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Solvent-free anhydrous Li^+ , Na^+ and K^+ salts of $[\text{B}(3,5\text{-(CF}_3)_2\text{C}_6\text{H}_3)_4]^-$, $[\text{BAR}^{\text{F}}_4]^-$. Improved synthesis and solid-state structures†

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A modified, convenient, preparation of solvent-free, anhydrous, Li^+ , Na^+ and K^+ salts of the ubiquitous $[\text{BAR}^{\text{F}}_4]^-$ anion is reported, that involves a simple additional recrystallisation step. Anhydrous $\text{Na}[\text{BAR}^{\text{F}}_4]$, $\text{K}[\text{BAR}^{\text{F}}_4]$, and $[\text{Li}(\text{H}_2\text{O})][\text{BAR}^{\text{F}}_4]$, were characterised by single-crystal X-ray diffraction.

The use of weakly coordinating anions¹ for the stabilisation of reactive low, or latent-low, coordinate cationic metal and main-group complexes now plays a central role in synthesis and catalysis,² both in solution and in the solid-state.³ The anion $[\text{BAR}^{\text{F}}_4]^-$ ($\text{Ar}^{\text{F}} = 3,5\text{-(CF}_3)_2\text{C}_6\text{H}_3$),⁴ Fig. 1, enjoys particular utility amongst the small suite of common anions used, *e.g.* $[\text{B}(\text{C}_6\text{F}_5)_4]^-$,⁵ $[\text{Al}(\text{OR}^{\text{F}})_4]^-$ ($\text{R}^{\text{F}} = \text{fluoroalkyl}$),⁶ $[\text{B}(3,5\text{-Cl}_2\text{C}_6\text{H}_3)_4]^-$,⁷ and $[\text{CB}_{11}\text{X}_{12}]^-$ ($\text{X} = \text{halogen}$)⁸ derivatives. A combination of synthetic accessibility, desirable properties of the resulting salts, *i.e.* solubility and crystallinity, and simple NMR-reporter groups, make $[\text{BAR}^{\text{F}}_4]^-$ 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 $\text{M}[\text{BAR}^{\text{F}}_4]$ ($\text{M} = \text{Li}, \text{Na}, \text{K}$), although alternative activating cations are also known, *e.g.* $[(\text{Et}_2\text{O})_2\text{H}][\text{BAR}^{\text{F}}_4]$ (Taubé and Brookhart)⁹ and $[\text{Ph}_3\text{C}][\text{BAR}^{\text{F}}_4]$ (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 $[\text{BAR}^{\text{F}}_4]^-$ 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,⁴ of the $[\text{BAR}^{\text{F}}_4]^-$ anion was first reported by Kobayashi in 1981, fol-

lowed by the preparation of hydrated $[\text{Na}(\text{H}_2\text{O})_3][\text{BAR}^{\text{F}}_4]$.¹⁹ Brookhart subsequently reported the synthesis of $\text{Na}[\text{BAR}^{\text{F}}_4]$, by drying under vacuum and a cold CH_2Cl_2 wash.^{9a} Both these preparations used the Grignard reagent $1,3,5\text{-XMg}(\text{CF}_3)_2\text{C}_6\text{H}_3$ ($\text{X} = \text{Br}, \text{I}$). In 2005, Bergman described an alternative protocol that avoided the use of the Grignard/magnesium metal mixture²⁰ for the preparation of anhydrous $\text{Na}[\text{BAR}^{\text{F}}_4]$,²¹ but required prolonged drying under vacuum over P_2O_5 . Synthetic protocols have been reported for hydrated Li^+ and K^+ salts;²² or where the water content has not been reported.²³ To date, the synthesis (Li^+ , K^+) and structures²⁴ (Li^+ , Na^+ , K^+) of anhydrous $\text{M}[\text{BAR}^{\text{F}}_4]$ have not been reported in the open literature. Such anhydrous salts are of importance when using the $[\text{BAR}^{\text{F}}_4]^-$

A Generation of a vacant site using $\text{M}[\text{BAR}^{\text{F}}_4]$



B Publications reporting the use of $[\text{BAR}^{\text{F}}_4]^-$ (period 1981–2018)

