleting substance emitted in the 21st century. In addition, N₂O is a very effective greenhouse gas. The concentration of N₂O in the atmosphere is increasing, and human activities contribute significantly to N₂O emissions. The extensive use of fertilizers fosters the formation of N₂O during enzymatic nitrification and denitrification. Furthermore, there are industrial processes in which N₂O is produced as side product, and part of this N₂O is still released in the atmosphere.

For a synthetic chemist, N₂O is of interests because it is a very strong oxidant from a thermodynamic point of view. Oxidation reactions typically result in the release of dinitrogen, which is an environmentally benign side product. However, reactions with N₂O are hampered by the highly inert character of this gas. The utilization of high pressure and temperature in combination with heterogeneous catalysts allows performing oxidation reactions with N₂O. These kinds of reactions have been summarized before, and they are not discussed in this overview. Instead, the focus will be on reactions which are carried out in homogeneous solution under (relatively) mild conditions. First, the utilization of N₂O as an oxidant is discussed. Due to the low intrinsic reactivity of N₂O, selective oxidation reactions of highly reactive compounds are possible. Furthermore, it is shown that transition metal complexes can be used to catalyze oxidation reactions, in some cases with high turnover numbers. In the final part of this overview, the utilization of N₂O as a building block for more complex molecules is discussed. It is shown that N₂O can be used as an N-atom donor for the synthesis of interesting organic molecules such as triazenes and azo dyes.

2 N₂O as O-atom donor

Chemical reactions with N₂O typically proceed via oxygen atom transfer and release of N₂. Due to the very inert character of N₂O, only highly reactive compounds are able to react with N₂O under mild conditions. For plain organic compounds such as olefins, on the other hand, rather harsh conditions are required. For example, it is possible to perform a solution-based oxidation of cyclohexene and cyclopentene to the corresponding cyclic ketones, but temperatures above 200 °C and elevated pressures (>25 bar) are needed to achieve good conversions.

The low intrinsic reactivity of N₂O can be advantageous because it allows performing very selective oxidation reactions,
Selective O-atom transfer reactions with N₂O have been used in particular in the context of synthetic inorganic chemistry. Low valent silicon compounds are suited substrates. For example, N₂O has been used to oxidize disilenes (Scheme 1a) [13], silanimines, [14] silaethenes, [15] silylenes (Scheme 1b) [16] and carbene-stabilized Si(0) compounds. [17] It is worth noting that a metallosilylene [18] and an osmium silylene complex [19] were also found to react with N₂O. Recently, it was shown that low-valent germanium compounds can be oxidized with N₂O as well. [20] A β-diketiminato germanium(II) hydride, for example, was converted into a hydroxide compound (Scheme 10b) [20b] and donor-stabilized germynes were oxidized to give germanones. [16a,20d,20e] Other main group compounds which react with N₂O under mild conditions are basic phosphines, [21,22] methylenetriphenylphosphorane (PPh₃CH₂), [23] sodium sulphite, [24] and boranes. [25] However, these reactions are less interesting from a synthetic point of view.

Reaction of transition metal complexes with N₂O are hampered by the fact that N₂O is a very poor ligand. [10] Accordingly, there are very few well-characterized LₙM(N₂O) complexes described in the literature. [26–28] A first example was reported by Armor and Taube in 1969. [26] They showed that N₂O can displace the water ligand in [Ru(NH₃)₅(OH₂)]⁺ to give the adduct [Ru(NH₃)₅(N₂O)]⁺ in a reversible fashion. Despite this early success, it was not until recently that a high-resolution crystallographic analysis of an N₂O vanadium complex was reported (Scheme 2). [28,29] As in the case of [Ru(NH₃)₅(N₂O)]⁺, the coordination of N₂O is weak and ligand release is triggered by applying a vacuum. The intermediate formation of an osmium–N₂O complex was proposed for the reaction of (PNP)OsH₃ (PNP = N(SiMe₂CH₂P₃Bu₂)) with N₂O, which ultimately leads to the formation of a dinitrogen complex and water (hydrogenation of N₂O). [30]

Even though the coordination of intact N₂O to a metal complex is a rarely observed phenomenon, there are numerous reports about transition metal complexes which react with N₂O in a stoichiometric fashion. [10] In the majority of these cases, N₂O acts as oxygen atom donor. Selected examples are summarized below.

