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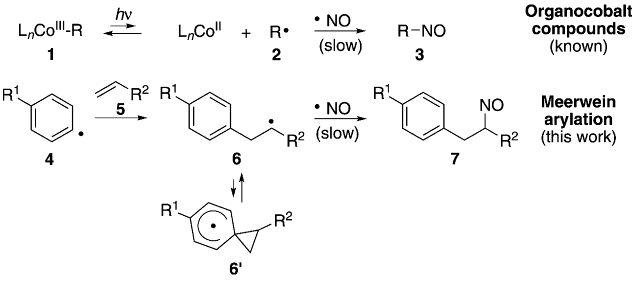
Radical Carbonitrosation and Recycling of the Waste Gas Nitrogen Monoxide

Cristina de Salas,[a] Olga Blank,[b] and Markus R. Heinrich*[a]

In radical reactions, carbon–nitrogen bonds can be formed by employing nitrogen-centered radicals[1] or nitrogen-centered radical scavengers.[2] In the field of nitrogen-centered radicals, nitrogen dioxide has recently been used for the halonitration of alkenes by Taniguchi et al.,[3] and Studer et al.[4] reported hydroamination reactions with *N*-aminated dihydropyridines. Among the reagents suitable for trapping radicals at their nitrogen atoms, sulfonyl azides[5] and arenediazonium salts[6] have received most attention over the last decade. In comparison, only a small number of reports has been published on the use of azo[7] and nitroso compounds,[8] imines[9] and diazirines[10] for the same purpose. Very recently, stannylimines have been introduced as new representatives of this reagent type.[11] With respect to the structural complexity within the group of nitrogen-centered radical scavengers, nitrogen monoxide[12] represents the most simple compound. Although the NO radical might therefore at first appear as a quite attractive reagent, its application is not only complicated by its toxicity,[13] but also by its low solubility in common solvents.[14] Moreover, reactions such as the Barton nitrite photolysis[15] indicate the comparatively low reactivity of nitric oxide towards carbon-centered radicals.[16] In turn, only very special carbon radical sources such as organocobalt compounds have so far been found effective in radical reactions with nitrogen monoxide.[17] Our interest in NO as a nitrogen-centered radical scavenger is based on the idea of combining emission control with organic synthesis by designing radical reactions that are able to run with NO arising as an industrial waste gas.[18] Herein, we present an intermolecular carbonitrosation reaction[19] as a new type of Meerwein arylation[20] capable of producing β-aryloximes by incorporation of nitrogen monoxide.

Known radical reactions of nitrogen monoxide point to the fact that especially carbon-centered radicals possessing a prolonged lifetime are useful for the trapping of NO.[17] A representative example is shown in Scheme 1. Photoinduced homolytic cleavage of the weak carbon-metal bond present in organocobalt complex **1** leads to the release of radical **2**.[21] Given that the following recombination of **2** with NO to form the nitroso compound **3** proceeds too slowly, radical **2** can safely evolve back to its precursor **1**. The modest reactivity of NO can thus be balanced by an upstream equilibrium that limits the probability of side reactions and increases the overall lifetime of **2** at the same time. For Meerwein arylations,[20] which generally proceed by the addition of an aryl radical **4** to an alkene **5**, we reasoned that a radical-stabilizing functional group R^2 is required to sufficiently prolong the lifetime of intermediate **6**. For some substitution patterns, a further stabilizing effect might arise from the ability of **6** to undergo a reversible cyclization to **6′**.[22]



Scheme 1. Reactions of carbon-centered radicals with nitrogen monoxide.

To probe the effectiveness of different intermediates **6** to function as scavengers for NO, a series of Meerwein arylations was carried out in the presence of nitrogen monoxide, various alkenes, and the reductant iron(II) sulfate.[23] Eight arenediazonium tetrafluoroborates **8**, which were readily available from their respective anilines,[6b] were used as aryl radical sources. The experimental results are summarized in Scheme 2.[24,25] Styrene (**5**, R^2 = Ph), acrylonitrile (**5**, R^2 = CN), and methyl acrylate (**5**, R^2 = COOMe), which are classical substrates for Meerwein arylations,[20] gave the desired β-aryloximes **9a–h** in moderate to high yields.[26] In these experiments, neither the primarily formed nitroso compounds **7** nor their respective dimers could be isolated.[27] The rapid tautomerization of intermediates **7** hereby turned out to be