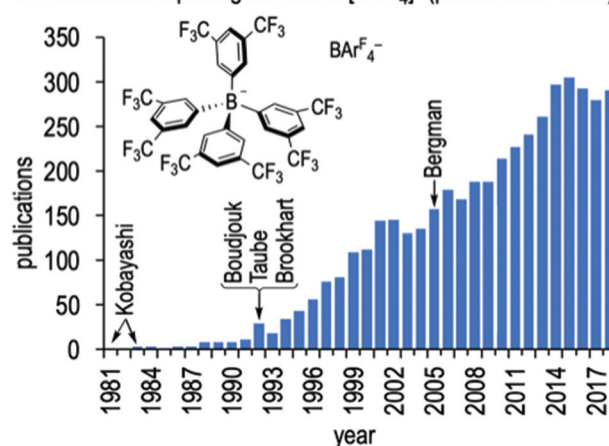


Fig. 1 (A) Generalised use of the $[\text{BAR}^{\text{F}}_4]^-$ anion for the generation of low-coordinate metal centres. (B) Number of publications per year reporting use of the $[\text{BAR}^{\text{F}}_4]^-$ anion. Scifinder CAS (<https://scifinder.cas.org>) accessed 18/12/2018.

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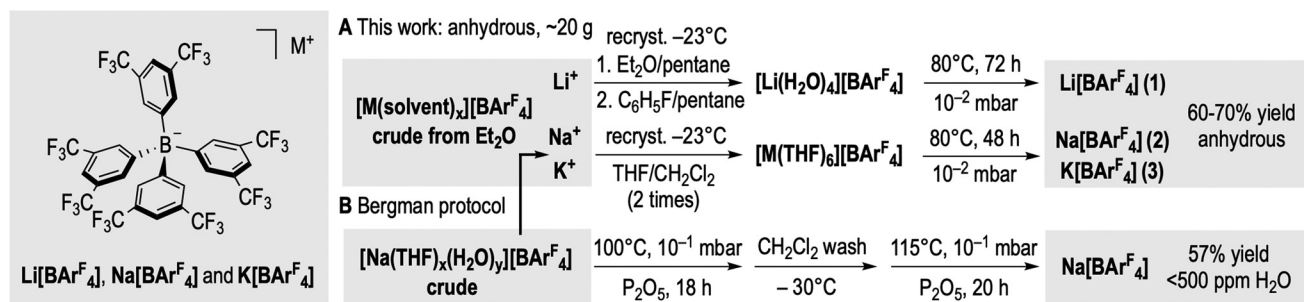


Fig. 2 Preparation and isolation of solvent-free anhydrous Li⁺, Na⁺ and K⁺ salts of [BArF₄]⁻ and comparison with the Bergman synthesis.

anion to access highly Lewis-acidic, and low-coordinate, complexes.²⁵

We now detail here a robust multigram protocol to prepare solvent-free anhydrous Li⁺, Na⁺ and K⁺ salts of the [BArF₄]⁻ anion on ~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 [BArF₄]⁻ to be determined.

Following a modified Kobayashi synthesis, Li⁺, Na⁺ and K⁺ salts of [BArF₄]⁻ (Fig. 2) were prepared from 1,3,5-BrMg(CF₃)₂C₆H₃/BF₃ 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][BArF₄] (solvent = H₂O and/or Et₂O). Our key improvement is a subsequent double recrystallisation step to yield the corresponding pure solvent-complexes in high yield. [Li(solvent)_x][BArF₄] was successively recrystallised from undried diethyl ether/*n*-pentane and then undried fluorobenzene/*n*-pentane at -23 °C to give [Li(H₂O)₄][BArF₄]^{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 (10⁻² mbar) at 80 °C for 72 h. Shorter drying times (24 h) gave [Li(H₂O)][BArF₄] **4**. Using [Li(H₂O)₄]⁺ is crucial, as any bound ether results in decomposition on drying. Anhydrous Na[BArF₄] **2** (68%, white solid), and K[BArF₄] **3** (58%, off-white solid), were obtained from drying the pure THF solvates [M(THF)₆][BArF₄] under vacuum (80 °C, 48 h).^{22c} [M(THF)₆][BArF₄] were themselves isolated by two consecutive recrystallisations of crude [M(solvent)_x][BArF₄] from THF/CH₂Cl₂. These two recrystallisation steps ensure high purity of the final anhydrous salts. These procedures routinely yield ~20 g of anhydrous hygroscopic Li⁺, Na⁺ and K⁺ salts of [BArF₄]⁻. This method also works for the Bergman synthesis, by recrystallising crude [Na(solvent)_x][BArF₄] prior to drying, to give anhydrous Na[BArF₄] (12.3 g isolated yield, 58%).

