



Cite this: *Dalton Trans.*, 2025, **54**,
2301Received 11th November 2024,
Accepted 29th November 2024

DOI: 10.1039/d4dt03148b

rsc.li/dalton

Donor-free 9-aluminafluorenes: molecular structures and reactivity†

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Aluminum-doped polycyclic aromatic hydrocarbons (PAHs) are underexplored despite the broad applications of boron-containing PAHs in areas such as catalysis and optoelectronics. We disclose the donor-free, sterically unprotected 9-methyl-9-aluminafluorene (Me-AlFlu; **2**), synthesized by heating a 9,9-dimethyl-9-stannafluorene and AlMe₃ in hexanes. The compound is a dimer, (**2**)₂, with *trans*-positioned AlMe substituents in the solid state. In solution, (**2**)₂ shows a dynamic *cis/trans*-interconversion rather than a monomer-dimer equilibrium (Tol-*d*₈, RT). Lewis bases L cleave (**2**)₂ into monomeric adducts **2**·L (L = OEt₂, thf, pyridine). Lewis acidic AlBr₃ transforms (**2**)₂ into a 2,2'-(Br₂Al)₂-1,1'-biphenyl (**3**), crystallographically characterized as dimeric (**3**)₂. (**3**)₂ is a synthetic equivalent for the elusive free Br-AlFlu: Treatment with donor molecules furnishes Br-AlFlu·L adducts (L = OEt₂, pyridine); the three-coordinate, monomeric aluminafluorene Mes*·AlFlu was prepared from (**3**)₂, Mes*Li, and a 2,2'-dilithio-1,1'-biphenyl in quantitative yield (Mes* = 2,4,6-(*t*Bu)₃C₆H₂).

Introduction

Doping organic π -electron systems with other p-block elements is an effective strategy to impart new chemical and physical properties to these species.¹ Specifically, the combination of a polycyclic aromatic hydrocarbon (PAH) such as fluorene with boron as a dopant to generate 9-borafluorenes (BFlus) can have a particularly pronounced effect,^{2,3} as a conjugation barrier (*i.e.*, the CH₂ fragment in the carbonaceous species) is removed and a vacant B(p_z) orbital is introduced instead, which can now: (i) mediate electron delocalization and bring about novel optoelectronic properties,⁴ (ii) facilitate reduction,^{5,6} and (iii) act as a Lewis acid to promote bond-activation reactions⁷ or the expansion of the five-membered central borole ring.⁸

Compared to the extensive research on BFlus, their heavier homologues, the 9-aluminafluorenes (AlFlus),^{9,10} are far less well explored. This is unfortunate, because AlFlus are expected to exhibit a lower degree of aryl-heteroatom double-bond character than BFlus,¹¹ leading to a greater propensity to form structurally intriguing aggregates through Al... π (Ar) complexes

or Al–C–Al' two-electron–three-center (2e3c) bonds. Relative to open-chain arylaluminum compounds, AlFlus should possess a structurally enforced enhanced Lewis acidity due to their small endohedral C–Al–C angle. This angle (108° in a regular five-membered ring) deviates more from the ideal 120° angle of three-coordinate AlR₃ species than from the corresponding angles of perfectly tetrahedral (109.5°) adducts. By the same token, the behavior of Al-based Lewis acids is more diverse than that of their B-based counterparts, as Al sites, unlike B centers, can readily accommodate coordination numbers larger than four.

In 1962, Eisch *et al.* reported the formation of Ph-AlFlu through the metalative cyclization of *o*-biphenyl(diphenyl) aluminum at 200 °C. Their claim was mainly based on the analysis of hydrolysis and iodolysis products.^{12,13} The topic lay dormant until 2015, when Chujo and Tanaka used salt-metalation protocols to synthesize AlFlus carrying Al-bonded phenyl rings with one or two chelating (dimethylamino)methyl substituents at their *ortho* positions (Fig. 1). Their research focused on the emission properties of the obtained four- and five-coordinate AlFlus.^{14,15} More recently, Braunschweig *et al.* disclosed the synthesis of various aluminafluorenes R-AlFlu [R = 1,2,4-(*t*Bu)₃C₅H₂ (92%; Fig. 1), Ph₂(*t*Bu)Si (44%), 2-C₄H₃S (79%), *t*Bu (23%; Fig. 1), Br (53%)]. The compounds were again prepared from 2,2'-dilithio-1,1'-biphenyl by salt-metalation reactions and isolated and structurally characterized as their ether adducts – with the exception of the η^5 -cyclopentadienide derivative, which is monomeric in the solid state, and the *t*Bu derivative, which crystallizes as a dimer.¹⁶

