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Homoleptic organolanthanide compounds supported by the bis(dimethylsilyl)benzyl ligand†

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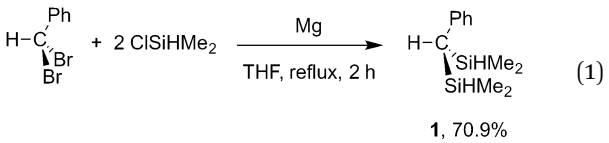
A β-SiH functionalized benzyl anion $[C(SiHMe_2)_2Ph]^-$ is obtained by deprotonation of $HC(SiHMe_2)_2Ph$ with KCH_2Ph or by reaction of KO*t*Bu and $(Me_2HSi)_3CPh$; $LnI_3(THF)_n$ and three equivalents of this carbanion combine to provide homoleptic tris(alkyl)lanthanide compounds $Ln\{C(SiHMe_2)_2Ph\}_3$ (Ln = La, Ce, Pr, Nd) containing secondary metal–ligand interactions.

Synthesis of homoleptic organolanthanide complexes, particularly those of the early trivalent lanthanides (La–Nd), is challenging due to the large radii of these elements, polar bonding, high charge, and high Lewis acidity.[1] Such homoleptic compounds should be valuable for the synthesis of new catalysts and new materials,[2] yet solvent- or donor-group-free, salt-free, and thermally robust organolanthanide compounds are not readily accessed for the larger metal centers. For example, the reaction of MeLi and $LaCl_3$ gives $Li_3[LaMe_6]$ as a TMEDA adduct.[3] Three THF molecules coordinate to the labile tris(benzyl)lanthanum allowing isolation of $LaBn_3(THF)_3$,[4,5] however, even this adduct eliminates toluene at room temperature with a half-life of *ca.* 2 h. The persistence of related compounds may be enhanced by chelating benzylic ligands, for example $Ln(CH(NMe_2)Ph)_3$[6] or $Ln(CH_2C_6H_4\text{-}2\text{-}NMe_2)_3$.[7] An alternative approach combines bulky β-$SiMe_3$ with the benzyl group in $C(SiMe_3)_2Ph$,[8] exemplified by a bis(alkyl)calcium compound possessing metal–aryl π-interactions. Coordinative unsaturation is important to the reactivity of organolanthanides, and donors such as TMEDA or THF can diminish reactivity,[9] facilitate alkane elimination,[10] or react by C–O bond cleavage.[11] While donor-free lanthanum and cerium compounds such as $Ln\{CH(SiMe_3)_2\}_3$ are known, they are inconveniently accessed through multistep synthesis *via* $Ln\{O(2,6\text{-}C_6H_3tBu_2)\}_3$.[12,13]

A strategy for stabilizing coordinatively unsaturated rare earth amides has involved the incorporation of SiH groups, which form labile secondary interactions with the lanthanide center.[14] Furthermore, the SiH moiety provides a powerful signature in ^1H and ^{29}Si NMR and IR spectra. This β-SiH strategy may also be applied to alkyls, and the ligand $C(SiHMe_2)_3$ supports trivalent yttrium and divalent ytterbium and samarium homoleptic alkyls containing secondary Ln···H–Si interactions.[15,16] Recently, we reported $Ce\{C(SiHMe_2)_3\}_3$ as a precursor to a zwitterionic hydrosilylation catalyst.[17] New chemistry might be accessed with alkyl ligand variations that include both β-SiH and benzylic functionalities, and these groups could compete to enhance the homoleptic compounds' resistance to undesired ligand elimination pathways. Both SiH and benzyl groups may have significant charge delocalization and secondary interactions that might stabilize homoleptic compounds. A single ligand containing both elements, namely $-C(SiHMe_2)_2Ph$, would test these ideas. Here we report the synthesis of alkane precursors, two routes to potassium alkyl reagents, and isolation and characterization of a series of homoleptic organolanthanide complexes.

Reductive coupling of $HCPhBr_2$ and $ClSiHMe_2$ affords $HC(SiHMe_2)_2Ph$ (**1**; eqn (1)) on preparative scale.



