Organoindium Reagents

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Crystallographic Characterization of Difluoropropargyl Indium Bromide, a Reactive Fluoroorganometallic Reagent[**]

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Dedicated to Professor Raymond G. Plevey
on the occasion of his 66th birthday

Indium-promoted reactions and their application to synthetic methodologies based on green chemistry have grown exponentially in recent years.[1] The interaction of allylic or propargylic halides with indium metal—through metal/halo-

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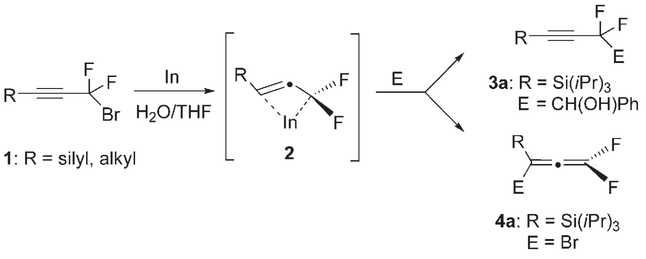
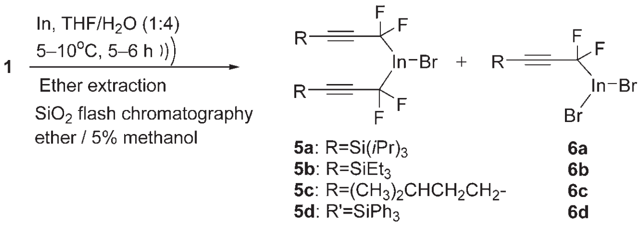
gen exchange or transmetalation—and their subsequent reaction with electrophiles continue to be actively pursued.[2] Initially, an indium sesquihalide ($R_3In_2X_3$) was regarded as a synthetic intermediate.[3] On the basis of recent NMR data, researchers have proposed that indium(I) and indium(III) complexes, or a combination thereof, could mediate allylation[4] and propargylation reactions.[5] Owing to their short-lived nature, the structure of the transient organoindium species is still a matter of debate. By incorporating fluorine on the propargylic carbon atom of **1** prior to its reaction with indium, we were able to stabilize the resulting organoindium complex. Herein we report the first crystallographic characterization of a reactive propargyl indium species.

Earlier, we had reported that the reaction of a silylfluoropropargyl bromide **1** with indium in predominantly aqueous media produced a stable complex, which is loosely represented as **2** (Scheme 1).[6] The organoindium compound **2** yielded **3** or **4**, depending on the nature of the electrophile (E) used.[7,8]



Scheme 1. Indium-mediated difluoroallenylation and -propargylation.

With the purpose of elucidating the structure of **2**, a 1:1 mixture of **1a** (R = Si(iPr)$_3$) and indium metal in predominantly aqueous media was sonicated at 5–10 °C and monitored by ^{19}F NMR spectroscopy (Scheme 2). Two slowly increasing resonance signals, centered at $\delta = -89$ ppm, were detected after 0.5 hours, and all the starting material was consumed after five to six hours. After ether extraction, the resulting solution was relatively stable toward treatment with a mild acid, but the complex decomposed if concentrated to dryness. We isolated each species by using SiO_2 flash chromatography and found that DMSO stabilized the resulting white solids. These compounds could be kept at room temperature for several weeks without decomposition, and could be stored for months in the refrigerator. Elemental analyses indicated that the indium/fluorine/bromine ratios were very close to 1:4:1 (1.03:4:1.11) and 1:2:2 (0.98:2.02:2) for the two compounds; satisfactory carbon and hydrogen analyses were also obtained. IR absorption as well as ^{19}F and ^{13}C NMR signals supported the presence of a propargyl species in solution. On the basis of this evidence, we proposed structures **5a** and **6a**. In a similar fashion, we isolated **5b–d** and **6b–d**.



Scheme 2. Synthesis of difluoropropargyl indium bromides.

