# Dalton Transactions



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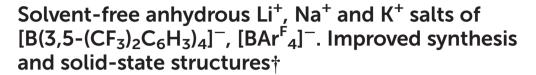
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A modified, convenient, preparation of solvent-free, anhydrous, Li<sup>+</sup>, Na<sup>+</sup> and K<sup>+</sup> salts of the ubiquitous  $[BAr^F_4]^-$  anion is reported, that involves a simple additional recrystallisation step. Anhydrous Na $[BAr^F_4]$ , K $[BAr^F_4]$ , and  $[Li(H_2O)][BAr^F_4]$ , were characterised by single-crystal X-ray diffraction.

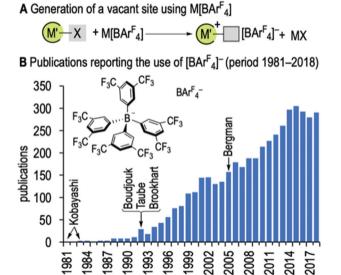
The use of weakly coordinating anions<sup>1</sup> for the stabilisation of reactive low, or latent-low, coordinate cationic metal and maingroup complexes now plays a central role in synthesis and catalysis, both in solution and in the solid-state. The anion  $[BAr_4^F]^-$  (Ar = 3,5-(CF<sub>3</sub>)<sub>2</sub>C<sub>6</sub>H<sub>3</sub>), Fig. 1, enjoys particular utility amongst the small suite of common anions used, e.g.  $[B(C_6F_5)_4]^{-5}$   $[Al(OR^F)_4]^{-1}$   $[R^F = fluoroalkyl)$ ,  $[B(3,5-Cl_2C_6H_3)_4]^{-5}$ and  $[CB_{11}X_{12}]^-$  (X = halogen)<sup>8</sup> derivatives. A combination of synthetic accessibility, desirable properties of the resulting salts, i.e. solubility and crystallinity, and simple NMR-reporter groups, make [BArF4] the go-to choice for many organometallic, main-group and catalytic applications. Very often such reactive species are generated by metathesis with the group 1 salts  $M[BAr^{F_4}]$  (M = Li, Na, K), although alternative activating cations are also known, e.g.  $[(Et_2O)_2H][BAr^F_4]$  (Taube and Brookhart)9 and [Ph3C][BArF4] (Boudjouk).10 The alkali salts have also been used as polymerisation initiators, 11 in electrochemistry, 12 as an additive in lithium ion batteries, 13 in ionic liquids, 14 and for the extraction of aqueous lanthanide ions. 15 While considered to be non-interacting, under appropriate conditions  $[BAr^F_{\phantom{F}4}]^-$  can coordinate to metal centres through its arene ring, 16,3a or via metal...F-CF2 interactions. 17 It can also undergo B-C bond cleavage. 18

The synthesis and use, as a phase transfer catalyst,<sup>4</sup> of the  $[BAr^F_{\ 4}]^-$  anion was first reported by Kobayashi in 1981, fol-

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lowed by the preparation of hydrated  $[Na(H_2O)_3][BAr^F_4]^{19}$  Brookhart subsequently reported the synthesis of  $Na[BAr^F_4]$ , by drying under vacuum and a cold  $CH_2Cl_2$  wash. Both these preparations used the Grignard reagent 1,3,5-XMg( $CF_3$ )<sub>2</sub> $C_6H_3$  (X = Br, I). In 2005, Bergman described an alternative protocol that avoided the use of the Grignard/magnesium metal mixture for the preparation of anhydrous  $Na[BAr^F_4]^{21}$  but required prolonged drying under vacuum over  $P_2O_5$ . Synthetic protocols have been reported for hydrated  $Li^+$  and  $K^+$  salts; or where the water content has not been reported. To date, the synthesis ( $Li^+$ ,  $K^+$ ) and structures  $Li^+$ ,  $Li^+$ , L



**Fig. 1** (A) Generalised use of the  $[BAr^F_4]^-$  anion for the generation of low-coordinate metal centres. (B) Number of publications per year reporting use of the  $[BAr^F_4]^-$  anion. Scifinder CAS (https://scifinder.cas.org) accessed 18/12/2018.

 $<sup>\</sup>dagger$  Electronic supplementary information (ESI) available: Full experimental details, characterisation, NMR and selected crystallographic X-ray data. CCDC 1886445–1886447. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c9dt00235a

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A This work: anhydrous, ~20 g recryst. -23°C 1. Et<sub>2</sub>O/pentane [Li(H<sub>2</sub>O)<sub>4</sub>][BAr<sup>F</sup><sub>4</sub> [M(solvent)x][BArF4] 60-70% vield crude from Et<sub>2</sub>O Na<sup>+</sup> Na[BArF<sub>4</sub>] (2) anhydrous K[BArF<sub>4</sub>] (3) (2 times) **B** Bergman protocol  $100^{\circ}$ C,  $10^{-1}$  mbar  $CH_2Cl_2$  wash  $[Na(THF)_x(H_2O)_v][BAr^F_4]$ 57% yield Li[BArF4], Na[BArF4] and K[BArF4] <500 ppm H<sub>2</sub>O