(1)

1, 70.9%

A diagnostic triplet in the ^1H NMR spectrum at 1.43 ppm ($^3J_{HH}$ = 4 Hz, 1 H) for the H on the central carbon is coupled to a signal at 4.34 ppm assigned to the SiH (2 H, $^1J_{SiH}$ = 186 Hz). The two $SiHMe_2$ groups are magnetically inequivalent giving a virtual octet for the SiH resonance (a $M(AX_3Y_3)(AX_3Y_3)'$ spin system). Compound **1** is also characterized by an intense ν_{SiH} absorbance at 2115 cm^{-1} in its IR spectrum.

While $HC(SiHMe_2)_3$[18] reacts readily with lithium diisopropylamide,[19] deprotonation of $HC(SiHMe_2)_2Ph$ is more challenging. Attempts to synthesize $[C(SiHMe_2)_2Ph]^-$ using $LiN(SiMe_3)_2$, *n*BuLi,

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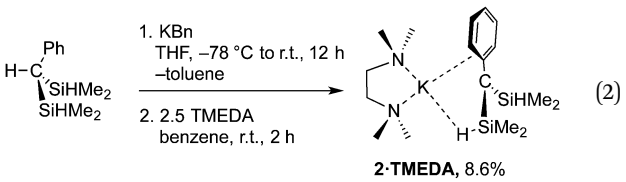
KH, or $KC(SiHMe_2)_3$ as bases returned $HC(SiHMe_2)_2Ph$. Potassium benzyl (KBn) gives Me_2SiBn_2 as the major product in its reaction with **1** at room temperature. Fortunately, reactions with KBn performed at −78 °C yielded a mixture now dominated by $KC(SiHMe_2)_2Ph$ (**2**), assigned to a doublet at 0.47 ppm in the ^{1}H NMR spectrum. This signal was affected by addition of TMEDA, which gave a new doublet at 0.57 ppm. In preparative scale reactions, the desired potassium alkyl is crystallized from pentane at −30 °C to provide $Ph(Me_2HSi)_2CK(TMEDA)$ (**2·TMEDA**) as dark red crystals (eqn (2)), albeit in low isolated yield.



(2)

2·TMEDA, 8.6%

The ^{1}H NMR spectrum of isolated **2·TMEDA** contained a septet at 4.78 ppm ($^1J_{SiH}$ = 162 Hz). This one-bond coupling constant was reduced compared to $HC(SiHMe_2)_2Ph$ (186 Hz). In **2·TMEDA**, the $SiMe_2$ groups appeared as one doublet ($^3J_{HH}$ = 3.6 Hz), unlike the diastereotopic methyls in $HC(SiHMe_2)_2Ph$ noted above. In addition, the IR spectrum of **2·TMEDA** revealed two ν_{SiH} bands at 2115 and 1995 cm^{-1}.

A single-crystal X-ray diffraction study revealed a polymeric structure for **2·TMEDA**,‡ with each K cation interacting with two $C(SiHMe_2)_2Ph$ groups (Fig. 1) through the H1s (2.82(4) Å), the C6 and C11 (from a phenyl group) of one ligand, and the C9 and C10 from a phenyl of the second. Notably, the K1–C1 distance (3.565(4) Å; *i.e.*, to the presumed carbanionic center) is exceedingly long and outside expected bonding range. For comparison, the K–C distance (3.030(5) Å) is much shorter in dimeric $\{(Me_2HSi)_3CK(TMEDA)\}_2$ than in **2·TMEDA**.[16] The SiH-free potassium alkyl $\{KC(SiMe_3)_2Ph\}_n$ (3.007(2) Å)[8] and the compound $\{KC(SiMe_2Ph)_2(SiHMe_2)\}_n$ (3.167(8) Å)[20] also have polymeric structures with π-coordinated arenes. While the central, carbanionic carbon adopts distorted, nearly planar geometries in these three examples (Σ_{angles} = 358.8°, 357.4° and 356.5°),[8,16,20] C1 in **2·TMEDA** is perfectly planar (Σ_{angles} = 360.0(5)°).