Although attempts to obtain suitable single crystals of **5a–c** and **6a–c** failed, we succeeded in obtaining X-ray quality crystals of **5d** by slow evaporation of a saturated solution in DMSO and dichloromethane at room temperature. This compound crystallized as colorless prisms in the $C2/c$ space group. Its ORTEP[9a] view (Figure 1) illustrates the first example of a crystallographically characterized In-C-C≡C complex. Indeed, no crystal structures have been reported to date in the Cambridge Structural Database for an indium atom that is bonded to sp^3 allylic or propargylic carbon atoms.[10] Compound **5d** adopts a trigonal-bipyramidal geometry about the central indium atom with the two 1,1-difluoro-3-triphenylsilylprop-2-ynyl ligands and the Br atom coordinating in the trigonal plane while two dmso ligands occupy axial positions. The In–C bond length (2.217(2) Å) is typical of trigonal-bipyramidal CH_3In complexes, and the In–Br (2.5363(5) Å) and In–O bond lengths (2.2432(18) Å) are also standard.[11] The C1-In-C1′ bond angle (129.12(13)°) is significantly greater than the ideal 120° while the Br1-In-C1 and Br1-In-C1′ angles are contracted (115.44(6)°) to accommodate the large C1-In-C1′ bond angle. To complete the trigonal bipyramid, the coordination of the axial dmso ligands is distorted slightly from linearity (O1-In-O1′ 176.48(10)°). Most significantly the $CF_2C{\equiv}C$ group shows the unprecedented presence of sp hybridization (C2–C3 1.201(4) Å; nearly linear C2-C3-Si1 (176.0(2)°) and C1-C2-C3 (174.3(3)°) angles) located in a position alpha to the CF_2 group.

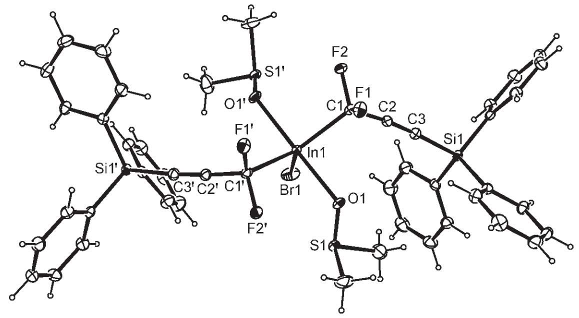


Figure 1. ORTEP showing 45 % displacement ellipsoids. H atoms are shown as spheres of arbitrary radii. Selected bond lengths [Å] and angles [°]: In1-C1 2.217(2), In1-Br1 2.5363(5), In1-O1 2.2432(18), F1-C1 1.398(3), F2-C1 1.392(3), C1-C2 1.456(3), C2-C3 1.201(4); C1-In1-C1 129.12(13), C1-In1-Br1 115.44(6), O1-In1-Br1 91.76(5), C2-C3-Si1 176.0(2), C3-C2-C1 174.3(3).

To demonstrate the reactive nature of these fluoroorganometallic complexes, we treated the obtained mixture of **5a** and **6a** (Scheme 2) with different electrophiles. With a less reactive electrophile (benzaldehyde), the reaction produced **3a** in 51 % yield after two hours in refluxing ether. With a more reactive electrophile such as bromine, **4a** was obtained in 76% yield under very mild conditions (−20°C, 0.5 hours).

In conclusion, we have synthesized and structurally characterized a hitherto unknown propargyl indium reagent, and we have used it to prepare a difluoroalkyne or -allene. The mechanism of formation of fluoroorganoindium complexes, their regiochemistry, and synthetic applications are currently under investigation.

Experimental Section

Indium powder (1 equiv) was added to a 0.15 M solution of **1a** (5 mmol) in a mixture of water and THF (4:1). This mixture was sonicated at 5–10°C for 6–8 h. The temperature in the ultrasound bath was adjusted by addition of ice, and the reaction was periodically monitored by ^{19}F NMR. After the starting material was consumed, the reaction mixture was extracted by ether, and the organic layer was washed with brine, dried over $MgSO_4$, and concentrated. The crude indium complex was dissolved in ether (5 mL) and separated by flash chromatography (80 g SiO_2). The column was eluted with ether (300 mL), then by 5% methanol in ether (300 mL). DMSO (1 mL) was added to each of the two fractions before complete solvent removal. The mixtures were filtered, and the solvent removed from the filtrate by rotary evaporation. The two white solids were washed with hexane and dried in vacuum to give **5a** (750 mg, 37%) and **6a** (400 mg, 13%).