Early studies by Bottomley et al. focused on cyclopentadienyl titanium complexes. The reaction of the Ti[η] complex (Cp₂TiCl)₂ (Cp = η⁵-C₅H₅) with N₂O was shown to give (Cp₂TiCl)₂O, whereas the Ti[η] complex Cp₂Ti gave the dinuclear complex (Cp₂Ti)₂O (Scheme 3a). [31,32] Subsequently, other cyclopentadienyl complexes of the early transition metals were oxidized with N₂O. The reaction of Cp₂Cr gave the tetramer (CpCrO)₄, which features...
a heterocubane structure (Scheme 3b). A similar reaction was observed for the pentamethylcyclopentadienyl complex Cp₂*Cr. Oxygen atom transfer was also demonstrated for cyclopentadienyl complexes of vanadium, tantalum, zirconium, and hafnium.

Oxygen atom transfer reactions are not restricted to complexes with cyclopentadienyl co-ligands. The Mindiola group has shown that vanadium⁹ and titanium⁶⁰ alkyl complexes can be oxidized with N₂O to give complexes with terminal oxo ligands. A representative example is depicted in Scheme 3c. L₃M(O) complexes were also obtained by reaction of N₂O with a titanium tellurido complex,⁴¹ with a niobium hydride complex,⁴² or with the V(III) complex V[Me₃SiNCH₂CH₂N].⁴³

A detailed kinetic study of the O-atom transfer reaction from N₂O to the V(III) complex V[N(bu)(3,5-C₆H₃Me₂)]₂ revealed that the reaction at room temperature is second order in concentration of the vanadium complex and first order in concentration of N₂O.⁴⁴ At low temperature, however, an overall second order was observed. These data suggest that the oxygen atom transfer proceeds via a bimetallic L₂V(N₂O)VL₃ complex with a bridging N₂O ligand.

The transfer of multiple oxygen atoms was observed for the reaction of Ar''CrCrAr' (Ar' = C₆H₆, 2,6-(C₆H₅)₂Pr₂) with an excess of N₂O (Scheme 3d). This reaction is good evidence for the utility of N₂O as a mild and selective oxidant because the product, Ar''Cr(μ-O)₂Cr(μ-O)Ar', is extremely air and moisture sensitive. Accordingly, no defined product could be isolated when O₂ was used instead of N₂O.

Reactions of N₂O with complexes of the late transition metal nickel were examined by the group of Hillhouse. They observed that complexes of the general formula L₃NiR₂ (L = neutral P- or N-donor; R = alkyl, aryl) give alkoxide or aryloxide complexes of the formula L₂Ni(OR).⁴⁶ For example, the metallocyclopentane (bipy)Ni(C₅H₅O) upon reaction with N₂O (Scheme 3e). Chemically induced demetallation of the latter results in the formation of 1-butanol, tetrahydrofuran or δ-valerolactone, respectively.⁴⁶b,d It should be noted that the oxametallacycle cannot be prepared with O₂, because cyclobutane is formed instead. More recently, it was shown that a Ni-carbene complex is able to react with N₂O to give an oxametallacyclopropane.⁴⁷ The oxidation of a Ni(0) carbonyl complex with N₂O was reported to give a complex with a chelating alkoxoy ligand.⁴⁸

