# Trapping of Radicals in the Coordination Spheres of Metals

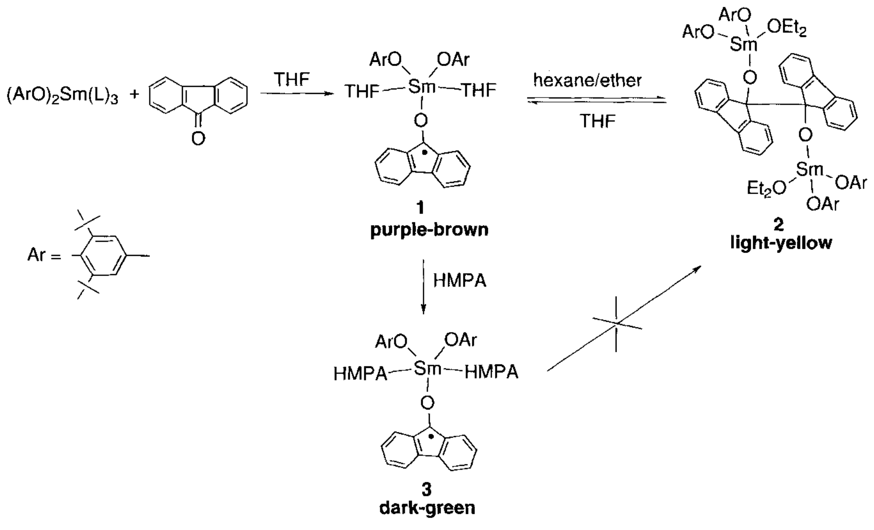
Zhaomin Hou* and Yasuo Wakatsuki

**Abstract:** The use of hexamethylphosphoramide (HMPA) or other sterically demanding groups as stabilizing ligands allows the successful isolation of a series of structurally characterizable complexes of ketyl radicals with alkali, alkaline earth, and lanthanide metal. It has been demonstrated that the stability and reactivity of the ketyl radicals strongly depend on both the nature of the metals to which they are bound and the steric and electronic properties of the ancillary ligands, as well as the structure of their parent ketones.

**Keywords:** alkali metals · calcium · ketyl radicals · radicals · samarium

The stabilization and isolation of inherently reactive organic fragments or reaction intermediates through binding to metal centers are of great importance for the mechanistic understanding of many important transformations, and are also a fundamentally interesting component of the application of inorganic and organometallic reagents to organic synthesis. Ketyls, or radical anions of ketones, which are usually generated through one-electron reduction of ketones by reducing metals, are among the most important intermediates in organic chemistry.[1] Since their discovery in the last century,[2] these species have received continuous attention as key intermediates in a variety of reactions involving organic carbonyl groups, such as reductions,[1c,f–h,j] pinacol couplings,[1a,b,d,f] olefin formations (the McMurry reaction),[1a,b,d,e,f,i] and Grignard reactions.[3] Sodium benzophenone ketyl,[2] for example, is the oldest ketyl, familiar to almost every chemist for its use in dehydration and deoxygenation of etheral solvents. However, owing to the extremely high reactivity of ketyls, which makes them difficult to isolate, structural information on these species was for a long time solely limited to spectroscopic data of species generated in situ,[4] and structurally characterized examples of ketyl complexes remained unknown until very recently.