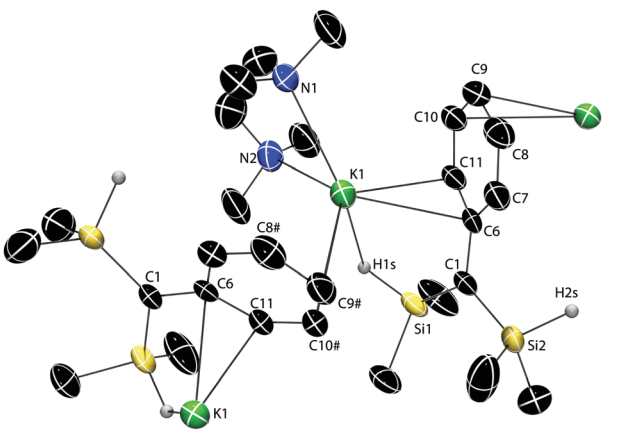
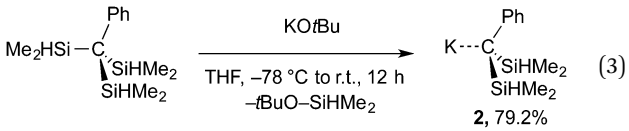


Fig. 1 Thermal ellipsoid plot of $Ph(Me_2HSi)_2CK(TMEDA)$ (**2·TMEDA**) at 50% probability. H1s and H2s were located objectively in the Fourier difference map and refined. H atoms bonded to C are not illustrated for clarity. Selected interatomic distances (Å): K1–C1, 3.565(4); K1–H1s, 2.82(4); K1–Si1, 3.844(2); K1–C6, 3.049(4); K1–C7, 3.389(5); K1–C8#, 3.359(5); K1–C9#, 3.085(5); K1–C10#, 3.038(4); K1–C11, 3.091(5); C1–C6, 1.446(6); C6–C7, 1.434(7); C7–C8, 1.376(7); C8–C9, 1.392(7); C9–C10, 1.383(7); C10–C11, 1.374(6); C11–C6, 1.422(6). Selected interatomic angles (°): K1–H1s–Si1, 124(2); C6–C1–Si2, 119.8(3); Si2–C1–Si1, 121.6(2); Si1–C1–C6, 118.6(3).

The formation of Bn_2SiMe_2 in these reactions implies nucleophilic attack by KBn on a $SiHMe_2$ group and suggests an alternative route to the desired $KC(SiHMe_2)_2Ph$ (**2**) *via* Si–C cleavage. A related Si–Si bond cleavage provides $MSi(SiMe_3)_3$ from $Si(SiMe_3)_4$ and LiMe or KO*t*Bu.[21] This idea was tested by the reaction of $(Me_2HSi)_3CPh$ and KO*t*Bu to give the desired $KC(SiHMe_2)_2Ph$ (**2**) in excellent yield (eqn (3)).

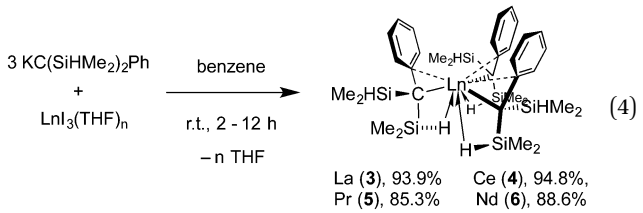


(3)

2, 79.2%

The spectroscopic features of the SiH group in **2** and **2·TMEDA** are similar, including the IR stretching frequency, the chemical shift, and the one-bond coupling constant.

Reactions of three equiv. of **2** or **2·TMEDA** and $LaI_3(THF)_4$, $CeI_3(THF)_4$, $PrI_3(THF)_3$, or $NdI_3(THF)_3$ provide $Ln\{C(SiHMe_2)_2Ph\}_3$ (Ln = La (**3**), Ce (**4**), Pr (**5**), Nd (**6**)) in excellent yields (eqn (4)).



(4)

La (**3**), 93.9% Ce (**4**), 94.8%,
Pr (**5**), 85.3% Nd (**6**), 88.6%

The series of compounds provide pale yellow, orange, yellow and green crystalline materials, respectively. IR spectra for **3**, **5**, and **6** (KBr) each contained a sharp, higher energy ν_{SiH} band (2109 ± 5 cm^{-1}) assigned to non-bridging SiH and a broad, lower energy band (1866 ± 6 cm^{-1}) attributed to a ν_{SiH} of the Ln⟝H–Si. In contrast, the cerium compound **4** showed only one ν_{SiH} band, which appeared at 2115 cm^{-1}. The solution IR spectra similarly showed two SiH absorbances for **3**, **5** and **6**. Although two ν_{SiH} bands were obtained for **4** in solution, the bands were low intensity and a number of the IR spectra were dominated by $HC(SiHMe_2)_2Ph$. We attributed these observations to labile secondary Ln⟝H–Si interactions present both in solution and solid state.