As mentioned above, some ruthenium complexes are able to bind intact N₂O in a reversible fashion.⁴⁹,⁵⁰ However, oxygen atom transfer has also been observed. Caulton et al. have shown that the Ru(IV) nitride complex (PNP)RuN is converted into the corresponding nitroso complex [PNP]RuNO upon exposure to N₂O.⁵¹ Insertion of oxygen into a Ru-hydride bond was observed by Kaplan and Bergman.⁵² They found that RuH₂(DMPE) [DMPE = Me₂PCH₂CH₂PMe₂] reacts with N₂O in a step-wise fashion to give first the hydroxo complex RuH(OH)(DMPE) and then the dihydroxo complex Ru(OH)₂(DMPE). We have examined the reaction of dinuclear organometallic Ru complexes with N₂O.⁵³ When a solution of (p-cymene)Ru(μ-Cl)₃Ru(IMes)(C₅H₅)Cl (IMes = 1,3-dimesitylimidazol-2-ylidine) was subjected to an atmosphere of N₂O, we observed the formation of a mixed-valence Ru(n)–Ru(n) complex with a chelating alkoxoy ligand (Scheme 3f).

The dinitrogen complex (p-cymene)Ru(μ-Cl)₃Ru(IMes)(N₂)Cl was identified as a reaction intermediate, providing indirect evidence that N₂ is released during the reaction. The Chang group has reported that a complex of the lighter homologue iron can also activate N₂O.⁵⁴ The reaction of a four-coordinate Fe(n) complex with N₂O was shown to give an iron hydroxo complex, presumably via an intermediate Fe(ν)-oxo complex.

Bleeke and Behm have examined the reaction of an iridium metallacycle with N₂O. As initial product, an iridacyclohexadiene complex was observed. The latter isomerizes slowly at room temperature (Scheme 3g).

The oxidation of low-valent lanthanide⁵⁴ and actinide⁵⁵ complexes with N₂O is a convenient method for the preparation of complexes with bridging or terminal oxo ligands. The μ-oxo complex (Cp*₂Sm)(μ-O) (Cp* = η⁵-C₅H₅Me₂), for example, can be obtained by reaction of (Cp*₂Sm)(THF)₃ with N₂O (Scheme 3h).⁵⁴ The Meyer group has shown that U(n) tris(aryloxide) complexes react with N₂O to give terminal U(n) oxo complexes (Scheme 3i).⁵⁵c

### 3 Metal-catalyzed reactions with N₂O

The fact that transition metal complexes are able to activate N₂O suggests that metal-catalyzed oxidation reactions with N₂O can be performed. A generic catalytic cycle is shown in Scheme 4. Reactions of this kind have been realized with heterogeneous catalysts⁵⁶ or in the gas phase,⁵⁶ but these systems are not discussed here. This section summarizes catalytic oxidation reactions with N₂O which are performed in homogeneous solution.

Initial attempts to use N₂O as an oxidant in metal-catalyzed reactions have focused on a rather ‘easy’ reaction: the oxidation of phosphines to phosphine oxides. It was shown that the hydride complex CoH(N₃)(PPh₃)₃ is able to catalyze the oxidation of PPh₃ to give POPh₃ (Scheme 5a).⁵⁷ The reaction was performed under ambient conditions and at least six turnovers were achieved. These findings are in line with observations by Pratt et al., who showed that Co(n) complexes are able to reduce N₂O to N₂.⁵⁸ The cobalt-catalyzed oxidation of PPh₃ was recently re-investigated by Beloglazkina et al. using different Co complexes and higher turnover numbers were obtained (≤73).⁵⁹

![Scheme 4](Image)

**Scheme 4** Metal-catalyzed oxidation reactions with N₂O.
Another competent catalyst system for the conversion of phosphines to phosphine oxides by N₂O is a mixture of NiCl₂(DPPP) (DPPP = 1,3-bis(diphenylphosphino)propane) and n-BuLi (Scheme 5b).

The active catalyst is assumed to be a low-valent Ni complex which is formed upon reduction of NiCl₂(DPPP) with n-BuLi.

