products in the absence of His$_6$-Gal80 ruled out the possibility of GST-AD self-labeling (Figure 4, lane 5). Biotinylation was not detected when the His$_6$ tag was removed from Gal80, or when Ni^{II} MMPP or biotin-tyramine were omitted from the reaction (data not shown).

The detailed mechanism of the affinity-labeling reaction remains to be elucidated. However, it most likely proceeds through initial oxidation of the Ni^{II}-peptide complex by MMPP to form a high valent Ni^{III}–oxo species,[7] which subsequently abstracts an electron from the phenol group of a biotin-tyramine. The radical formed following loss of a proton from the radical cation could then couple to tyrosine or other suitably reactive amino acids on a tagged protein and any other proteins in the immediate vicinity. It is speculated that protein biotinylation is localized to the immediate region of the metal-binding tag by efficient quenching of the radical by excess biotin-tyramine in solution through phenolic coupling (Scheme 1).

In summary, we have demonstrated that two simple Ni^{II}–peptide complexes can mediate localized affinity-biotinylation reactions. This is a potentially useful tool for studying protein–protein interactions, particularly in the context of large complexes where it is difficult or impossible to label a particular protein uniquely with an azide- or benzophenone-containing reagent by using standard methods. Experiments in which this system is applied to such complex systems are underway.

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Expanding Divalent Organolanthanide Chemistry: The First Organothulium(II) Complex and the In Situ Organodysprosium(II) Reduction of Dinitrogen[**]

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Although historically the organometallic chemistry of the divalent lanthanides has involved just three ions, Eu^{2+}, Yb^{2+}, and Sm^{2+}, these elements have provided an extensive series of unusual structures and reactions.[1] Recently, however, opportunities have arisen to expand divalent lanthanide chemistry to other metals in the series.[2] The isolation of the first molecular complex of divalent thulium, $[\mathrm{TmI_2(dme)_3}]$ (dme = dimethoxyethane) in 1997,[2a] provided an analogue of the commonly used $[\mathrm{SmI_2(thf)}_x]$,[3] a precursor to organosamarium(II) complexes such as $[\mathrm{(C_5Me_5)_2Sm(thf)}_x]$.[4] Ionic metathesis reactions with $[\mathrm{TmI_2(dme)_3}]$ could provide a direct route to divalent organothulium complexes, but the high reactivity of Tm^{2+} made this challenging (reduction potentials versus NHE: Tm^{2+} −2.3 V; Sm^{2+} −1.5 V).[5] In fact, since 1997 only one other Tm^{2+} derivative has been reported in the literature.[6]

The discovery of TmI_2 as an in situ organic reagent[7] initiated a study of the organometallic chemistry of Tm^{2+} showing why organothulium(II) complexes are so difficult to isolate. Nitrogen is not inert to these species; they react to form complexes such as $[\{[\mathrm{C_5H_3(SiMe_3)_2}]_2\mathrm{Tm}\}_2\mathrm{N_2}]$, $[\{\mathrm{(C_5Me_5)_2Tm}\}_2\mathrm{N_2}]$, and $[\{\mathrm{(C_5H_4SiMe_3)_2Tm(thf)}\}_2\mathrm{N_2}]$.[8] Initial attempts to isolate organothulium(II) complexes under argon led to decomposition of the diethyl ether solvent to make ethoxide and oxide products.[8] Herein, we report that by choosing the proper combination of solvents, ligand, and reaction conditions, the first organometallic complex of Tm^{2+} has been isolated and structurally characterized.

Although the reaction of $\mathrm{KC_5Me_5}$ with $[\mathrm{TmI_2(thf)_3}]$ in Et_2O under argon leads to diethyl ether decomposition, the use of

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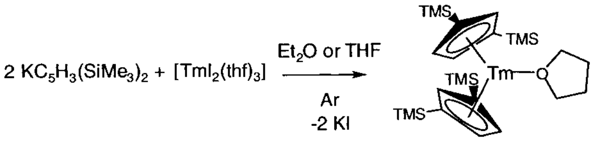
$KC_5H_3(SiMe_3)_2$ (KCp'')[9] in either diethyl ether or THF allows the isolation of the organometallic thulium(II) complex $[Cp''_2Tm(thf)]$ (**1**) in 90% yield [Eq. (1); TMS = $SiMe_3$].