5a·3dmso: M.p. 53–55°C; ^{1}H NMR (500 MHz, $CDCl_3$, 25°C, TMS): $\delta = 1.00$–1.04 (m, 42H, $CH(CH_3)_2$), 2.73 ppm (s, 18H, dmso); ^{13}C NMR (126 MHz, $CDCl_3$, 25°C, TMS): $\delta = 11.3$, 18.8, 39.5 (dmso), 92.5, 104.0 (t, $J = 24.4$ Hz), 131.0 ppm (t, $J = 285$ Hz); ^{19}F NMR (470 MHz, $CDCl_3$, 25°C, CF_3Cl): $\delta = -88.8$ ppm (s, 2F). Elemental analysis (%) calcd for $C_{30}H_{60}BrF_4InO_3S_3Si_2$: C 40.40, H 6.78; found: C 40.59, H 6.52.

6a·3dmso: M.p. 90–92°C; ^{1}H NMR (500 MHz, $CDCl_3$, 25°C, TMS): $\delta = 1.00$–1.07 (m, 21H, $CH(CH_3)_2$), 2.73 ppm (s, 18H, dmso); ^{13}C NMR (126 MHz, $CDCl_3$, 25°C, TMS): $\delta = 11.3$, 18.8, 39.5 (dmso), 93.5, 103.0 (m), 130.0 ppm (m); ^{19}F NMR (470 MHz, $CDCl_3$, 25°C, CF_3Cl): $\delta = -89.1$ ppm (s, 2F). Elemental analysis (%) calcd for $C_{18}H_{39}Br_2F_2InO_3S_3Si$: C 29.20, H 5.31; found: C 29.43, H 5.23.

A colorless crystal of **5d** (dimensions $0.21 \times 0.19 \times 0.16$ mm^3) was mounted on a glass fiber for collection of X-ray data on a Bruker SMART APEX CCD diffractometer. The SMART[9b] software package (version 5.628) was used to acquire a total of 1868 thirty-second-frame ω-scan exposures of data at 100 K ($2\theta_{max} = 56.18°$) using monochromated $Mo_{K\alpha}$ radiation (0.71073 Å) from a sealed tube and a monocapillary. Frame data were processed using SAINT[9c] (version 6.36) to determine the final unit cell parameters ($a = 34.025(3)$ Å, $b = 10.1163(9)$ Å, $c = 13.1193(11)$ Å, $\beta = 95.925(2)°$, $V = 4491.6(7)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.505$ Mg m^{-3}) to produce raw *hkl* data that were then corrected for absorption (transmission min./max. = 0.700/0.764, $\mu = 1.615$ mm^{-1}) by using SADABS.[9d] The structure was solved by Patterson methods in the space group *C*2/*c* by using SHELXS-90[9e] and refined by least-squares methods on F^2 by using SHELXL-97[9f] as part of the SHELXTL[9g] suite of programs. All nonhydrogen atoms were refined anisotropically. Hydrogen atoms were placed in their geometrically generated positions and refined as a riding model. Methyl H atoms were included as fixed contributions with $U(H) = 1.5 \times U_{eq}$ (attached C atom) while the torsion angle which defines its orientation was allowed to refine on the attached C atom. Phenyl H atoms were assigned $U(H) = 1.2 \times U_{eq}$. For all 5225 unique reflections ($R(int) = 0.0381$) the final anisotropic full-matrix least-squares refinement on F^2 for 265 variables converged at $R1 = 0.0363$ and $wR2 = 0.0896$ with a GOF of 1.05.

CCDC-614782 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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