The oxidation of different organic substrates in the presence of Ru–porphyrin complexes was investigated by Yamada et al. First, they were able to show that the Ru(Ⅵ) complex Ru(TMP)(O)₂ (TMP = tetramesitylporphyrinato) is a catalyst for the epoxidation of olefins, including structurally complex substrates such as steroids (Scheme 6a). The reactions were performed under rather forcing conditions (140 °C, 10 bar) and aromatic solvents, in particular fluoro- and chlorobenzene, gave the best results. Soon after, the same group reported that Ru(TMP)(O)₂ can be used as a catalyst for the oxidation of secondary and primary benzylic alcohols (Scheme 6b), as well as for the oxidation of 9,10-dihydroanthracene derivatives (Scheme 6c). Again, rather harsh reactions conditions were applied. In this context, a study by Groves and Roman is worth mentioning. They have shown that the Ru(Ⅱ) complex Ru(TMP)(THF)₂ can be oxidized with N₂O to give Ru(TMP)(O)(THF) or Ru(TMP)(O)₂, depending on the reaction conditions.

The utilization of polyoxometalates as catalysts for N₂O-based oxidation reactions was investigated by the group of Neumann. The vanadium-containing polyoxometalate [PV₂Mo₁₀O₄₀]⁵⁻ was shown to catalyze the oxidation of alcohols (Scheme 7a) and alkylarenes (Scheme 7b). The reactions were performed at ambient pressure and a temperature of 150 °C. The combination of H₅PV₂Mo₁₀O₄₀ with a Pd complex featuring a phenanthroline ligand decorated with a crown ether allowed to perform Wacker-type oxidation reactions of olefins with N₂O (Scheme 7c).

Again, an elevated temperature of 150 °C was employed for these reactions. More recently, the Neumann group has shown that H₄PSbMo₁₁O₄₀, H₄PVMo₁₁O₄₀ or H₃PMo₁₂O₄₀ can be used for the oxidation of dihydrophenanthrene to phenanthrene (1 bar N₂O, 110 °C). However, better results were obtained when O₂ was used instead of N₂O.

The Sita group has investigated oxygen atom transfer reactions mediated by organometallic Mo complexes. They were able to demonstrate the catalytic oxidation of an isocyanide to an isocyanate (Scheme 8). During the reaction, the catalysts cycles between Mo(Ⅱ) and Mo(Ⅳ). At present, the reaction is less interesting from a synthetic point of view because low turnover numbers and frequencies (1 per week) were achieved. Still, the reaction is quite remarkable because catalysis occurs under ambient conditions (1 bar N₂O, 25 °C).

We have recently reported that N₂O can be used as an oxidant for the metal-catalyzed homo-coupling of Grignard...
reagents (Scheme 9). Simple metal salts such as Fe(acac)₃, CoCl₂, or Li₂CuCl₄ were employed as catalyst precursors. For most reactions, catalyst concentrations of 0.1–1.0 mol% were sufficient to obtain good yields. Coupling reactions of some arylmagnesium compounds could be performed with less than 0.01 mol% under very mild conditions. The corresponding turnover numbers of up to 9400 are unprecedented for solution-based oxidation reactions with N₂O. Compared to alternative procedures which utilize O₂ as oxidant, our method offers some important advantages. First, it is possible to use lower amounts of catalyst since N₂O is less prone to undergo metal-independent side reactions. Second, sterically demanding aryl Grignard reagents as well as highly reactive alkyllithium reagents can be used as substrates. Another noteworthy feature is the fact that aryl-alkyl and alkenyl-alkyl cross-coupling reactions can be achieved with good selectivity. All these characteristics should make the method attractive for applications in organic synthesis.