The most difficult problem in the isolation of a ketyl species is its rapid hydrogen abstraction and/or coupling reactions. In 1995 it was found in our laboratories that the use of a sterically demanding samarium(II) reducing agent, $Sm(OAr)_2(THF)_3$ ($Ar = C_6H_2$-2,6-$t$Bu$_2$-4-Me), and a highly conjugated aromatic ketone, fluorenone, could sufficiently suppress these decomposition reactions of the generated ketyl species. With this combination, the first structurally characterizable metal ketyl complex **1** was successfully isolated as purple-brown crystals (Scheme 1).[5] This complex possesses a distorted trigonal bipyramidal structure with one fluorenone ketyl and two ArO ligands at the equatorial and two THF ligands at the apical positions. When **1** was dissolved in hexane/ether, the two THF ligands were substituted by one molecule of $OEt_2$, and the ketyl radical dimerized into a pinacolate (**2**) (Scheme 1). The newly formed C–C bond in **2**, which was unusually long (1.613(9) Å), could be readily broken to quantitatively regenerate the ketyl **1** by dissolving **2** in THF (Scheme 1). This unequivocally demonstrates that the pinacol coupling process of a ketyl radical is completely reversible. Addition of 2 equiv of HMPA to a THF solution of **1** or **2** yielded the corresponding HMPA-coordinated



Scheme 1. The first structurally characterizable metal ketyl complex **1** and its reactions.

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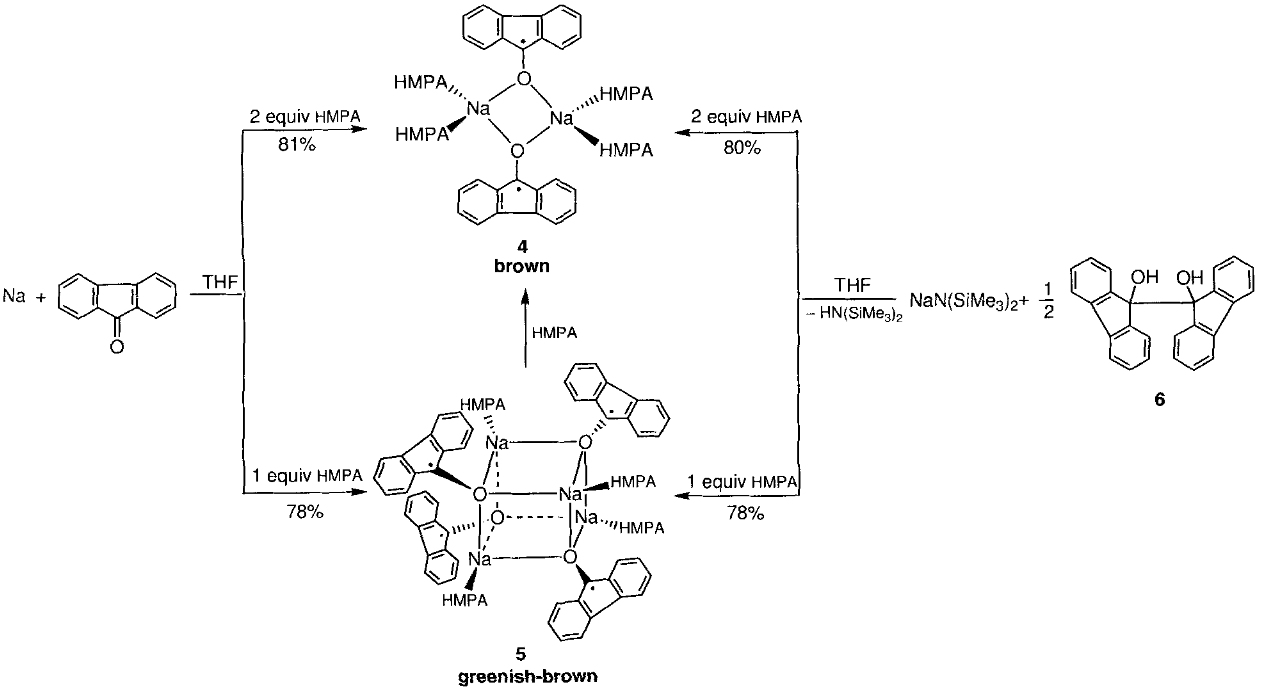