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† Electronic supplementary information (ESI) available: Synthetic procedures, NMR spectra, X-ray crystallographic data and computational details. CCDC 2394332–2394341. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d4dt03148b>



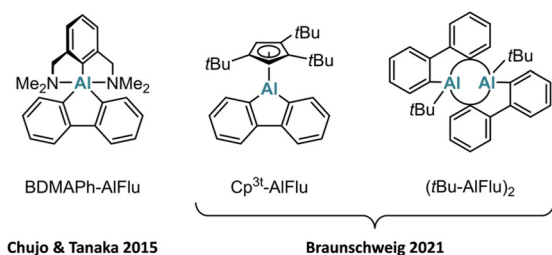


Fig. 1 Known mono- and dimeric 9-aluminafluorenes featuring 2,6-bis[(dimethylamino)methyl]phenyl (BDMAPh), 1,2,4-(*t*Bu)₃C₅H₂ (Cp^{3t}), and *tert*-butyl (*t*Bu) substituents.

One aim of our study outlined herein was to develop straightforward, high-yield synthesis protocols for base-free R-AlFlus featuring (i) the small substituent R = Me to minimize steric shielding of the Al center, and (ii) the reactive substituent R = Br for late-stage derivatization. Particular emphasis was placed on the molecular structure of Me-AlFlu in non-donor solvents and in the solid state, as well as on the synthesis of the first base-free, three-coordinate, monomeric aluminafluorene, Mes^{*}-AlFlu (Mes^{*} = 2,4,6-(*t*Bu)₃C₆H₂). All our AlFlus were equipped with *t*Bu groups in their 2,7-positions to enhance solubility in non-polar solvents and to facilitate NMR-spectroscopic analysis.

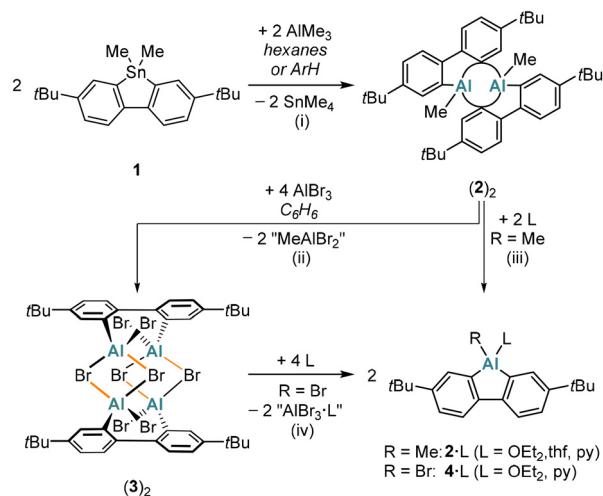
Results and discussion

Syntheses

The base-free Me-AlFlu (**2**) was synthesized by heating the 9,9-dimethyl-9-stannafluorene **1** with 1 equiv. of AlMe₃¹⁷ in either hexanes or C₆H₆/toluene (Scheme 1). The only by-product formed is the volatile and relatively inert SnMe₄.^{18,19} An advantage of using hexanes as the solvent is that the dimer (**2**)₂ precipitates in pure form already upon cooling the reaction mixture to room temperature (yield: 74%); when C₆H₆/toluene is employed, the yield of (**2**)₂ is higher (91%), but some further workup is required. In the presence of the donor molecules Et₂O, THF, or pyridine, (**2**)₂ is cleanly split into its constituting monomers to furnish the monoadducts 2-OEt₂, 2-thf, or 2-py (Scheme 1).