1

(1)

The purple solution of **1** in diethyl ether under argon is stable for several hours at 25 °C and for several weeks at −30 °C. While the THF of solvation aids in the isolation of single crystals, the dark green solutions of **1** in THF have lower stability; dilute solutions transform to the yellow color of Tm^{3+} complexes over a period of 30 min at 25 °C. Addition of THF to a purple ethereal solution of **1** initiates a color change to dark green. Such intense colors and color changes due to the addition of donor ligands are typical of divalent lanthanides.[1e, 10]

Complex **1** can be isolated as purple single crystals at −30 °C (Figure 1), and is isomorphous with the ytterbium analogue $[Cp''_2Yb(thf)]$ reported in 1996.[11] This is not unusual considering the similarity of the ionic radii; Tm^{2+} and Yb^{2+} differ by about 0.01 Å.[12] The Tm^{2+} ion in **1** lies on a crystallographic twofold axis. The (Cp″ ring centroid)-Tm-(Cp″ ring centroid) angle is 135.1° compared to 136° in the Yb analogue. The Tm−(Cp″ ring centroid) and Tm−O(THF) distances of 2.394 and 2.365(5) Å, respectively, are also very close to those for Yb, 2.39 and 2.34(1) Å, respectively.

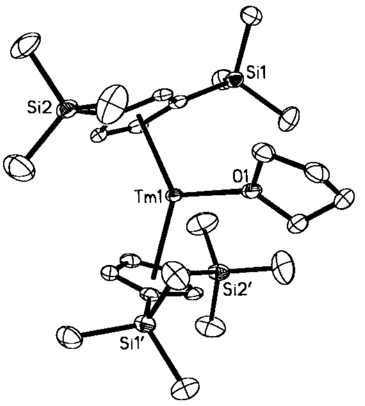
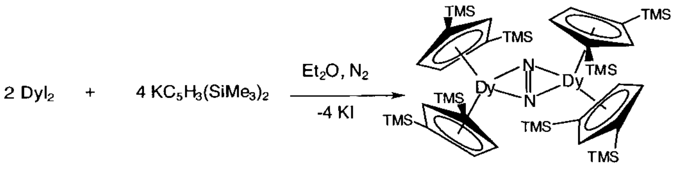


Figure 1. Molecular structure of **1** (with thermal ellipsoids drawn at the 50% probability level).

Since divalent thulium is isoelectronic with Yb^{3+} ($\mu = 4.5$) and ^1H NMR spectra have been successfully obtained for organometallic Yb^{3+} complexes,[13] the NMR spectra of **1** were examined. Spectra were observed, but since small amounts of Tm^{3+} can have a drastic effect on the observed shifts, and the spectra degrade with time as Tm^{2+} ($\mu = 4.6$) converts to Tm^{3+} ($\mu = 7.6$), specific assignments should not be made until data on related complexes are obtained. The ^1H NMR spectrum contained resonance signals with half height peak widths of 50–100 Hz in the range $\delta = -74$ to 15. The ^{13}C NMR spectrum shows a peak at $\delta = -4$, which is assigned to a methyl resonance signal on the basis of a DEPT experiment.

In efforts to expand divalent organolanthanide chemistry to the even more reducing Dy^{2+} (−2.5 V versus NHE), in situ organometallic chemistry with DyI_2[2f, 14] was examined. Reaction of DyI_2 with KCp″ in Et_2O under nitrogen allows isolation of an organodysprosium(II) reduction product, the Dy^{III} dinitrogen complex, $[\{[C_5H_3(SiMe_3)_2]_2Dy\}_2N_2]$ (**2**) [Eq. (2)].



2

(2)

Although detailed information about the bond lengths could not be obtained due the quality of the crystals, the structural data showed that the structure of **2** (Figure 2) is the same as that of $[\{[C_5H_3(SiMe_3)_2]_2Tm\}_2N_2]$.[8] Hence, complex **2** has the same planar Ln_2N_2 array as previously observed for the metallocenes $[\{(C_5Me_5)_2Ln\}_2N_2]$ (Ln = Sm,[15] Tm[8]), $[\{[C_5H_3(SiMe_3)_2]_2Tm\}_2N_2]$,[8] and $[\{(C_5H_4SiMe_3)_2Tm(thf)\}_2N_2]$.[8] This once rare planar Ln_2N_2 geometry[15] has now been found in many lanthanide systems[2c, 16] and appears to be a general structural feature for lanthanide–dinitrogen complexes.