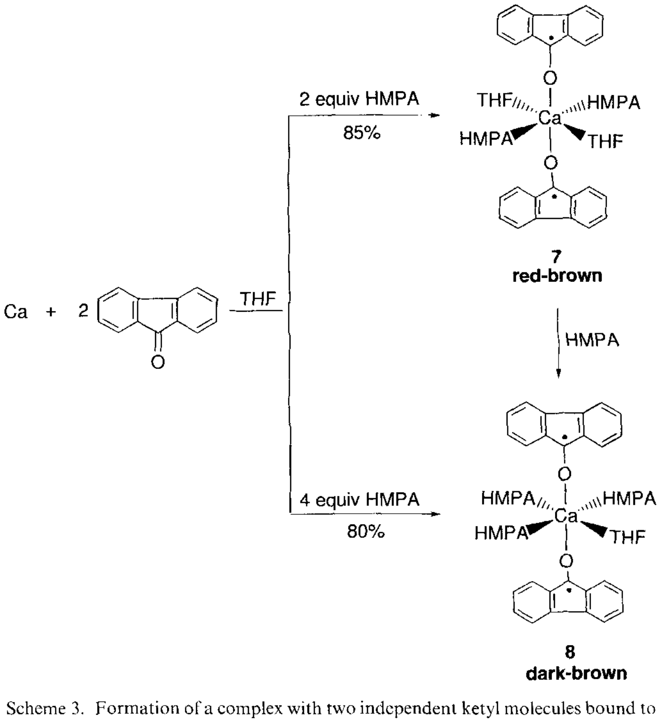
Scheme 2. Isolation of alkali metal ketyls.

ketyl complex **3** (Scheme 1).[6] Complex **3** was much more stable than **1**, and no reaction was observed when **3** was treated with ether or hexane; this shows that HMPA is an excellent ligand for the stabilization of a ketyl species, probably owing to the strong coordination ability of the HMPA ligands.