Interestingly, it is also possible to perform metal-catalyzed reductions in the presence of N₂O. A system of this kind was recently described in a communication by Higuchi. They were able to show that alkynes can be reductively dimerized in the presence of metalloporphyrin catalysts using simultaneously the reductant NaNH₂ and the oxidant N₂O (Scheme 10). The best results were obtained with the iron tetraphenylporphyrinato complex Fe(TPP)Cl. For the dimerization of 2,3-dimethyl-2,3-diphenylbutane, a turnover number of 1380 was obtained.

The following mechanism is proposed: reduction of Fe(TPP)Cl by NaNH₂ in the presence of the alkene gives the dimerization product along with a highly reduced [Fe(TPP)]⁻ complex. The latter is oxidized by N₂O to regenerate an Fe(III) porphyrin complex, and close the catalytic cycle. This proposition is supported by the fact that a reduced form of myoglobin containing Fe(I) can be oxidized by N₂O.

### 4 N₂O as N-atom donor

This section describes reactions with N₂O in which nitrogen atoms are incorporated into the final product. A first reaction of this kind was reported in 1892 by Wislicenus. He showed that sodium azide is obtained upon exposure of NaNH₂ to N₂O at elevated temperatures (Scheme 11a). KNH₂ and Zn(NH₂)₂ were found to react in a similar fashion. The 'Wislicenus reaction' is nowadays used by industry to produce sodium azide on a larger scale. The mechanism of the reaction has been investigated by Clusius et al. Using ¹⁵N-labelled nitrous oxide (N₁⁵NO and ¹⁵NNO) can be prepared by decomposition of either NH₄¹⁵NO₃ or ¹⁵NH₄NO₃, they were able to show that two reaction pathways are operational. An attack of the amide at the terminal and the central nitrogen atom were proposed. Amides of aromatic amines can also be converted into azides. Meier showed that lithium anilide reacts with N₂O to give azobenzene, biphenyl, and a small amount of a yellow oil, which he assumed to be phenyl azide. The reaction was later reinvestigated by Koga and Anselme. By optimizing the reaction conditions, they were able to increase the amount of phenyl azide to 35% (Scheme 11b). Amides derived from p-toluidine, p-anisidine, and cyclohexylamine were found to react in a similar fashion, but the yields were likewise low. Apart from simple amides, hydrazine anions are also able to react with N₂O, giving rise to a mixture of products. Organometallic compounds of the alkali and the alkaline-earth metals often react with N₂O under mild conditions. Already in 1928, it was shown that the sodium salt of triphenylmethane adds N₂O to give a diazotate. The latter is converted into triphenylcarbinol upon reaction with ethanol (Scheme 12a).

A first comprehensive study about the reaction of organolithium compounds with N₂O was published by Beringer et al. They showed that primary, secondary, and tertiary alkylolithium compounds and most aryllithium compounds are able to react with N₂O. For example, the reaction of nBuLi with N₂O gave a hydrazone, which could be isolated with a yield of 24% (Scheme 12b).
For phenyl lithium, they observed a complex mixture of products including biphenyl, azobenzene, triphenylhydrazine and phenol. The mechanism this reaction was investigated by Meier. He proposed that the initially formed phenyldiazotate reacts with a second equivalent of PhLi to give azobenzene and Li₂O. Side products arise from decomposition of the diazotate and from the fact that azobenzene can react further with PhLi.

The reaction of N₂O with the simplest organolithium compound, CH₃Li, was investigated by the group of Müller. They were able to show that diazomethane is formed after basic workup (Scheme 12c). Under optimized conditions, a yield of 70% can be obtained.

The reaction of lithiated ferrocene with N₂O allows the preparation of azoferrocene in 25% yield (Scheme 12d). A similar reaction was used to synthesize azo-bridged ferrocene oligomers, albeit in very low yield. For the preparation of simple aromatic azo compounds, aryl calcium reagents appear to be best suited. This was first shown by Meier and Rappold, who isolated azobenzene along with larger amounts of biphenyl from the reaction of PhCal with N₂O in diethyl ether. More recently, the reaction was reinvestigated by Hays and Hanusa. Under optimized reaction conditions, they were able to increase the yield of azobenzene to 61% (Scheme 12e), but they mentioned problems with reproducibility and the substrate scope was very narrow.