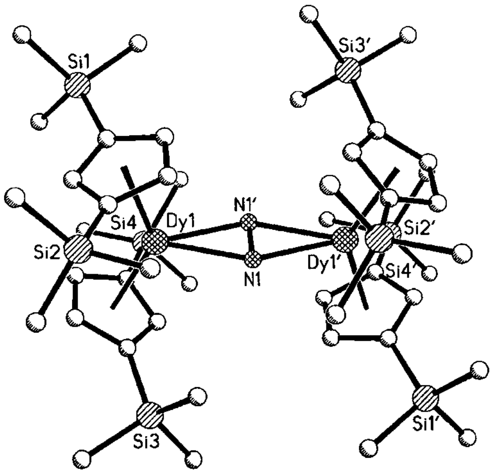


Figure 2. Molecular structure of **2**.

The isolation of **1** demonstrates that under the proper conditions with suitable combinations of solvents and ligands, organometallic complexes of Tm^{II} are isolable directly from Tm^{2+} precursors. The formation of **2** shows that organodysprosium(II) chemistry is viable in situ, but it should be conducted under an atmosphere more inert than nitrogen. Preliminary studies under argon show Dy^{II} to be highly reactive.

Experimental Section

1: In an argon-filled glovebox, the addition of $KC_5H_3(SiMe_3)_2$ (175 mg, 0.70 mmol) to an emerald green solution of $[TmI_2(thf)_3]$ (200 mg, 0.35 mmol) in THF or diethyl ether (10 mL) caused an immediate color change to dark green, with the concurrent production of white insoluble material. After centrifugation to remove the insoluble material, removal of the solvent under vacuum gave a purple powder (230 mg, 90 %). Dissolving the purple solid in Et_2O/hexanes and cooling to $-30\,^{\circ}C$ provided crystals suitable for X-ray diffraction. ^1H NMR (500 MHz,[D$_8$]THF,25 °C): $\delta = 12$ ($\Delta\nu_{1/2} = 370$ Hz), 4 ($\Delta\nu_{1/2} = 45$ Hz), -3 ($\Delta\nu_{1/2} = 50$ Hz), -4 ($\Delta\nu_{1/2} = 370$ Hz), -74 ($\Delta\nu_{1/2} = 50$ Hz); ^{13}C NMR (125 MHz,[D$_8$]THF,25 °C): $\delta = -4$ (CH_3-, by DEPT); IR (KBr): $\tilde{\nu} = 2953$, 1768, 1703, 1365, 1359, 1283, 1223, 1207, 1174, 1136, 1114, 1082, 1027 cm^{-1}; μ_{eff} (298 K) $= 4.6\,\mu_B$; elemental analysis (%) calcd for $C_{26}H_{50}Si_4OTm$ (659.95): Tm 25.60; found: Tm 25.2. Compound **1** crystallizes in the space group *Pbcn* with $a = 11.3735(8)$, $b = 13.6274(10)$, $c = 21.2905(16)$ Å, $V = 3299.8(4)$ Å^3, and $\rho_{calcd} = 1.328$ Mg m^{-3} for $Z = 4$ at 168(2) K. At convergence, $wR2 = 0.0909$ and GOF = 1.231 for 246 variables refined against 2786 data (0.85 Å resolution). As a comparison for refinement on *F*, $R1 = 0.0317$ for those 2158 data with $I > 2.0\sigma(I)$.

2: In a nitrogen-filled glovebox, solvent-free DyI_2[2f] (100 mg, 0.24 mmol) was added to a solution of $KC_5H_3(SiMe_3)_2$ (125 mg, 0.5 mmol) in Et_2O (10 mL). After 2 h at $-15\,^{\circ}C$, the solution was centrifuged to remove a white precipitate (KI) leaving a dark orange solution. Addition of hexanes at $-30\,^{\circ}C$ gave crystals suitable for X-ray analysis (120 mg, 75 %). Compound **2** crystallizes in the space group $P\bar{1}$ with $a = 11.4581(9)$, $b = 11.965(1)$, $c = 12.653(1)$ Å, $\alpha = 118.1662(11)^{\circ}$, $\beta = 102.3962(13)^{\circ}$, $\gamma = 96.1780(13)^{\circ}$, $V = 1449.134(0.341)$ Å^3. The X-ray data established connectivity, but were not sufficient for detailed bond length analysis.

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