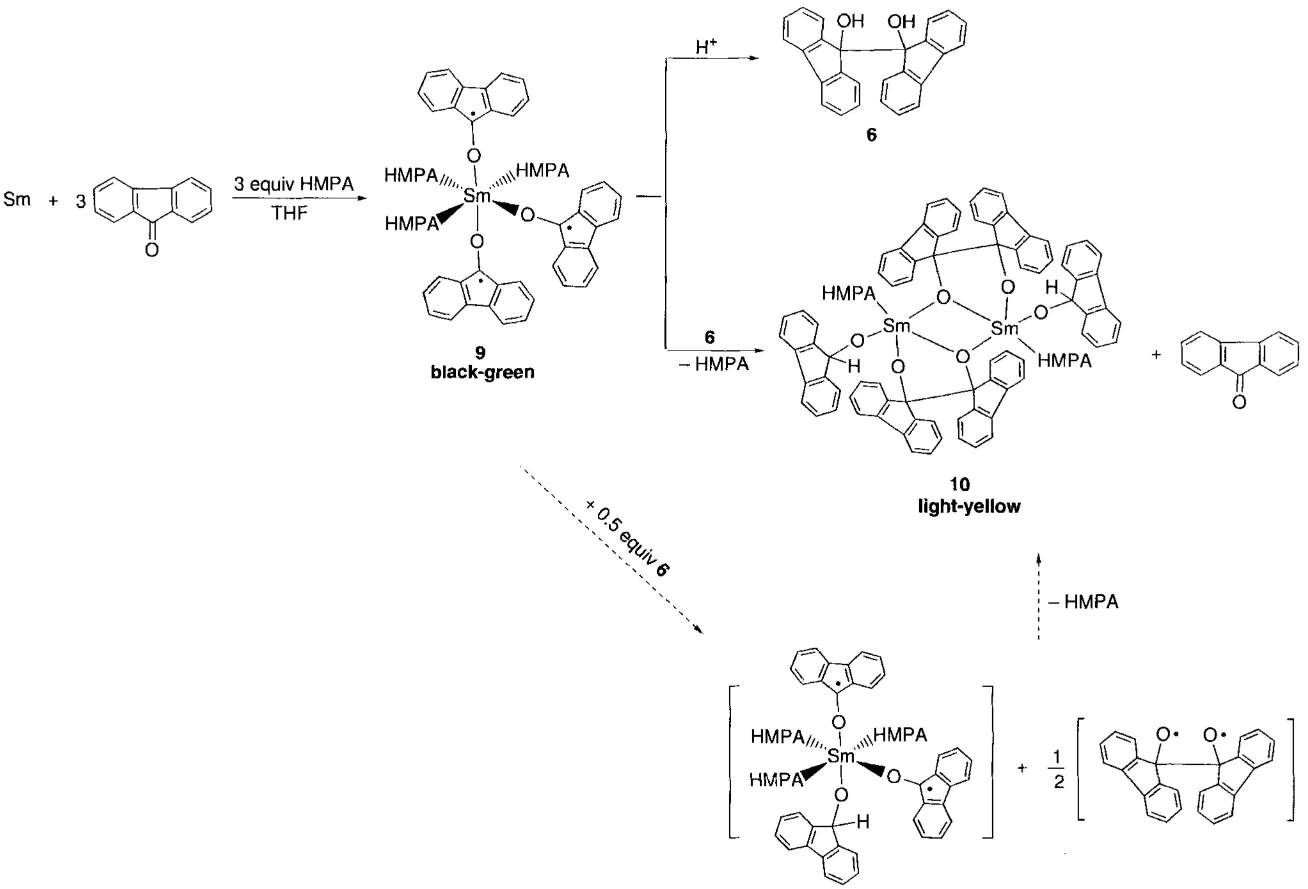
The use of HMPA as a stabilizing ligand was then applied to the isolation of alkali metal ketyls. Addition of 2 equiv of HMPA to a green THF solution of sodium fluorenone ketyl yielded **4** as brown blocks (Scheme 2).[7] An X-ray analysis revealed that **4** is a fluorenone ketyl bridged dimeric sodium complex in which each sodium atom is also bound to two terminal HMPA ligands. When only 1 equiv of HMPA was used in this reaction, greenish-brown crystals of **5** were obtained (Scheme 2). Although its UV/Vis and ESR spectra in THF are very similar to those of **4**, an X-ray analysis shows that **5** is a $\mu_3$-ketyl-bridged tetrameric sodium complex with an $Na_4O_4$ cubane core. Each Na atom in **5** is coordinated to one terminal HMPA ligand. The formation of **5** can formally be regarded as the dimerization of two molecules of **4** by removal of one of the two HMPA ligands attached to each Na atom. It is surprising that this dimerization is not a pinacol-coupling of the ketyls, but aggregation of the ketyls through Na–O(ketyl) interactions. This is in sharp contrast to what was observed in the case of the samarium ketyl **1**, which underwent pinacol coupling when the steric hindrance around the central metal was decreased.[5] Reaction of the tetramer **5** with four or more equivalents of HMPA yielded only the dimer **4** (Scheme 2); a monomeric ketyl was not isolated. Reactions of lithium and potassium with fluorenone in THF/HMPA also afforded the corresponding ketyl complexes,[8] although some structural differences, which resulted from the differences in ion radii, were observed.

Ketyl complexes **4** and **5** could also be obtained by reaction of the pinacol **6** with $NaN(SiMe_3)_2$ with C–C bond cleavage of the pinacolate intermediate (Scheme 2).[7] This demonstrates that deprotonation of pinacols followed by C–C bond cleavage of the resulting pinacolates might constitute a new method for the synthesis of ketyls.

Through the use of HMPA as a stabilizing ligand, multi(ketyl)metal complexes, in which several independent ketyls are bound to the same central metal, could also be isolated. In the presence of 2 equiv of HMPA, reaction of calcium with 2 equiv of fluorenone in THF gave the bis(ketyl)calcium complex **7** (Scheme 3).[9] An X-ray analysis showed that **7** possesses a dis-



Scheme 3. Formation of a complex with two independent ketyl molecules bound to the central metal.