The [BArF₄]⁻ salts **1–4** were fully characterised in solution using multinuclear ¹H, ¹¹B, ¹³C and ¹⁹F 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 ⁷Li NMR spectrum of **1** a single resonance is observed at δ

−0.54, which shifts to δ −0.38 in **4**. The H₂O ligand in complex **4** is observed at δ 4.02 as a sharp singlet (2 H) in the ¹H NMR spectrum. While elemental analysis did not suggest the presence of water in **1–3**, following Bergman's procedure, (η⁵-C₅H₅)₂ZrMe₂ was used to determine H₂O content, using ¹H NMR spectroscopy to measure the thus formed oxo-bridged complex (and CH₄).²¹ No evidence of residual H₂O was observed in any of the dried salts. Importantly, this ¹H NMR titration method confirmed the presence of one molecule of H₂O in **4**.

Single-crystals of solvent-free anhydrous Na[BArF₄] **2** and K[BArF₄] **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 C₆H₅F/CH₂Cl₂ (Fig. 3). For Li[BArF₄] **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(H₂O)][BArF₄] **4** being isolated (Fig. 3A). Complexes **2**, **3**, and **4** crystallise in the tetragonal space group *P*4/*n* as contact ion-pairs (Fig. 3A–C). The contents of asymmetric units include 1/4 of the alkali metal and [BArF₄]⁻ anion (*S*₄ symmetry), with an additional quarter of one molecule of water for **4**. The [BArF₄]⁻ anions dictate the microenvironment around the [Li(H₂O)]⁺, Na⁺ and K⁺ cations, and eight [BArF₄]⁻ 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⁺ ion in **4** has a square pyramidal geometry, interacting with CF₃ groups from four distinct [BArF₄]⁻ 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 CF₃...H₂O interactions are also present in **4** (F...H, 1.854(5)–2.09(1) Å). In **2** and **3** the Na⁺ and K⁺ centres, respectively, interact with a total of eight CF₃ groups from the [BArF₄]⁻ anions that surround each cation (Fig. 3E and F) through M...F interactions. The increase in the ionic radius,²⁶ 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[BArF₄], Na[BArF₄] and K[BArF₄] has been prepared in multigram scale following a revised protocol, that rests upon a simple recrystallisation