Treatment of (**2**)₂ with 4 equiv. of AlBr₃¹⁷ in C₆H₆ results not only in quantitative AlMe/AlBr exchange but also in the incorporation of two AlBr₃ molecules to afford dimeric 2,2'-(Br₂Al)₂-1,1'-biphenyl [(**3**)₂, 95%; Scheme 1]. Upon addition of Et₂O to (**3**)₂ in C₆H₆, the donor adduct of Br-AlFlu, 4-OEt₂, precipitates quantitatively as a colorless solid. In terms of yield, our overall synthesis cascade to 4-OEt₂ improves upon the published protocol¹⁶ by about 40 percentage points. Although pyridine can also reconstitute the AlFlu scaffold from (**3**)₂, it proved challenging to separate the target product 4-py from by-products such as [AlBr₂(py)₄][X] ([**5**][X]; X = Br⁻, AlBr₄⁻; Fig. S44 and S45[†]).

A particularly notable application of (**3**)₂ as a synthetic equivalent of donor-free Br-AlFlu is the preparation of Mes^{*}-AlFlu

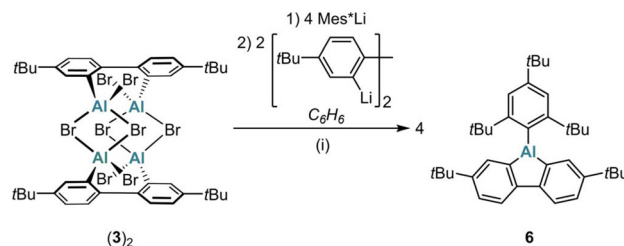


Scheme 1 Synthesis of donor-free (**2**)₂ through Sn/Al exchange between the 9-stannafluorene **1** and AlMe₃ (ArH: C₆H₆/toluene). The addition of AlBr₃ to (**2**)₂ furnishes (**3**)₂. Lewis bases (L: Et₂O, THF, or pyridine), cleave (**2**)₂ or (**3**)₂ into the monomeric adducts 2-L or 4-L. (i) Hexanes, 140 °C, 3 d (74% yield) or C₆H₆/toluene, 120 °C, 3 d (91% yield); sealed glass ampoule. (ii) C₆H₆, room temperature, 1 d (95% yield). (iii) 2-OEt₂: in Et₂O, room temperature; 2-thf: C₆D₆, room temperature; 2-py: C₆H₆, room temperature (quantitative conversions). (iv) 4-OEt₂: C₆H₆, room temperature (quantitative conversion); 4-py: C₆D₆, room temperature (not isolated). Note: in (**3**)₂, four bonds were arbitrarily chosen as formally intermolecular (highlighted in orange) to facilitate the distinction between the monomers M and M'.

(**6**): sequential addition of Mes^{*}Li (4 equiv.) and 2,2'-dilithio-4,4'-di-*tert*-butyl-1,1'-biphenyl (2 equiv.) to (**3**)₂ in C₆H₆ gave **6** in 97% yield (Scheme 2).

Solid-state structures

In the solid state, Me-AlFlu forms centrosymmetric dimers, with the Al-bonded Me substituents adopting a *trans*-configuration (*trans*-(**2**)₂; Fig. 2).²⁰ The individual monomers, M and M', are linked by two Al...C interactions, resulting in two Al(1) ...Al(1') bridging aryl rings (Ar_b) and two terminal rings (Ar_t), with bridging [C(11)] and terminal [C(21)] *ipso*-C atoms. The position of Ar_b is asymmetric between Al(1) and Al(1'), as indicated by the differing angles Al(1)-C(11) ... C(14) = 153.13(17)° and Al(1')-C(11) ... C(14) = 128.38(16)°. The fact that the



Scheme 2 Synthesis of Mes^{*}-AlFlu (**6**) using (**3**)₂ as a synthetic equivalent of the elusive Br-AlFlu. (i) C₆H₆, room temperature, 1 d (97% yield).