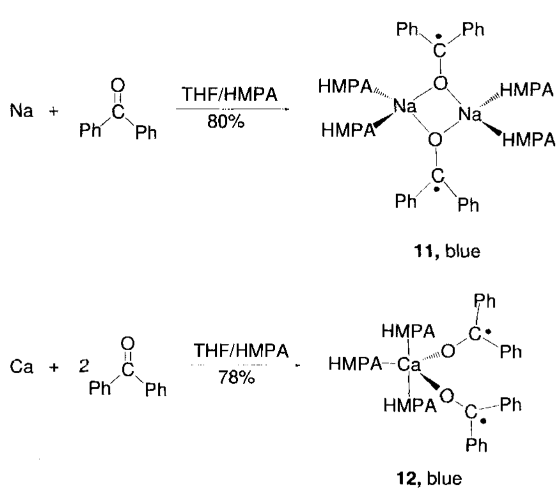


Scheme 4. Formation and transformations of complex **9**, which has three independent ketyl molecules bound to the central metal.

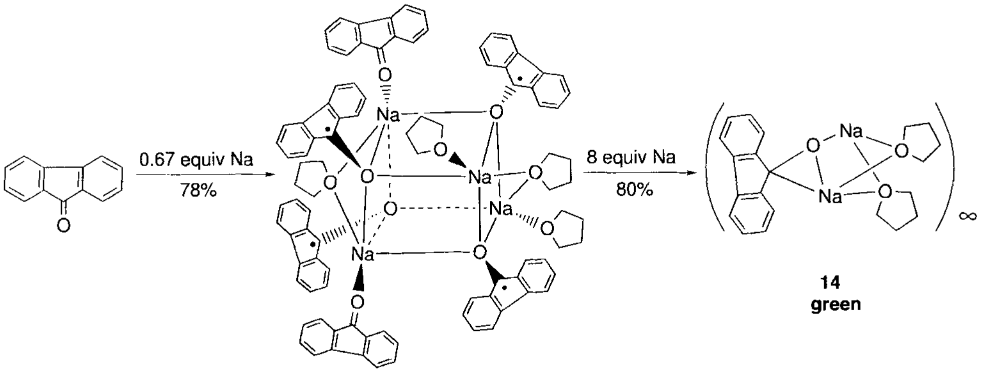
torted octahedral structure in which the two ketyls are mutually *trans*. Upon further reaction with HMPA, one of the two THF ligands in **7** was replaced by an HMPA ligand to give **8** (Scheme 3).

A similar reaction of samarium metal with 3 equiv of fluorenone and 3 equiv of HMPA in THF afforded the tris(ketyl)-samarium(III) complex **9** as black-green blocks (Scheme 4).[10] This complex also possesses an octahedral structure in which the central Sm atom is coordinated in *mer* fashion by three fluorenone ketyls and three HMPA ligands. Hydrolysis of **9** gave almost quantitatively the corresponding pinacol **6**. Interestingly, reaction of **9** with 0.5 equiv of **6** resulted in the formation of a dimeric $Sm^{III}$ fluorenoxide/pinacolate complex **10** and fluorenone (Scheme 4). Further studies showed that **10** was formed by hydrogen radical abstraction from the pinacol **6** by one ketyl, followed by pinacol-coupling of the other two ketyls together with simultaneous release of two HMPA ligands in **9** (Scheme 4). It is noteworthy that the small steric change, which was caused by the formation of a bulkier fluorenoxy unit from its planar parent fluorenone ketyl, signicantly influenced the stability and reactivity of the whole molecule. In the case of complexes **4**–**8**, such a reaction was not observed when they were treated similarly with **6**; this indicates that the reactivity of a ketyl species is metal-dependent.