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[a] C. de Salas, Prof. Dr. M. R. Heinrich
Department für Chemie und Pharmazie, Pharmazeutische Chemie
Friedrich-Alexander-Universität Erlangen-Nürnberg
Schuhstrasse 19, 91052 Erlangen (Germany)
Fax: (+49) 9131-852-2585
E-mail: Markus.Heinrich@medchem.uni-erlangen.de

[b] Dr. O. Blank
Fakultät für Chemie und Biochemie, Organische Chemie 1
Technische Universität München
Lichtenbergstrasse 4, 85747 Garching bei München (Germany)

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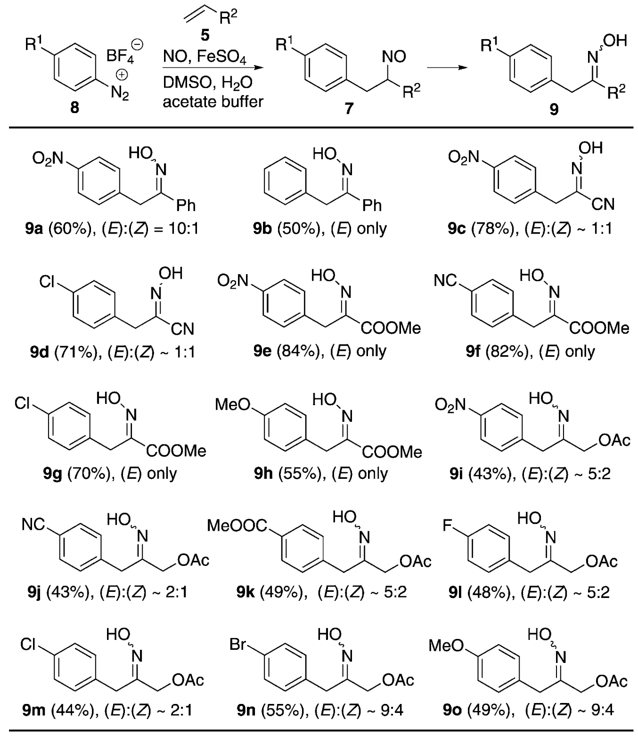
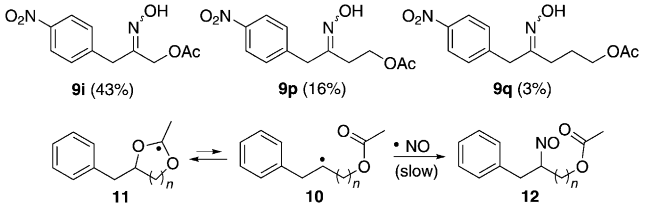


Scheme 2. Synthesis of β-aryloximes.[24,25]

an important feature. Since nitroso compounds can act as efficient radical scavengers to give nitroxides, a longer persistency of **7** could otherwise significantly complicate the overall reaction course.[28]

With the exception of the oximes **9c** and **9d** derived from acrylonitrile, the β-aryloximes were obtained with a clear preference for the *E* stereoisomer.[25] In comparison to the activated substrates mentioned above, the addition of aryl radicals **4** to non-activated alkenes **5** proceeds about 10 times slower (Scheme 1).[29] Despite this disadvantage, slightly lower but still useful yields could be achieved in reactions with allyl acetate (**5**, $\mathrm{R^2 = CH_2OAc}$). Again, β-aryloximes **9i–o** were formed as final products, but in contrast to the activated alkenes shown above, complete tautomerization did not already occur in the reaction mixture but mainly during workup.

As an alternative to the use of NO from a pressure cylinder, we prepared oxime **9o** by in situ generation of NO from sodium nitrite. In this case, iron(II) sulfate first served as a reductant for nitrite to give NO and later for the diazonium ions to generate aryl radicals. Interestingly, a sharp drop in NO trapping efficiency was observed in experiments with alkenes bearing $\mathrm{C_2}$ or $\mathrm{C_3}$ spacers between the acetate group and the terminal double bond (Scheme 3).



Scheme 3. Stabilization of intermediate **10** by reversible cyclization.