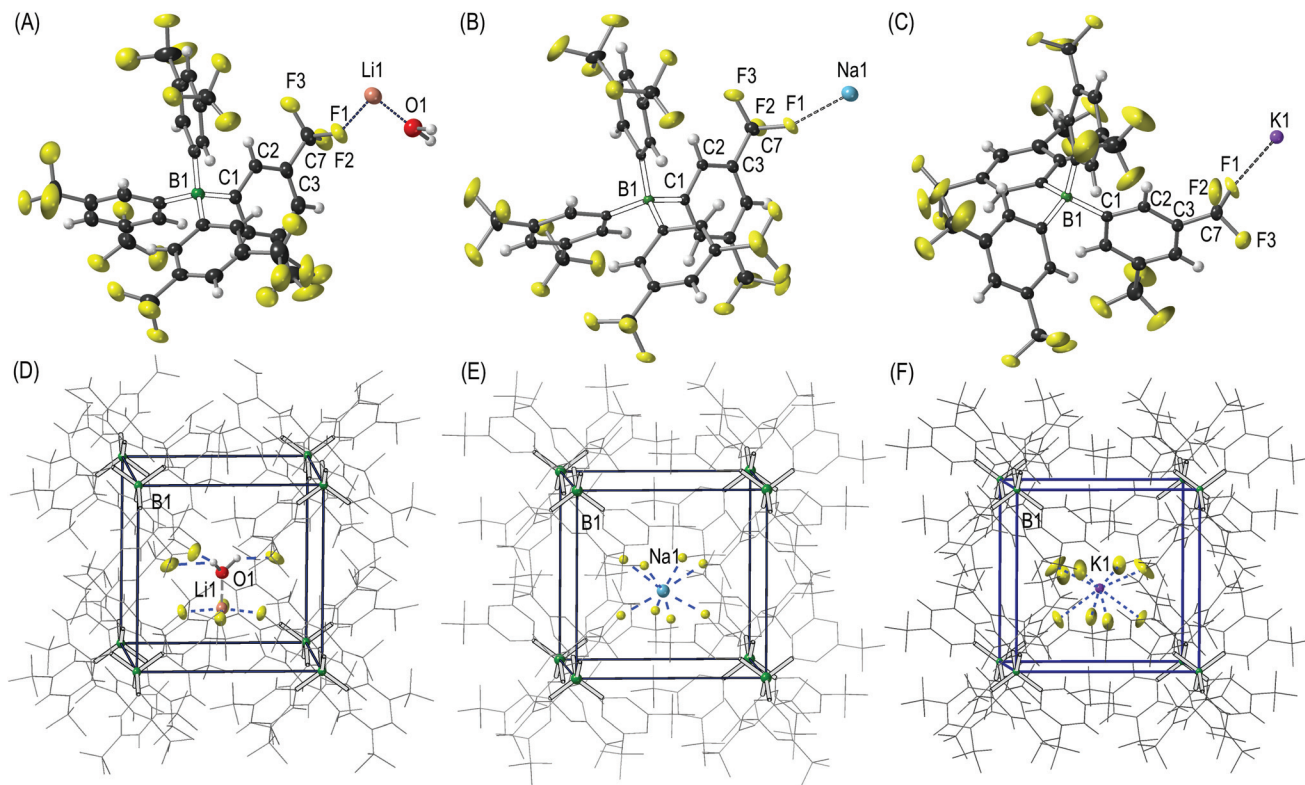


Fig. 3 Molecular structures of (A) $[\text{Li}(\text{H}_2\text{O})][\text{BARF}_4]$ **4**, (B) anhydrous $\text{Na}[\text{BARF}_4]$ **2** and (C) $\text{K}[\text{BARF}_4]$ **3**. Crystal packing diagrams showing the cubic arrangement of $[\text{BARF}_4]^-$ anions around (D) $[\text{Li}(\text{H}_2\text{O})]^+$, (E) Na^+ and (F) K^+ cations. Minor disordered components for the CF_3 groups have been omitted for clarity. Displacement ellipsoids are shown at 50% probability. Selected bond lengths (Å) and angles ($^\circ$): **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 Li^+ , Na^+ and K^+ salts of the $[\text{BARF}_4]^-$ 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.

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References

- (a) S. H. Strauss, *Chem. Rev.*, 1993, **93**, 927–942; (b) C. A. Reed, *Acc. Chem. Res.*, 1998, **31**, 133–139;
- (c) I. Krossing and I. Raabe, *Angew. Chem., Int. Ed.*, 2004, **43**, 2066–2090.
- (a) W. Beck and K. Suenkel, *Chem. Rev.*, 1988, **88**, 1405–1421; (b) T. A. Engesser, M. R. Lichtenthaler, M. Schleep and I. Krossing, *Chem. Soc. Rev.*, 2016, **45**, 789–899; (c) S. D. Pike, M. R. Crimmin and A. B. Chaplin, *Chem. Commun.*, 2017, **53**, 3615–3633; (d) I. M. Riddlestone, A. Kraft, J. Schaefer and I. Krossing, *Angew. Chem., Int. Ed.*, 2018, **57**, 13982–14024.
- (a) S. D. Pike, F. M. Chadwick, N. H. Rees, M. P. Scott, A. S. Weller, T. Krämer and S. A. Macgregor, *J. Am. Chem. Soc.*, 2015, **137**, 820–833; (b) A. J. Martínez-Martínez, B. E. Tegner, A. I. McKay, A. J. Bukvic, N. H. Rees, G. J. Tizzard, S. J. Coles, M. R. Warren, S. A. Macgregor and A. S. Weller, *J. Am. Chem. Soc.*, 2018, **140**, 14958–14970.
- H. Kobayashi, T. Sonoda, H. Iwamoto and M. Yoshimura, *Chem. Lett.*, 1981, **10**, 579–580.
- (a) A. G. Massey and A. J. Park, *J. Organomet. Chem.*, 1964, **2**, 245–250; (b) E. Martin, D. L. Hughes and S. J. Lancaster, *Inorg. Chim. Acta*, 2010, **363**, 275–278.
- (a) S. M. Ivanova, B. G. Nolan, Y. Kobayashi, S. M. Miller, O. P. Anderson and S. H. Strauss, *Chem. – Eur. J.*, 2001, **7**, 503–510; (b) I. Krossing, *Chem. – Eur. J.*, 2001, **7**, 490–502;