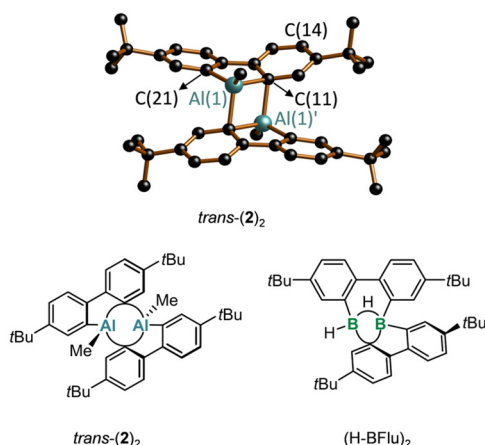


Fig. 2 Top: molecular structure of *trans*-(**2**)₂ in the solid state; H atoms omitted for clarity (C: black, Al: turquoise). Bottom: structural formulae of *trans*-(**2**)₂ and of the comparable 9-borafluorene dimer (H-BFlu)₂.

Al(1)'-C(11)-C(14) angle is significantly closer to 90° than the Al(1)-C(11)-C(14) angle can still be viewed as a remnant of the initial intermolecular Al... π (Ar) complex when the two heterofluorene units first encountered each other. Correspondingly, the 'intermonomer' Al(1)-C(11) bond (2.148(3) Å) is longer by 0.055 Å than the 'intramonomer' Al(1)-C(11) bond (2.093(3) Å; *cf.* Al(1)-C(21) = 1.971(3) Å). The range of C-C bond lengths in Ar_b (1.382(5)-1.427(5) Å) is close to that in Ar_t (1.389(5)-1.409(5) Å), indicating that the bridging mode does not lead to a systematic bond-length alternation. However, the two C-C bonds involving the bridging C(11) atom are slightly longer than the other four (1.409(4) and 1.427(5) Å vs. 1.382(5)-1.401(5) Å). Finally, we note that *trans*-(**2**)₂ has very similar structural parameters to Braunschweig's (*t*Bu-AlFlu)₂,¹⁶ while the comparable 9-borafluorene dimer (H-BFlu)₂ shows one B-(μ -H)-B two-electron-three-center bond and one B...B'-bridging aryl ring (the three other rings remain terminally bonded).²¹

X-ray crystallography reveals that the compound (**3**)₂ no longer contains the 9-aluminafluorene motif but instead forms a centrosymmetric 2,2'-(Br₂Al)₂-1,1'-biphenyl dimer (Fig. 3).

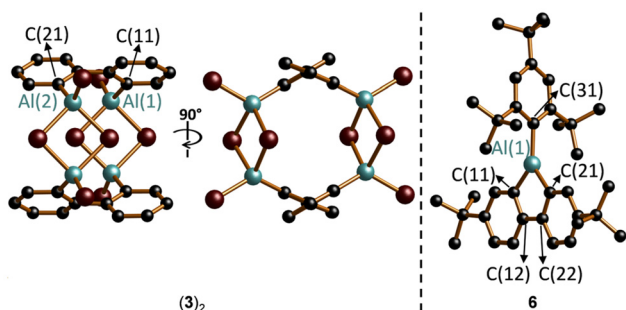


Fig. 3 Left: molecular structure of (**3**)₂ in the solid state, viewed from two different perspectives; *t*Bu-groups in the 2,7-positions of the biphenyl backbones and H atoms omitted for clarity. Right: molecular structure of **6** in the solid state; H atoms omitted for clarity (C: black, Al: turquoise, Br: brown).