The ^{1}H NMR spectrum of diamagnetic **3** revealed signals at 4.24, 0.43, and 0.32 ppm attributed to equivalent $SiHMe_2$ groups with diastereotopic methyl moieties. A doublet resonance at 5.84 ppm, assigned to an *ortho*-C_6H_5, appeared upfield compared to its chemical shift in the alkane starting material (6.97 ppm), suggesting a multihapto benzyl-Ln coordination. Evidence for La⟝H–Si interactions were provided by the $^1J_{SiH}$ of 144 Hz. The equivalence of the $SiHMe_2$ in the room

temperature NMR spectrum contrasts the two types of SiH groups observed in the IR spectra, suggesting fluxional process(es). A ^{1}H NMR spectrum collected at −73 °C in toluene-d_8 revealed that two $SiHMe_2$ groups were inequivalent: signals at 4.67 ($^1J_{SiH}$ ∼ 180 Hz) and 3.82 ($^1J_{SiH}$ ∼ 120 Hz) ppm were assigned to nonbridging SiH and bridging Ln←H–Si moieties, respectively. These resonances correlated in a COSY experiment to signals at 0.35 and 0.08 ppm (with the downfield SiH) and 0.77 and 0.67 ppm (with the upfield SiH) of the now inequivalent methyl groups. Notably, one of the *ortho*-C_6H_5, whose resonance appeared unusually upfield at 4.15 ppm, was even more shielded than the nonbridging SiH. Moreover, all five H in the C_6H_5 were inequivalent. Thus, the alkyl ligands are equivalent in the low temperature solution-phase structure, with each ligand containing one La←H–Si and a π-coordinated aryl group.

Single crystal X-ray diffraction reveals that the molecular structure of **3** ($P\bar{3}$) contains three, crystallographically related $C(SiHMe_2)_2Ph$ ligands, each of which interacts with the lanthanum center through the central carbon (C1), through a benzylic-type coordination of the C6, and also through one La←H–Si (Fig. 2).§ The three ligands are arranged in a trigonal geometry around the lanthanum center ($\Sigma_{C1\text{–}La1\text{–}C1}$ = 357.15(6)°). This structure is consistent with the low temperature NMR and IR spectroscopic data. A few of the notable structural features include the sharp La1–C1–Si1 angle (93.0(1)°), short La1···Si1 and La1···H1s distances (3.3141(9) and 2.69(4) Å), and an unusually long La1–C1 distance (2.674(3) Å). The corresponding La–C distances in six-coordinate tris(benzyl)-lanthanum compounds, *e.g.*, $La(CH_2Ph)_3(THF)_3$ (2.648(2) Å),[5] are shorter, and the distance in $La(CH(SiMe_3)_2)_3$ (2.515(9) Å) is much shorter.[12] These trends extend to the comparisons of structures of **4–6** to the analogous benzyllanthanide species. Moreover, the close contacts in the series (*i.e.*, Ln–C, Ln···Si, and Ln···H) follow the expected trend based on ionic radius (La > Ce > Pr > Nd).

Interestingly, isomorphous cerium **4**, praseodymium **5** and neodymium **6** compounds' structures ($P2_1/c$) are inequivalent with that of La **3**. The two molecules in the unit cells for **4**, **5** and **6** have inequivalent configurations, with one of the molecules containing only two Ln←H–Si bridging moieties (Fig. 3).¶ The Ce–C distances for the five ligands that contain bridging Ce←H–Si interactions average 2.65 ± 0.02 Å, whereas the η^2-benzyl-only ligand (Ce2–C56, 2.587(3) Å) distance is shorter. This distinction is also apparent in compounds **5** (Pr–C_{ave}, 2.63 ± 0.02; Pr2–C56, 2.556(5) Å) and **6** (Nd–C_{ave}, 2.61 ± 0.02; Nd2–C56, 2.541(4) Å).