Fig. 2 Preparation and isolation of solvent-free anhydrous Li<sup>+</sup>, Na<sup>+</sup> and K<sup>+</sup> salts of [BAr<sup>F</sup><sub>4</sub>]<sup>-</sup> and comparison with the Bergman synthesis

anion to access highly Lewis-acidic, and low-coordinate, complexes. <sup>25</sup>

We now detail here a robust multigram protocol to prepare solvent-free anhydrous Li $^{+}$ , Na $^{+}$  and K $^{+}$  salts of the [BAr $^{F}{}_{4}$ ] $^{-}$  anion on  $\sim$ 20 g scale in 60–70% yields, by adding a simple recrystallisation step of the crude product prior to drying under vacuum. As well as being synthetically expedient, this allows for the structures of solvent-free anhydrous Na $^{+}$  and K $^{+}$ , and mono aquo Li $^{+}$  salts of [BAr $^{F}{}_{4}$ ] $^{-}$  to be determined.

Following a modified Kobayashi synthesis, Li<sup>+</sup>, Na<sup>+</sup> and K<sup>+</sup> salts of [BAr<sup>F</sup><sub>4</sub>]<sup>-</sup> (Fig. 2) were prepared from 1,3,5-BrMg (CF<sub>3</sub>)<sub>2</sub>C<sub>6</sub>H<sub>3</sub>/BF<sub>3</sub> followed by treatment with the aqueous alkali metal carbonate of choice (M2CO3, M = Li+, Na+ and K+). Extraction into diethyl ether gave the corresponding crude  $[M(solvent)_x][BAr_4^F]$  (solvent = H<sub>2</sub>O and/or Et<sub>2</sub>O). Our key improvement is a subsequent double recrystallisation step to yield the corresponding pure solvent-complexes in high yield. [Li(solvent)<sub>x</sub>][BAr<sup>F</sup><sub>4</sub>] was successively recrystallised from undried diethyl ether/n-pentane and then undried fluorobenzene/ *n*-pentane at -23 °C to give  $[Li(H_2O)_4][BAr_4^F]^{22a}$  as determined by NMR spectroscopy and single-crystal X-ray diffraction (ESI). Anhydrous Li[BArF4] 1 was then conveniently obtained as a highly hygroscopic off-white solid (64% yield) after drying under dynamic vacuum (10<sup>-2</sup> mbar) at 80 °C for 72 h. Shorter drying times (24 h) gave  $[Li(H_2O)][BAr^F_4]$  4. Using  $[Li(H_2O)_4]^+$ is crucial, as any bound ether results in decomposition on drying. Anhydrous Na[BArF4], 2 (68%, white solid), and K[BArF<sub>4</sub>], 3 (58%, off-white solid), were obtained from drying the pure THF solvates [M(THF)<sub>6</sub>][BAr<sup>F</sup><sub>4</sub>] under vacuum (80 °C, 48 h). <sup>22c</sup> [M(THF)<sub>6</sub>][BAr<sup>F</sup><sub>4</sub>] were themselves isolated by two consecutive recrystallisations of crude  $[M(solvent)_x][BAr^F_4]$  from THF/CH2Cl2. These two recrystallisation steps ensure high purity of the final anhydrous salts. These procedures routinely yield ~20 g of anhydrous hydroscopic Li<sup>+</sup>, Na<sup>+</sup> and K<sup>+</sup> salts of [BAr<sup>F</sup><sub>4</sub>]. This method also works for the Bergman synthesis, by recrystalising crude [Na(solvent)<sub>x</sub>][BAr<sup>F</sup><sub>4</sub>] prior to drying, to give anhydrous Na[BAr<sup>F</sup><sub>4</sub>] (12.3 g isolated yield, 58%).

The [BAr $_4$ ]<sup>-</sup> salts **1–4** were fully characterised in solution using multinuclear  $^1$ H,  $^{11}$ B,  $^{13}$ C and  $^{19}$ F NMR spectroscopy in THF- $d_8$  (298 K) and ESI-MS, and these data are consistent with previously reported examples (ESI $^+$ ).  $^{21,22a,23}$  Additionally, in the  $^7$ Li NMR spectrum of **1** a single resonance is observed at  $\delta$ 

-0.54, which shifts to  $\delta$  -0.38 in 4. The H<sub>2</sub>O ligand in complex 4 is observed at  $\delta$  4.02 as a sharp singlet (2 H) in the <sup>1</sup>H NMR spectrum. While elemental analysis did not suggest the presence of water in 1–3, following Bergman's procedure,  $(\eta^5-C_5H_5)_2$ ZrMe<sub>2</sub> was used to determine H<sub>2</sub>O content, using <sup>1</sup>H NMR spectroscopy to measure the thus formed oxo-bridged complex (and CH<sub>4</sub>). <sup>21</sup> No evidence of residual H<sub>2</sub>O was observed in any of the dried salts. Importantly, this <sup>1</sup>H NMR titration method confirmed the presence of one molecule of H<sub>2</sub>O in 4.

