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New Trends towards Well-Defined Low-Valent Iron Catalysts

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In the past few years iron catalysis has emerged as an important and challenging research area for the development of alternative, more affordable, and sustainable methods. Besides the traditional applications of iron catalysts as Lewis acids and for reduction/oxidation processes in organic synthesis, organoiron species have been shown to be suitable catalysts for a broad range of nonrelated transformations such as cross-coupling reacions, allylations, and hydrogenations.[1] Simple and stable commercially available iron compounds such as iron(II) or (III) chlorides, [Fe(acac)$_3$] (acac = acetylacetonate), and [Fe(CO)$_5$] have been largely employed for these purposes. However, the complexity of the reaction mixtures makes it extremely difficult to identify the active iron species[1i] and the reaction mechanisms, thus hampering the rational design and modification of the catalytic systems. In view of the rapidly growing interest in highly reactive low-valent organoiron catalysts,[2,3] the preparation of such well-characterized iron compounds is essential for a better understanding and the further development of modern iron catalysis. Much progress has been made in this direction,[1–3] from which the reduction of iron(II) species,[4] typically with alkali-metal and more recently zinc reagents, has become an established method to generate low-valent iron catalysts. Following the first report on cross-coupling reactions by using in situ formed low-valent iron catalysts by Tamura and Kochi,[5] several research groups have utilized this approach to broaden the scope of low-valent iron catalysis (Figure 1).[2]

Although the enormous potential of low-valent iron catalysts is already known, there is still a necessity to generate well-defined species to obtain more mechanistic insight and enlarge the synthetic applicability. Fürstner et al. have contributed significantly in this regard, not only by the development of a number of iron-catalyzed transformations and their application in total synthesis[1f,g] but also by the systematic mechanistic study of several isolable low-valent ferrate complexes[2c,d] (for example, Scheme 1, left and middle). It was proposed that interconnected Fe^{-II}/Fe^0, Fe^0/Fe^{II}, and Fe^I/Fe^{III} redox cycles may be operative within these systems.

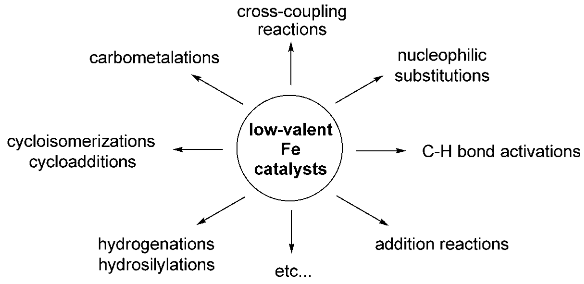

Figure 1. Overview of the reaction scope of low-valent iron catalysts.

Scheme 1. Selected well-defined low-valent iron precatalysts developed by Fürstner et al. (left, middle) and Chirik and co-workers (right).[2a–d,6] pdi = pyridine diimine.

The research groups of Chirik and Wieghardt have joined forces to understand the character and performance of well-defined formal low-valent iron species with bis(imino)pyridine ligands (e.g. Scheme 1, right).[6] A more complex scenario is envisioned in this case, since these tridentate ligands can also participate actively in the reduction/oxidation steps. Consequently, the ligand might preferentially take part in the redox processes while the iron atom retains its oxidation state.

Recently, Ritter and co-workers developed an effective new method to obtain well-defined and relatively stable low-valent iron catalysts (Scheme 2).[7] In their approach, the well-known two-electron reductive elimination reaction of transition metals (such as Pd, Rh, Ru, or Ni) was applied to iron complexes for the first time. To accomplish this transformation, the carefully designed new bis(aryl)iron(II) complex **1** was prepared from inexpensive FeCl$_2$, pyridine, and (2-[(*N*,*N*-dimethylamino)methyl]phenyl)lithium.[8] The use of the chelating amino aryl ligand, which places the C donors in a pseudo-*trans* conformation, was crucial to prevent reductive elimination at this stage and allow the isolation of the stable intermediate **1**. The low-valent iron complexes **2** were achieved in a clever manner by the subsequent addition of