This work extends the idea that the β-SiH group supports large, coordinatively unsaturated rare earth centers in homoleptic, solvent-free compounds to include a new mixed benzyl dimethylsilyl ligand. Tris(alkyl) lanthanides $Ln\{C(SiHMe_2)_2Ph\}_3$ are synthesized in good yields, and the secondary interactions involving β-SiH and aryl moieties are likely important to the facile isolation of these compounds. The structural parameters (*e.g.*, Ln–C, Si–H, Si–C distances) for moieties involved in

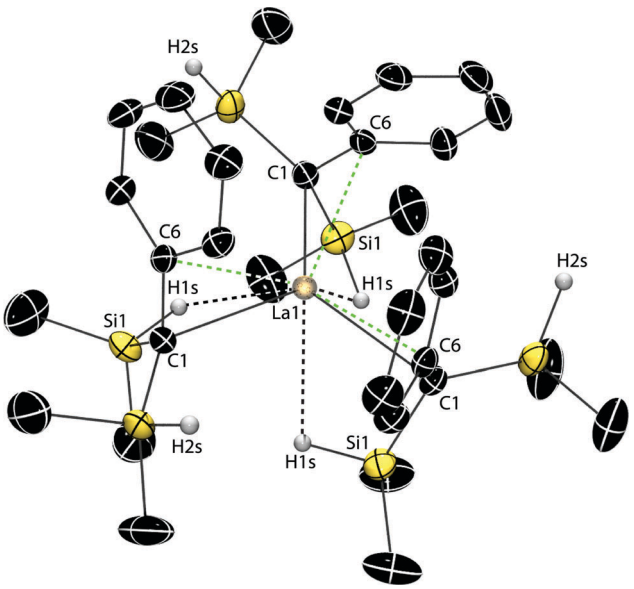


Fig. 2 Thermal ellipsoid plot of $La(C(SiHMe_2)_2Ph)_3$ (**3**). La1 is located on a crystallographic 3-fold axis. H atoms bonded to Si are located in the Fourier difference map, their positions are refined and are illustrated. All other H atoms and a disordered pentane molecule (0.5) are not shown for clarity. Short La–C (green) and Ln←H–Si (black) distances are highlighted with dashed lines. Selected interatomic distances (Å): La1–C1, 2.674(3); La1–C6, 2.822(2); La1–Si1, 3.3141(9); La1–H1s, 2.69(4); C1–Si1, 1.821(3); Si1–H1s, 1.37(4); C1–Si2, 1.853(3); Si2–H2s, 1.45(4); C1–C6, 1.483(4); C6–C7, 1.415(5); C6–C11, 1.409(4). Selected interatomic angles (°): C1–La1–C1, 119.05(2); La1–C1–C6, 80.0(1); La1–C1–Si1, 93.0(1); La1–C1–Si2, 128.3(1).

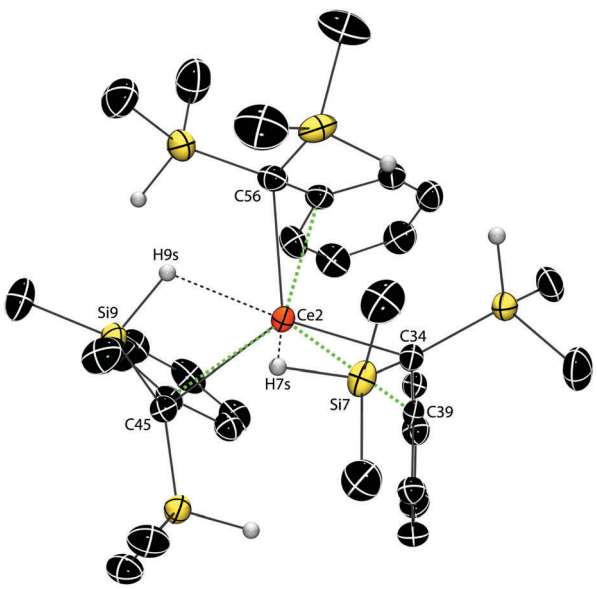


Fig. 3 Thermal ellipsoid plot of one of two crystallographically distinct molecules of $Ce(C(SiHMe_2)_2Ph)_3$ (**4**). H atoms bonded to Si are located in the Fourier difference map, their positions are refined and are illustrated. All other H atoms are not shown for clarity. Short Ce–C (green) and Ln←H–Si (black) distances are highlighted with dashed lines. Selected interatomic distances (Å): Ce2–C34, 2.613(3); Ce2–C45, 2.671(2); Ce2–C56, 2.587(3); Ce2–Si7, 3.1947(9); Ce2–H7s, 2.47(2); C34–Si7, 1.829(2); Si7–H7s, 1.48(3); Ce2–Si9, 3.2379(9); Ce2–H9s, 2.46(3); C45–Si9, 1.829(3); Si9–H9s, 1.48(3); Selected interatomic angles (°): C34–Ce2–C45, 118.57(9); Ce2–C34–C39, 83.8(2); Ce2–C34–Si7, 90.1(1).