- (c) I. Krossing and A. Reisinger, *Eur. J. Inorg. Chem.*, 2005, **2005**, 1979–1989.
- 7 A. B. Chaplin and A. S. Weller, *Eur. J. Inorg. Chem.*, 2010, **2010**, 5124–5128.
- 8 C. Douvris and J. Michl, *Chem. Rev.*, 2013, **113**, PR179–PR233.
- 9 (a) M. Brookhart, B. Grant and A. F. Volpe, *Organometallics*, 1992, **11**, 3920–3922; (b) R. Taube and S. Wache, *J. Organomet. Chem.*, 1992, **428**, 431–442.
- 10 S. R. Bahr and P. Boudjouk, *J. Org. Chem.*, 1992, **57**, 5545–5547.
- 11 C.-T. Chang, C.-L. Chen, Y.-H. Liu, S.-M. Peng, P.-T. Chou and S.-T. Liu, *Inorg. Chem.*, 2006, **45**, 7590–7592.
- 12 F. Barrière, N. Camire, W. E. Geiger, U. T. Mueller-Westerhoff and R. Sanders, *J. Am. Chem. Soc.*, 2002, **124**, 7262–7263.
- 13 F. Kita, H. Sakata, S. Sinomoto, A. Kawakami, H. Kamizori, T. Sonoda, H. Nagashima, J. Nie, N. V. Pavlenko and Y. L. Yagupolskii, *J. Power Sources*, 2000, **90**, 27–32.
- 14 A. Bösmann, G. Franciò, E. Janssen, M. Solinas, W. Leitner and P. Wasserscheid, *Angew. Chem., Int. Ed.*, 2001, **40**, 2697–2699.
- 15 H. Suzuki, H. Naganawa and S. Tachimori, *Phys. Chem. Chem. Phys.*, 2003, **5**, 726–733.
- 16 (a) J. Powell, A. Lough and T. Saeed, *J. Chem. Soc., Dalton Trans.*, 1997, 4137–4138; (b) T. M. Douglas, E. Molinos, S. K. Brayshaw and A. S. Weller, *Organometallics*, 2007, **26**, 463–465.
- 17 (a) P. Holze, T. Corona, N. Frank, B. Braun-Cula, C. Herwig, A. Company and C. Limberg, *Angew. Chem., Int. Ed.*, 2017, **56**, 2307–2311; (b) M. Everett, A. Jolleys, W. Levason, D. Pugh and G. Reid, *Chem. Comm.*, 2014, **50**, 5843–5846; (c) J. B. Smith, S. H. Kerr, P. S. White and A. J. M. Miller, *Organometallics*, 2017, **36**, 3094–3103.
- 18 (a) W. V. Konze, B. L. Scott and G. J. Kubas, *Chem. Commun.*, 1999, 1807–1808; (b) H. Salem, L. J. W. Shimon, G. Leitens, L. Weiner and D. Milstein, *Organometallics*, 2008, **27**, 2293–2299.
- 19 H. Nishida, N. Takada, M. Yoshimura, T. Sonoda and H. Kobayashi, *Bull. Chem. Soc. Jpn.*, 1984, **57**, 2600–2604.
- 20 J. L. Leazer, R. Cvetovich, F.-R. Tsay, U. Dolling, T. Vickery and D. Bachert, *J. Org. Chem.*, 2003, **68**, 3695–3698.
- 21 N. A. Yakelis and R. G. Bergman, *Organometallics*, 2005, **24**, 3579–3581.
- 22 (a) J. H. Golden, P. F. Mutolo, E. B. Lobkovsky and F. J. DiSalvo, *Inorg. Chem.*, 1994, **33**, 5374–5375; (b) M. R. Kita and A. J. M. Miller, *J. Am. Chem. Soc.*, 2014, **136**, 14519–14529; (c) L. Carreras, L. Rovira, M. Vaquero, I. Mon, E. Martin, J. Benet-Buchholz and A. Vidal-Ferran, *RSC Adv.*, 2017, **7**, 32833–32841.
- 23 W. E. Buschmann, J. S. Miller, K. Bowman-James and C. N. Miller, *Inorg. Synth.*, 2002, **33**, 85.
- 24 The structure of solvent-free Na[BAR^F₄] has been deposited as a private communication to the Cambridge Structural Database (VEGDAP, DOI: 10.5517/ccdc.csd.cc1ptr7h). Detailed synthesis and structural discussion were not reported.
- 25 A. D. Piascik, R. Li, H. J. Wilkinson, J. C. Green and A. E. Ashley, *J. Am. Chem. Soc.*, 2018, **140**, 10691–10694.
- 26 M. Rahm, R. Hoffmann and N. W. Ashcroft, *Chem. – Eur. J.*, 2016, **22**, 14625–14632.