The two Br₂Al substituents in each monomer adopt an approximate *s-trans* configuration with a torsion angle Al(1)-C(11)-C(21)-Al(2) of 129.55(19)° [Al(1)-C(11) = 1.945(5) Å, Al(2)-C(21) = 1.956(4) Å]. Four Br atoms occupy bridging positions between Al centers of different monomers, assembling the cage-like structure of (**3**)₂. The underlying structural feature, a four-membered R(Br)Al-(μ -Br)₂-Al(Br)R ring, is common not only for aluminum tribromide (R = Br) but also for numerous dibromo(organo)alanes.²²

The 2,4,6-(*t*Bu)₃C₆H₂-substituted Mes*-AlFlu (**6**) exists as a monomeric species with a three-coordinate Al center in the crystal lattice (Fig. 3). The sum of C-Al-C angles is 360°, confirming a trigonal-planar ligand environment, although the endocyclic C(11)-Al(1)-C(21) bond angle is nearly rectangular (91.79(6)°). All three Al-C bonds are of equal length, regardless of whether they are endo- or exocyclic, or whether the respective *ipso*-C(*p_z*) orbital is positioned parallel or orthogonal to the vacant Al(*p_z*) orbital [Al(1)-C(11)/C(21)/C(31) = 1.9611(14)/1.9516(14)/1.9606(13) Å]. Within the five-membered AlC₄ core, the length of the central C(12)-C(22) bond (1.5024(19) Å) approaches that of a typical C-C single bond (1.54 Å),²³ while the benzannulated bonds are significantly shorter [C(11)-C(12)/C(21)-C(22) = 1.4208(18)/1.4134(18) Å]. The other ten C-C bonds within the biphenyl fragment fall within a narrow range of 1.389(2)-1.4041(19) Å, closely matching the corresponding bonds in C₆H₆ (1.39 Å).²⁴ Taken together, this analysis of bond lengths suggests that the AlFlu moiety of **6** preserves two largely unperturbed Clar sextets within its two C₆H₃ fragments, with no indication of a delocalized (antiaromatic) π -system, nor any significant Al(1)=C(11)/C(21) double-bond character in the AlC₄ heterocycle.

The donor adducts 2-OEt₂, 2-py, and 4-py were subjected to X-ray analysis to confirm that (**2**)₂ and (**3**)₂ can indeed serve as precursors of Me-AlFlu and Br-AlFlu, respectively (Fig. S40, S41, S43[†]). Furthermore, compared to donor-free **6**, the C-C bond lengths within the C₆H₃-C₆H₃ units of 2-py and 4-py were found to differ by no more than 3 σ (and much less for most bonds).²⁵ This observation again suggests that the vacant Al(*p_z*) orbital exerts no significant electron-withdrawing mesomeric effect on the π -electron system.

NMR analysis

At room temperature, **2** gives severely broadened ¹H NMR signals, providing limited diagnostic value (Tol-*d*₈; Fig. 4 and S7[†]). At 70 °C, two sharp resonances are detectable in the aliphatic region of the spectrum (integral ratio 3H : 18H); the aromatic region contains one broad feature and two doublets with coupling constants of about 8.2 Hz (Fig. 4 and S6[†]). At -30 °C, the ¹H NMR spectrum of **2** is characterized by two well-resolved sets of signals attributable to two different but closely similar components (Fig. 4 and S8[†]); the same is true for the ¹³C{¹H} NMR spectrum (Fig. S9[†]). The proton-integral values of the two sets indicate a minor-to-major component ratio of approximately 0.12 : 1 (Fig. S8[†]). Focusing on the major component, the ¹H NMR spectrum reveals one singlet at -0.67 ppm (6H), and two additional singlets at 1.47 and



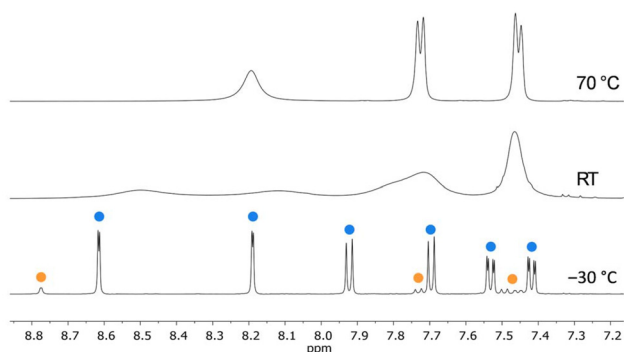


Fig. 4 Aromatic regions of ^1H NMR spectra of $(2)_2$ in Tol- d_8 (500.2 MHz). Top: 70 °C. Middle: room temperature. Bottom: -30 °C. ●: *trans*-(2) $_2$. ●: *cis*-(2) $_2$.