Compared to fluorenone ketyl, benzophenone ketyl was more unstable and more difficult to isolate. Previous attempts to isolate benzophenone ketyl complexes of titanium[4e] and lanthanides[5, 11] were unsuccessful, resulting in the formation of either coupling or hydrogen-abstraction products.[12, 13] We recently found that, when sodium or calcium was used in the reaction with benzophenone in THF/HMPA, the corresponding structurally characterizable benzophenone ketyl complexes could be successfully isolated (Scheme 5).[14] The sodium benzophenone ketyl complex **11** adopts a similar dimeric structure to its fluorenone analogue **4**, but the calcium benzophenone ketyl **12** possesses a trigonal bipyramid structure, which is in contrast to its octahedral fluorenone analogue **8**. This result shows that benzophenone ketyl is sterically more demanding



Scheme 5. Characterizable benzophenone ketyl complexes.



**13**
**dark-green**

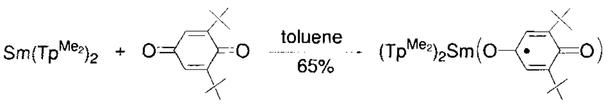
**14**
**green**

Scheme 6. Synthesis of HMPA-free sodium fluorenone ketyl complex **13**.

than fluorenone ketyl, probably owing to the rotation of the phenyl groups. Similar to fluorenone ketyl complexes, the radical carbon atoms in **11** and **12** are still in a $sp^2$-hybridized state.

Although the use of HMPA as a stabilizing ligand was a crucial factor for the isolation of a structurally characterizable metal ketyl complex in most of the above reactions, single crystals of the HMPA-free sodium fluorenone ketyl complex **13**, which possesses an $Na_4O_4$ cubane core similar to that of **5**, could also be obtained when an *excess* of fluorenone was used in the reaction with sodium in THF (Scheme 6).[15] In contrast to the HMPA-coordinated ketyl **5**, two of the four Na atoms in **13** are each terminally coordinated by a fluorenone and the other two Na atoms by a THF ligand. The Na atoms are also bridged in pairs by a THF ligand. The whole molecule can formally be viewed as a $\eta^1$-fluorenone-coordinated ketyl dimer $[Na(\mu_2,\eta^1\text{-ketyl})(\text{fluorenone})]_2[\mu_2\text{-THF}]$ and a THF-coordinated ketyl dimer $[Na(\mu_2,\eta^1\text{-ketyl})(\text{THF})]_2[\mu_2\text{-THF}]$ bound to one another through Na–O(ketyl) interactions. The isolation of the ketone-coordinated ketyl complex **13** suggests that, in ketyl-mediated reactions, some substrates might approach the ketyl species through coordination to the central metal ion. When **13** was allowed to react with an excess of sodium, the polymeric sodium fluorenone dianion complex **14** was formed (Scheme 6).[15]

Closely related to ketyls, a benzoquinone radical anion complex **15** was recently isolated and structurally characterized by Takats (Scheme 7).[13] Isolation and structures of two azobenzene radical anion complexes, $(Tp^{Me_2})_2Sm(\eta^2\text{-}N_2Ph_2)$ and $(C_5Me_5)_2Sm(\eta^2\text{-}N_2Ph_2)(THF)$, were also reported by Takats[13, 16] and Evans,[17] respectively.



**15, red**

Scheme 7. $Tp^{Me_2} = BH(3,5\text{-dimethylpyrazolyl})_3$).

It is now rather clear from the above studies that the stability and reactivity of ketyl radicals strongly depend on both the nature of the metals to which they are bound and the steric and electronic properties of the ancillary ligands, as well as the structure of their parent ketones. It has been demonstrated that fine-tuning of these parameters could indeed control the stability and reactivity of these species. Since the structural studies of ketyl complexes are just beginning, and structurally characterized examples of these species are still very limited, isolation and structural characterization of more and new ketyl complexes will continue to be of great importance and interest. In particular, the isolation of structurally characteriz-able alkyl ketone and aldehyde ketyl complexes remains a challenge.

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