We currently attribute this effect to an additional stabilization of intermediate **10** arising from the reversible cyclization to **11**, which is known from acyloxy migrations (Scheme 3).[30] With longer spacers ($n=2$ or 3) than in allyl acetate ($n=1$), the cyclization pathway becomes far less effective. The lifetime of intermediate **10** is thus decreased and as a result its ability to capture NO and to give **12**. This assumption is further supported by experiments in which allyl acetate was replaced by allyl alcohol. Owing to the missing acetate functionality the radical adduct related to **10** was not sufficiently stabilized, and only trace amounts of the corresponding oximes could be isolated. For activated olefins, a comparable effect is apparently provided by the delocalization of the intermediate radical **6** into the phenyl, cyano, or ester group (Scheme 1, $\mathrm{R^2 = Ph}$, CN, COOMe).

With regard to an application of carbonitrosation reactions for the recycling of NO occuring as waste gas, the oxime synthesis needs to tolerate the presence of oxygen. A metal-free version of the process could be even more attractive. Results of our first experiments to determine the influence of air and iron(II) sulfate are summarized in Figure 1. Owing to the known sensitivity of Meerwein arylations towards the reactivity of the diazonium ions[31] and the type of alkene,[29] three oximes (**9e**, **9i**, and **9m**) were included in this study representing possible combinations of more or less reactive arenediazonium ions and alkenes.

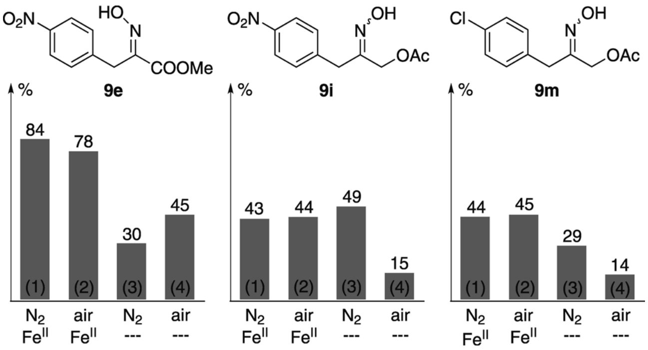
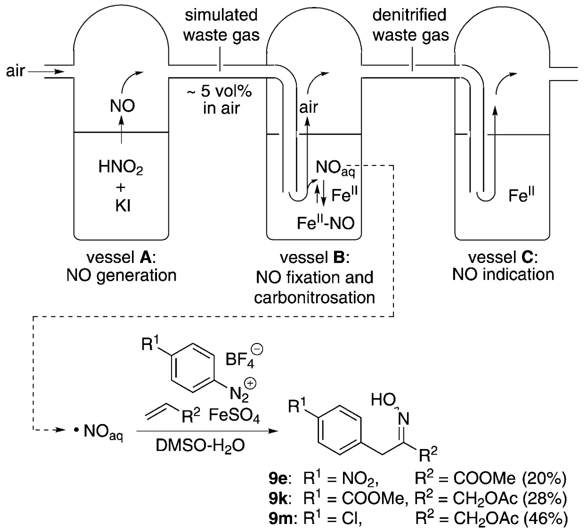


Figure 1. Sensitivity of the carbonitrosation reaction towards air and the absence of iron(II) sulfate.

For all three oximes, no significant change in yield was observed when the previously employed standard conditions ((1), c.f. Scheme 2) were modified in the way that the reactions were now simply conducted under air without using degassed solvents (2). With regard to a possible metal-free version of the oxime synthesis under nitrogen (3), the combination of an electron-poor diazonium salt with a non-activated alkene to give products such as **9i** appears to be favorable. The absence of the protecting gas and the iron(II) salt (4) was best tolerated in the reaction producing oxime **9e**.