1.28 ppm ($2 \times 18\text{H}$), assignable to two equivalent AlMe substituents and two pairs of non-equivalent *t*Bu groups, respectively. In the aromatic region, four doublets ($4 \times 2\text{H}$; $2 \times {}^3J_{\text{H,H}} = 8.2\text{ Hz}$, $2 \times {}^4J_{\text{H,H}} = 2.2\text{ Hz}$) and two doublets of doublets ($2 \times 2\text{H}$) are observed, indicative of two pairs of non-equivalent C_6H_3 fragments. In principle, these NMR features would align with both the molecular structure of the *cis*- and *trans*-(2) $_2$ dimer (as observed in the solid state). *Vice versa*, the minor signal set likely arises from *trans*- or *cis*-(2) $_2$. At low temperatures, both isomers are present in an (essentially) static mixture, while some dynamic rearrangement equilibrium is established at higher temperatures. This preliminary conclusion raises two questions: (i) Does *cis*- or *trans*-(2) $_2$ dominate at low temperatures? (ii) Is the dynamic equilibrium at high temperatures due to monomer/dimer association/dissociation, or is it the result of a rapidly interconverting *cis/trans* dimeric form of $(2)_2$?

To address question (i), quantum-chemical calculations predict that the crystallographically characterized *trans*-(2) $_2$ is 1.6 kcal mol $^{-1}$ more favorable in energy than *cis*-(2) $_2$ (Scheme S1†; experimental value, determined at -30 °C from the proton-integral values of the minor/major component: $\Delta G^\circ = 0.7\text{ kcal mol}^{-1}$). Furthermore, the relative proportion of the minor component increases with solvent polarity, consistent with the existing dipole moment of *cis*-(2) $_2$ (^1H NMR spectroscopic control; Table S1 and Fig. S1, S2†). Finally, the computed ^{13}C chemical shift values for *cis/trans*-(2) $_2$ align more closely with the assumption that the major component is *trans*-(2) $_2$ rather than *vice versa* (Tables S9–S11†). It is therefore safe to assume that the major component in an equilibrating *cis/trans*-(2) $_2$ mixture is the *trans* isomer.

Regarding question (ii), we note that the computed energy required for cleaving *trans*-(2) $_2$ into its constituting monomers is 19.4 kcal mol $^{-1}$ (in CH_2Cl_2). In contrast, the computed energy barrier of the *cis/trans* interconversion of $(2)_2$ is only $\Delta G^\ddagger = 14.8\text{ kcal mol}^{-1}$, which agrees well with the value of $\approx 14.5\text{ kcal mol}^{-1}$ experimentally determined from the coalescence temperature (T_c) in conjunction with the maximum peak separation ($\Delta\nu$) in the slow-exchange limit (CD_2Cl_2 ; see the

ESI† for full details). The observed NMR features are therefore more convincingly attributed to a dynamic *cis/trans* equilibrium rather than to a monomer/dimer association/dissociation equilibrium.

In the temperature range of -30 to 70 °C, $(3)_2$ exhibited only extremely broadened signals in the ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR spectra, providing no structural information.

The ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR spectra of all adducts formed between our R-AlFlus and Lewis bases are in accord with the proposed molecular structures, as is the case for ligand-free **6** (see the ESI† for the fully assigned spectra). In addition to aiding in structure elucidation, $^{13}\text{C}\{^1\text{H}\}$ NMR spectroscopy is also a valuable tool for mapping the π -charge density distribution in conjugated systems, as the shielding of a specific $\text{C}(\text{sp}^2)$ atom depends linearly on the corresponding π -electron density at that position.²⁶ Given this background, we compared the ^{13}C chemical shift values of the C atoms constituting the C_6H_3 - C_6H_3 fragment of **6** with those of the equivalent atoms in the corresponding fragments of the adducts 2-OEt $_2$, 2-thf, 2-py, 4-OEt $_2$, and 4-py. Except for the Al-bonded *ipso*-C atoms, whose shift differences varied from $\delta(\mathbf{6}) - \delta(\text{adduct}) = 3.3$ to -4.7 ppm without a systematic trend, the $\Delta\delta(^{13}\text{C})$ values for all other structurally analogous C atoms were less than ± 1.8 ppm. In other words, we found no evidence of an overall ^{13}C -deshielding effect or π -electron depletion in **6** that could be attributed to a mesomerically electron-withdrawing $\text{Al}(\text{sp}^2)$ center.