Single-crystals of solvent-free anhydrous Na[BArF4] 2 and K[BAr<sup>F</sup><sub>4</sub>] 3 suitable for X-ray diffraction studies were obtained by slow diffusion of dry n-pentane into a solution of the corresponding anhydrous salt in a 1:1 mixture of dry C<sub>6</sub>H<sub>5</sub>F/CH<sub>2</sub>Cl<sub>2</sub> (Fig. 3). For Li[BAr<sup>F</sup><sub>4</sub>] 1, although isolated in bulk in its anhydrous form, its highly hygroscopic nature meant that adventitious moisture present during the recrystallisation process routinely resulted in single crystals of [Li(H<sub>2</sub>O)][BAr<sup>F</sup><sub>4</sub>] 4 being isolated (Fig. 3A). Complexes 2, 3, and 4 crystallise in the tetragonal space group P4/n as contact ion-pairs (Fig. 3A-C). The contents of asymmetric units include 1/4 of the alkali metal and [BAr<sup>F</sup><sub>4</sub>] anion ( $S_4$  symmetry), with an additional quarter of one molecule of water for 4. The  $[BAr^{F}_{4}]^{-}$  anions dictate the microenvironment around the  $[Li(H_2O)]^+$ ,  $Na^+$  and  $K^+$  cations, and eight  $[BAr^F_4]^$ anions encapsulate each alkali metal cation through CF3···alkali metal interactions forming an essentially cubic environment (Fig. 3D-F). The alkali metal sits in a pseudo body centred position, displaced towards one face of the cube. The Li<sup>+</sup> ion in 4 has a square pyramidal geometry, interacting with CF<sub>3</sub> groups from four distinct [BAr<sup>F</sup><sub>4</sub>] anions [Li···F, 1.995(7)-2.045(4) Å] with the water molecule [Li-O, 1.842(8) Å] in the apical position (Fig. 3D). Additional CF<sub>3</sub>···H<sub>2</sub>O interactions are also present in 4 (F...H, 1.854(5)-2.09(1) Å). In 2 and 3 the Na<sup>+</sup> and K<sup>+</sup> centres, respectively, interact with a total of eight CF<sub>3</sub> groups from the [BArF4] anions that surround each cation (Fig. 3E and F) through M···F interactions. The increase in the ionic radius,<sup>26</sup> in the series Li < Na < K, translates into correspondingly longer M···F distances [Li: 1.995(7)-2.045(4); Na: 2.473(2)-2.631(3); and K: 2.72(3)-2.74(2) Å].

In conclusion, solvent-free anhydrous  $Li[BAr^F_4]$ ,  $Na[BAr^F_4]$  and  $K[BAr^F_4]$  has been prepared in multigram scale following a revised protocol, that rests upon a simple recrystallisation

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(A) (B) (C)

F3 Li1 O1 F3 Na1

B1 C1 C2 C7 F2

B1 C1 C2 C3 T F3

(C) (F) (F)

Fig. 3 Molecular structures of (A) [Li(H<sub>2</sub>O)][BAr<sup>F</sup><sub>4</sub>] **4**, (B) anhydrous Na[BAr<sup>F</sup><sub>4</sub>] **2** and (C) K[BAr<sup>F</sup><sub>4</sub>] **3**. Crystal packing diagrams showing the cubic arrangement of [BAr<sup>F</sup><sub>4</sub>]<sup>-</sup> anions around (D) [Li(H<sub>2</sub>O)]<sup>+</sup>, (E) Na<sup>+</sup> and (F) K<sup>+</sup> cations. Minor disordered components for the CF<sub>3</sub> groups have been omitted for clarity. Displacement ellipsoids are shown at 50% probability. Selected bond lengths (Å) and angles (°): **4**, C1–B1 1.641(2), Li1–O1 1.842(8), Li1···F1 2.045(4), Li1···F1a 1.995(7), H1a···F5a' 1.854(5), H1b····F5'' 2.096(10), H1b····F5a'' 1.894(5), C1–B1–C1' 110.41(6), C1–B1–C1'' 107.6(1); **2**, C1–B1 1.639(2), Na1····F1 2.473(2), Na1····F5' 2.631(3), C1–B1–C1'' 110.68(7), C1–B1–C1'' 107.1(2); **3**, C1–B1 1.641(2), K1····F1 2.72(3), K1····F1a 2.74(2), C1–B1–C1' 110.59(7), C1–B1–C1'' 107.3(1). Intermolecular B···B distances (Å): **4**, 9.51755(7) and 9.66072(13); **2**, 9.44044(10) and 9.3899(2); and **3**, 9.53420(15) and 9.4747(5).

step. Our method stands by its simplicity to obtain the  $\operatorname{Li}^+$ ,  $\operatorname{Na}^+$  and  $\operatorname{K}^+$  salts of the  $[\operatorname{BAr}^F_{\ 4}]^-$  anion and high purity. This allows for the characterisation of these salts by single-crystal X-ray diffraction. Given the importance of these salts in synthesis and catalysis we hope the community finds these improvements useful.

#### Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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