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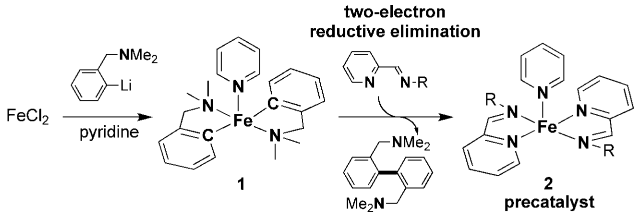
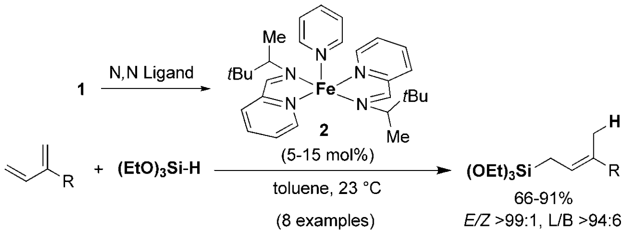


Scheme 2. Synthesis of a formal low-valent iron complex by Ritter and co-workers through reductive elimination of the ligand.[7a]

an exogenous iminopyridine ligand; a controlled reductive elimination may take place after ligand rearrangement.

In analogy to the recent observations reported by Chirik, Wieghardt, and co-workers in which the related iron(0) species (d^8 electron configuration) are avoided (e.g. Scheme 1, right),[6] the authors suggested the formal low-valent complex **2** to be a iron(II) species in which two radical-anion ligands are coordinated to the iron atom. An interesting feature of this catalyst is, therefore, the presence of two potentially redox-active ligands bound to the iron center. These ligands might be able to compensate the electronic requirements of the iron center involved in the catalytic cycle and lower the activation barriers by internal metal–ligand charge-transfer processes.

Related catalytic systems, in which the low-valent iron catalysts were generated in situ by reduction with magnesium metal, were already employed efficiently in 1,4-hydroboration reactions and in the addition of α-olefins to dienes.[7b,c] However, this approach led to nondefined active species, from which mechanistic information could not be obtained. One of the key advantages of employing the defined homogeneous iron catalysts **2** is that reactions could be followed kinetically. Consequently, Ritter et al.[7a] were able to extend their applicability to a highly regioselective 1,4-hydrosilylation of 1,3-dienes (Scheme 3).[9]



Scheme 3. Defined low-valent iron catalyst for the regioselective hydrosilylation of 1,3-dienes; L = linear, B = branched.[7a]

Kinetic studies with isolated low-valent complex **2** gave valuable information about the iron intermediates involved in the catalytic cycle. Thus, it was proposed that only one chelating N,N ligand was present in the catalytically active species. Moreover, by making use of the easy in situ preparation of a variety of catalysts **2** from stable complex **1** through simple variation of the added exogenous iminopyridine ligand, a highly selective catalyst **2** with R = CH(Me)*t*Bu could be prepared (Scheme 3).

In conclusion, there is no doubt of the importance of iron catalysis in modern chemistry. However, there is also a clear necessity to understand the catalytic mode of action of these systems to achieve key advances in this promising research area. In this regard, the access to well-defined true (Scheme 1, left and middle) or formal (Scheme 1, right) low-valent iron catalysts is significant.

As discussed in this Highlight, both the isolation and the easy in situ generation of the active low-valent iron species, which permits the rational fine-tuning of the electronic and steric properties of the catalyst, makes this method especially attractive. Although it was not confirmed whether or not the active catalyst is a real low-valent iron species, this simple protocol offers great potential for developing new iron catalysts and for their use in preparative syntheses; furthermore, it offers an approach to prepare new low-valent iron systems. Significant advances in the field of iron catalysis are certainly expected in the next few years.

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