$^{13}\text{C}\{^1\text{H}\}$ NMR spectroscopy on 2-py and 4-py provides a method to evaluate the relative Lewis acidities of free, monomeric Me-AlFlu and Br-AlFlu: in pyridine complexes of main-group elements, stronger acids induce increased shielding of the C-2,6 and deshielding of the C-3,4,5 nuclei of the ligand.²⁷ For 2-py/4-py, our observations consistently indicate that Me-AlFlu is the stronger acid, comparable in this respect to BPh_3 .²⁸ X-ray crystallography, however, offers a contrasting view: 4-py exhibits a shorter Al-N bond and a more pyramidalized Al center, implying higher Lewis acidity for Br-AlFlu.²⁸ Given the small differences in the key NMR and structural parameters between 2-py and 4-py, these conflicting observations highlight the limitation of relying on a single method to determine Lewis acidity, emphasizing the need for complementary approaches.

Conclusions

We synthesized the donor-free 9-aluminafluorene Me-AlFlu (**2**), which was characterized as its dimer $(2)_2$ through X-ray crystallography and VT NMR spectroscopy (Tol- d_8). The key to this success was the highly selective reaction between the 9,9-dimethyl-9-stannafluorene **1** and AlMe_3 ,^{17,18} which proceeds in non-donor solvents and releases volatile SnMe_4 as the sole by-product. Unlike the bulky *tert*-butyl group in *t*Bu-AlFlu,¹⁶ the sterically less demanding methyl substituent in Me-AlFlu allows relatively unhindered access to the electrophilic Al center, as demonstrated by the straightforward formation of



various base adducts 2·L (L = OEt₂, thf, py). In terms of an umpolung of the Al center, exploring the reduction of 2 on a preparative scale could be promising (a non-benzannulated alumole has previously been reduced to its corresponding dianion).¹⁰ The resulting product, [2]²⁻, could potentially serve as an Al-centered nucleophile – analogous to the [H-BFlu]²⁻ dianion, which is a valuable B-centered nucleophile.^{3,6,29}

Treatment of (2)₂ with AlBr₃ furnishes the 2,2'-(Br₂Al)₂-1,1'-biphenyl (3)₂. Although this ring-opened product no longer retains the AlFlu motif, it rearranges back to afford Br-AlFlu adducts, such as 4·L (L = OEt₂, py), in the presence of Lewis bases. The use of Mes*Li, which provides the extremely bulky, negatively charged Lewis base [Mes*]⁻, grants unprecedented access to three-coordinate, monomeric aluminafluorenes, specifically Mes*-AlFlu (6), via LiBr elimination. This reaction proves the utility of (3)₂ as a synthetic equivalent for the still-elusive free Br-AlFlu. A comparison of characteristic structural and NMR features of 6 with those of 2·L/4·L reveals that the three-coordinate Al center exerts only a negligible π-electron withdrawing effect and does not mediate significant π-electron delocalization.

Author contributions

P. L. L. performed the experimental studies and characterized all new compounds. P. L. L. and J. G. performed the quantum-chemical calculations. A. V. performed the X-ray crystal structure analyses of all compounds. H.-W. L. and M. W. supervised the project. The manuscript was written by P. L. L. and M. W. and edited by all co-authors.

Data availability

The datasets supporting this article have been uploaded as part of the ESI.†

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are grateful to Gabriele Sentis for performing all VT NMR measurements. We thank the center for scientific computing (CSC) Frankfurt and the University of Kent for providing HPC resources that contributed to the computational investigation of this work.

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