In contrast to organocalcium reagents, Grignard reagents were believed to be inert towards N₂O. An early attempt to combine an organomagnesium compound with N₂O was reported by Zerner in 1913. He observed that solutions of MeMgI in Et₂O did not react with N₂O even upon heating. Since then, statements about the unreactivity of Grignard reagents towards N₂O have appeared in several articles.

We have recently demonstrated that this generalization is not correct. Some primary and secondary aliphatic Grignard reagents such as EtMgCl, BnMgCl or iPrMgCl (Scheme 12f) are converted to hydrazones when THF solutions are subjected to an atmosphere of N₂O. When the reactions are combined with an acidic work-up, it is possible to obtain alkylhydrazinium salts on a preparative scale.

As mentioned in Section 2, olefins are able to react with N₂O under forcing conditions to give ketones. Calculations suggest that these reactions proceed via 1,3-dipolar cycloadditions of N₂O to the double bond of the olefins. The latter decomposes to give the ketone and dinitrogen. Banert and Plefka have shown that cyclic alkynes are much more reactive towards N₂O than simple olefins. Reactions were found to proceed at temperatures between -25 °C and RT using pressures between 15 and 50 bar. Interestingly, they were able to obtain products which contain all three atoms of nitrous oxide (Scheme 13).

The incorporation of all three atoms of N₂O into the final product was also observed for reactions with some transition metal complexes. The diphenylacetylene complexes of permethyltitanocene and zirconocene react with N₂O to give azoxymetallacyclopentene complexes (Scheme 14a). The Zr complex is thermally labile and undergoes extrusion of dinitrogen to give an oxametallacyclobutane complex. The carbon-metal bond of the latter can be cleaved with a variety of substrates processing acidic protons. It is noteworthy that the oxametallacyclobutane complex can be obtained in quantitative yield by exposure of the solid Zr diphenylacetylene complex to N₂O. Recently, it was shown that the labile azoxymetallacyclopentene complex can be trapped by reactions with MeO₃SCF₃ (alkylation of the β-N-atom). The reaction product can be isolated and is stable as a solid if stored at -35 °C. In case of Ti, the initial N₂O adduct is more stable and can be used for further reactions. Apart from an alkylation reaction with MeO₃SCF₃ (O- and β-N-alkylation), it was shown that the complex can be reduced to give a stable radical anion.

Scheme 12 Reaction of organometallic compounds of the alkali and the alkaline-earth metals with N₂O.

Scheme 13 Reactions of cyclic alkynes with N₂O.
Some organometallic samarium complexes are also able to insert N₂O into metal–carbon bonds. When a solution of Cp*₂Sm(CH₂Ph)(THF) was subjected to an atmosphere of N₂O, a dinuclear complex was formed (Scheme 14b). A related reaction was observed for allyl complexes of the formula Cp*₂M(η³-C₃H₅) (M = Y, Sm, La).

A rarely observed phenomenon is the addition of N₂Ot o transition metal complexes with concomitant cleavage of the N–N bond. Cummins has shown that three-coordinate Mo(III) complexes are able to react with N₂O in this fashion to give a nitrosyl complex along with a nitride complex (Scheme 15a). It is interesting to note that the reverse reaction, the formation of N₂O from a metal nitride complex and nitric oxide, has been observed for an osmium and a ruthenium nitride complex. More recently, the Sita group has shown that a Mo carbonyl complex (generated in situ by photolysis of a dicarbonyl complex) can add N₂O to give a nitrosyl, isocyanate complex (Scheme 15b).