Encouraged by the overall observation that the presence of oxygen is acceptable with iron(II) salts in the reaction mixture, we finally investigated the possibility to recycle nitrogen monoxide from waste gas. In our experiments a simulated stream of waste gas containing 5 vol% of NO was generated by passing air through a reaction vessel (vessel A, Scheme 4), in which NO was produced from the reduction of nitrous acid with potassium iodide. The gas mixture was then passed through a solution of iron(II) sulfate (vessel B), which led to the absorption of NO mainly by reversible formation of iron(II) NO complexes.[32] Denitrification by complexation of NO with iron(II) complexes is known and has been evaluated as a part of the BioDeNO_x process.[33] Since the formation of iron(II) NO complexes in vessel B can easily be observed by their brown color (c.f. classical "brown-ring" probe),[32c] we used a third vessel C to monitor that most of the NO had been absorbed in vessel B. In the following step, the NO-containing solution from vessel B was used in the carbonitrosation reaction. For this purpose, the alkene and the diazonium salt were added without any further modification.



Scheme 4. Carbonitrosation using a simulated stream of waste gas.

The formation of the oximes **9e**, **9k**, and **9m** demonstrates that Meerwein-type carbonitrosation reactions are capable of recycling NO from waste gases. Oxime **9e**, for which the best yields had been obtained with pure NO and iron(II) sulfate under air (Figure 1), now turned out to be the least well-suited for the recycling reaction. As the concentration of NO in the reaction mixture is significantly lower in the recycling experiments than in all other carbonitrosations described before (Figure 1 and Scheme 2), the oligomerization of the alkene starts to occur as an undesired side process. Owing to the fact that radical oligomerization is far more pronounced for acrylates than for non-activated olefins such as allyl acetate,[34] it appears comprehensible that carbonitrosations involving activated alkenes are more affected by lower concentrations of NO. Favorably, the process is not significantly disturbed by NO_2 resulting from the reaction of NO with oxygen, and the secondary products formed from NO_2 in aqueous solution.[35] In the overall context, industrial processes such as the chemical etching of silicon wafers by concentrated nitric acid are especially interesting since gas mixtures with an NO content of up to 20% are produced.[36,37] Owing to the very unsteady evolution of NO, denitrification is particularly difficult by known selective catalytic reduction (SCR)[38] or selective non-catalytic reduction (SNCR)[39] methods. NO fixation and later conversion, as is done in the carbonitrosation protocol, might therefore be a valuable alternative.

In summary, we have described a new type of Meerwein arylation that is able to produce β-aryloximes by incorporation of nitrogen monoxide. Until now, demanding precursors such as organocobalt complexes were mainly used for radical nitrosation reactions,[17] and carbonitrosations have only been described as intramolecular reactions employing organonitrites.[19] With the new procedure, β-aryloximes are readily accessible from activated alkenes and arenediazonium salts in one step. For non-activated alkenes, additional functional groups, such as acetates, are required in allylic positions. β-Aryloximes represent versatile synthetic building blocks of natural products[40] and numerous synthetic applications have been reported. Besides the well-known Beckmann[41] and Neber[25a] rearrangements, the reduction of compounds such as **9e**–**9h** to aromatic amino acids[42,43] is a further example. Owing to the low sensitivity of the carbonitrosation reaction towards oxygen, we have been able to demonstrate its applicability for recycling of nitrogen monoxide occuring as waste gas. Current research is directed towards an extension of the process to industrial scale.

Experimental Section

Representative procedure for the synthesis of β-aryloximes (Scheme 2): $FeSO_4\cdot 7H_2O$ (3.00 mmol, 834 mg) was added to a mixture of DMSO and H_2O (10:1 v/v) (50 mL) containing NaOAc (2.00 mmol, 164 mg) and AcOH (2.00 mmol, 0.160 mL). The resulting solution was flushed with nitrogen (ca. 2 min) and afterwards nitrogen monoxide (>99 vol%, from a pressure cylinder) was bubbled through the solution for 15 s. The alkene (30.0 mmol) was added to the stirred mixture and a solution of the arenediazonium tetrafluoroborate (1.00 mmol) in DMSO (3 mL) was added dropwise over 3 min. The mixture was stirred for another 2 min, the remaining nitrogen monoxide was removed through a stream of nitrogen, and ascorbic acid (5.00 mmol, 881 mg) was added. After stirring for an additional 30 min, the solution was diluted with water (50 mL) and extracted with ethyl acetate (4×50 mL). The combined organic phases were washed with saturated aqueous NaCl and dried over Na_2SO_4. Removal of the solvents under reduced pressure and purification by column chromatography on silica gel gave the desired products.

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Keywords: arenediazonium · Meerwein arylation · nitrogen oxides · oximes · radicals

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