secondary Ln←H–Si interactions are different than those with nonbridging SiH groups, and the Ln–C distances are also affected by the presence or lack of secondary Ln←H–Si interactions. The ligand itself is synthesized by deprotonation of the new alkane $HC(SiHMe_2)_2Ph$ with KBn, but Me_2SiBn_2 and other side products in reactions of $HC(SiHMe_2)_2Ph$ and KBn suggested a competing reaction involving nucleophilic attack on a Si center to cleave the C–Si bond. Therefore we developed an alternative route to $KC(SiHMe_2)_2Ph$ by reacting $PhC(SiHMe_2)_3$ with KO*t*Bu that affords the desired product in excellent yield. This straightforward two-step synthesis to homoleptic organolanthanides may allow their application in the preparation of heteroleptic lanthanide complexes and as precursors for new catalytic chemistry.

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‡ X-ray data for **2**·**TMEDA** (CCDC 1517682): $C_{17}H_{35}KN_2Si_2$; FW 362.75; monoclinic; *a*: 8.7354(6), *b*: 23.003(1), *c*: 11.6433(7), *β*: 100.207(4), volume: 2302.5(3); *P*121/*c*1; *Z* = 4; temp. 173 K; reflections: collected, 20 907; independent, 3284; R_{int} 0.1552; 2217 data $I > 2\sigma(I)$: R_1 0.0705, wR_2 0.1845; R_{all}: R_1 0.0996, wR_2 0.2145.
§ X-ray data for **3** (CCDC: 1517683): $C_{33}H_{57}LaSi_6\cdot(C_5H_{12})_{1/2}$; FW 797.31; trigonal; *a*: 12.4380(6), *c*: 16.157(1), volume, 2164.7(3); $P\bar{3}$; *Z* = 2; temp. 173 K; reflections: collected, 23 107; independent, 3715; R_{int} 0.0345; 3439 data $I > 2\sigma(I)$: R_1 0.0309, wR_2 0.0828; R_{all}: R_1 0.0351, wR_2 0.0928.
¶ X-ray data for **4** (CCDC: 1517684): $C_{33}H_{57}CeSi_6$; FW 762.44; monoclinic; *a*: 22.324(2), *b*: 19.841(1), *c*: 19.921(1), *β*: 116.076(1), volume: 7925.5(9); *P*121/*c*1; *Z* = 8; temp. 173 K; reflections: collected, 79 198; independent, 18 762; R_{int} 0.0485; 14 549 data $I > 2\sigma(I)$: R_1 0.0315, wR_2 0.0698; R_{all}: R_1 0.0515, wR_2 0.0836; X-ray data for **5** (CCDC 1517686): $C_{33}H_{57}PrSi_6$; FW 763.23; monoclinic; *a*: 22.3310(6), *b*: 19.8399(5), *c*: 19.8802(5), *β*: 116.047(1), volume: 7913.2(4); *P*121/*c*1; *Z* = 8; temp. 173 K; reflections: collected, 79 681; independent, 15 456; R_{int} 0.0653; 14 828 data $I > 2\sigma(I)$: R_1 0.0695, wR_2 0.1909; R_{all}: R_1 0.0710, wR_2 0.1931; X-ray data for **6** (CCDC: 1517685): $C_{33}H_{57}NdSi_6$; monoclinic; *a*: 22.335(2), *b*: 19.843(2), *c*: 19.855(2), *β*: 116.017(1), volume: 7908(1); *P*121/*c*1; *Z* = 8; temp. 173 K; reflections: collected, 113 017; independent, 20 627; R_{int} 0.0711; 15 075 data $I > 2\sigma(I)$: R_1 0.0346, wR_2 0.0623; R_{all}: R_1 0.0624, wR_2 0.0768.

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