The formation of stable covalent adducts of N₂O can be achieved without transition metals. In 2009, the group of Stephan has shown that the frustrated Lewis pair (FLP) tBu₃P/B(C₆F₅)₃ reacts with N₂O at ambient conditions to give the adduct tBu₃P(N₂O)B(C₆F₅)₃ (Scheme 16a). A crystallographic analysis of the product revealed that the tBu₃P and the OB(C₆F₅)₃ group are oriented trans with respect the N=N double bond. Upon thermal or photochemical activation, the adduct liberates dinitrogen to give (tBu₃PO)B(C₆F₅)₃. The B(C₆F₅)₃ group in the adduct tBu₃P(N₂O)B(C₆F₅)₃ is labile and can be replaced by the Lewis acid Zn(C₆F₅)₂. Subsequent studies showed that the adduct tBu₃P(N₂O)B(C₆H₄F)₃ is particularly well suited for exchange reactions, since it features the relatively weak Lewis acid B(C₆H₄F)₃. Clean exchange reactions were observed for boron-based Lewis acids such as PhB(C₆F₅)₂ and MesB(C₆F₅)₂, as well as for cationic metallocene complexes and the tritylium cation (Scheme 16b). The Al analogue tBu₃P(N₂O)Al(C₆F₅)₃ can be prepared by slow addition of N₂O to a cooled solution containing tBu₃P (2 eq.) and Al(C₆F₅)₃. Subsequent reaction with additional Al(C₆F₅)₃ results in cleavage of the N–O bond to generate the highly reactive radical ion pair [tBu₃P(C₆F₅)₃][tBu₃PO]Al(C₆F₅)₃ that can activate C–H bonds. First steps towards the preparation of N₂O sensors based on FLPs were recently reported by the groups of Aldridge and Tamm. They showed that FLPs containing organometallic sandwich complexes (e.g. ferrocene, Scheme 16c) change their color upon binding to N₂O.

Covalent capture of intact N₂O can also be achieved by N-heterocyclic carbenes (NHCs). This was first demonstrated by our group in 2012. The reactions occur at room temperature and ambient pressure to give the adducts NCH–N₂O in (mostly) good yields (Scheme 17). Conveniently, the carbenes can be prepared in situ by deprotonation of the corresponding imidazolium salts. Owing to the strong C–N bond, most adducts show a good stability at room temperature. On heating, however, they decompose to give dinitrogen and the corresponding urea. The decomposition reaction was found to depend strongly on the nature of the carbene and the solvent. Aqueous solutions of the adduct derived from 1,2-dimethylimidazol-2-ylidene (R = R’ = Me), for example, could be heated to 100 °C for a prolonged period of time without significant decomposition. A noteworthy characteristic of NHC–N₂O adducts is the long N–N bond (1.27–1.33 Å), which is in contrast to what has been observed for N₂O adducts.

![Scheme 14](image)

**Scheme 14** Insertion of N₂O into metal–carbon bonds.

![Scheme 15](image)

**Scheme 15** Metal-induced rupture of the N–N bond of N₂O.

![Scheme 16](image)

**Scheme 16** Covalent capture of N₂O by frustrated Lewis pairs.
of frustrated Lewis pairs (N–N ~ 1.25 Å). This structural feature suggests that the activation of N₂O by carbenes might facilitate N–N bond rupture. In fact, when NHC–N₂O adducts were allowed to react with MeI, HCl (Scheme 18a), or acetyl chloride, rupture of the N–N bond was observed.¹⁰⁷,¹⁰⁸ Reaction with the tritylium tetrafluoroborate, on the other hand, led to the formation of the adduct (IMes–N₂O–CPh₃)(BF₄) (Scheme 18b).

Reactions of IMes–N₂O with different transition metal complexes have been investigated. When combined with simple 3d transition metal salts, IMes–N₂O can act as an N-donor, as an O-donor, or as a chelating N,O-donor.¹⁰⁸ More interesting results were obtained with the low-valent vanadium complex V(Mes)₃(THF) and the Ni(0) complex Ni(COD)₂. In case of the highly oxophilic V(Mes)₃(THF), the addition of IMes–N₂O resulted in N–O bond cleavage with oxygen atom transfer to the metal center and formation of a deprotonated hydrazone ligand (Scheme 18c).¹¹¹ With Ni(COD)₂, on the other hand, insertion of the metal in the N–N bond was observed.¹¹² The product of the reaction is an unusual three-coordinate Ni nitrosyl complex with bridging imidazolin-2-iminato ligands (Scheme 18d).

Recently, we found that AlCl₃ is able to induce cleavage of the N–O bond of NHC–N₂O adducts. When the reactions are performed in the presence of an aromatic compound, azoimidazolium salts are formed in good yields (Scheme 19).¹¹³ These kinds of salts are of interest because they are strongly colored dyes. They are produced industrially (e.g. Basic Red 51) and used for a variety of applications such as dying of synthetic and natural fibers. An advantage of the N₂O-based procedure is its flexibility. The heterocyclic coupling partner can have aliphatic as well as aromatic substituents on the nitrogen atoms. Furthermore, it is possible to use a wide range of aromatic coupling partners including deactivated arenes such as C₆H₅F, heterocycles, and polycyclic arenes such as pyrene and azulene (Scheme 19). As such, the method complements existing procedures for the synthesis of these dyes, each of which has its own limitations.

Triazenes are compounds of the general formula R–N=N=N–RR’. They have been used extensively in synthetic organic chemistry.¹¹⁴ Furthermore, triazenes have been examined as potential anti-tumor drugs, and the triazenes dacarbazine and temozolomide are currently used in the clinic for the treatment of cancer.¹¹⁵ We have recently shown that triazenes can be prepared by coupling of lithium amides and organomagnesium compounds with N₂O.¹¹⁶ The reaction is best performed in a sequential fashion, with initial addition of N₂O to a solution of the amide, followed by reaction with the Grignard reagent (Scheme 20). A key advantage of the new procedure is the ability to access triazenes with alkenyl and alkynyl substituents (some selected examples are show in Scheme 20). These compounds are difficult to synthesize by conventional methods.
because the required starting materials are unstable. Interestingly, some of the new alkylnitriazenes were found to display high cytotoxicity in in vitro tests on ovarian and breast cancer cell lines. Recent results from our laboratory show that alkylnitriazenes are versatile starting materials for subsequent reactions, and details about these reactions will be reported in due course.

5 Conclusions

The examples discussed above show that nitrous oxide is an interesting reagent for synthetic organic and inorganic chemistry. The inert character of N₂O allows selective oxygen atom transfer reactions to highly reactive species, while minimizing the risk of over-oxidation. Stoichiometric reactions of this kind have been used in particular for the oxidation of low-valent silicon compounds and for transition metal complexes.

Catalytic reactions with N₂O have been examined extensively because N₂O is a cheap and environmentally benign oxidant. Initially, solution-based reactions with transition metal catalysts have shown only very limited success. High temperatures and/or pressures were needed, and low turnover numbers were achieved. However, recent results demonstrate that efficient catalytic processes at ambient conditions are possible. Based on these initial results, it appears that catalytic reactions which involve low-valent transition metal complexes are particularly well suited.

For reactions with N₂O, the transfer of oxygen is the most commonly observed mode of reactivity. Nevertheless, it is possible to use N₂O as a donor of nitrogen atoms. Reactions of this kind are known for many decades, but applications in organic synthesis were sparse. The formation of side products, low yields, and the existence of more attractive alternative procedures have hampered the utilization of N₂O in N-atom transfer reactions. But this might change in the future. As demonstrated by synthesis of triazenes and azoimidazolium dyes, it is possible to perform high yield N-atom transfer reactions with N₂O. Notably, the N₂O-based methods can offer distinct advantages over more established synthetic procedures.

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