Nucleophilic vinylic substitution in bicyclic methyleneaziridines: $S_N V_\pi$ or $S_N V_\sigma$?

Vitalii Palchykov, Peter C. Dale and Jeremy Robertson

A stereodefined monodeuterated methyleneaziridine is shown to be prepared via coordinated reductive ring-opening of an alkynyl epoxide and diastereoselective tethered allene aziridination. Ring-opening of this aziridine with copper-based organometallics follows a pathway that results in stereoretentive replacement, replacing the exo-C–N bond with a corresponding C–C bond; this stereochemical outcome supports either an overall $S_N V_\sigma$ mechanism or a C–N insertion/reductive coupling process.

Introduction

In 2010 both we\(^1\) and Blakey\(^2\) reported the first examples of intramolecular allene aziridination with sulfamate substrates, with the major products being derived in most cases via 2-amidoallylation intermediates.\(^3\) Our group followed this up with the first report\(^4\) of analogous reactions of carbamate substrates 1 (Scheme 1) and, in that work, somewhat unstable bicyclic 1,3-oxazolidin-2-one methyleneaziridines 2 were obtained following Lebel’s modification\(^5\) of the Du Bois protocol\(^6\) for Rh(II)-nitrenoid generation. Soon afterwards, Schoemaker’s group took on the area and developed it extensively, optimising the conditions for generating the methyleneaziridines, engineering the substrates for synthetic tractability (non-terminal allenes, formation of 1,3-oxazinan-2-ones), and elaborating the products into a variety of hydroxy/amino stereotriads and -tetrads and rearranged heterocycles.\(^7\)

In our original publication we noted that the methyleneaziridines were constrained by the ring-fusion such that only the exocyclic aziridine C–N bond is electronically activated in the ground state through hyperconjugation with the carbamate carbonyl π-system. This suggested the possibility of effecting direct substitution/ring-opening at the sp\(^2\)-carbon, in contrast to the prevailing reactivity of unconstrained methyleneaziridines in which ring-opening occurs preferentially at the sp\(^3\)-carbon.\(^8\) At the time, the only sp\(^2\)-C–N bond-cleaving processes involved either transition metal-mediated processes\(^9\) or stepwise radical addition/β-scission.\(^10\) In the event, treatment of methyleneaziridine 2 (R = i-Pr) with lithium diphenylecuprate, or various Grignard reagents in the presence of Cul, led to moderate to good yields of the products 3 of nucleophilic vinylic substitution ($S_N V$).\(^11\) That publication concluded with an intention to clarify the stereochemical details of the $S_N V$ reaction; the current paper describes studies to that end.

Results and discussion

A stereochemically defined monodeuterated analogue 4 (Scheme 2) of methyleneaziridine 2 (R = i-Pr) was targeted that would allow the stereochemistry of the $S_N V$ process to be probed without presenting any steric or electronic bias compared with the original methyleneaziridine. At the outset of this study, a dissociative mechanism for the substitution reaction was ruled out on the basis of the aprotic, low-temperature conditions for the process and the relative instability of a vinylic cation. An out-of-plane (relative to the cleaving C–N bond) stepwise π-addition/elimination process, proceeding via a short-lived formal carbanion located on the terminal methylene carbon, or an equivalent concerted mechanism, would proceed with retention of configuration ($S_N V_\pi$ pathway, → 5). An in-plane concerted process, akin to an $S_N 2$ reaction in aliphatic

---

\(^1\) Research Institute of Chemistry and Geology, Oles Honchar Dnipro National University, 72 Gagarina Avenue, Dnipro 49010, Ukraine
\(^2\) Department of Chemistry, University of Oxford, Chemistry Research Laboratory, Mansfield Road, Oxford OX1 3TA, UK. E-mail: jeremy.robertson@chem.ox.ac.uk
\(^3\) Electronic supplementary information (ESI) available. See DOI: 10.1039/d1nj01458g
substrates, would lead to inversion of configuration (SnV$_\alpha$ pathway, → 6). The operation of either of these reaction modes would then be revealed in the relative disposition of the newly-formed C–C bond and the adjacent H/D atoms, as shown.

In the absence of any literature precedent for the synthesis of a stereodefined terminally monodeuterated buta-2,3-dienol, a synthesis of methyleneaziridine 4 was proposed based upon diastereoselective coordinated delivery of hydride$^{13}$ to deuterated alkynyl epoxide 7 (Scheme 3) and the known stereochemical course of the intramolecular aziridination. Following this proposal, trans-2-ethynyl-3-isopropyloxirane 14 was stirred with an excess of D$_2$O under basic conditions$^{15}$ to yield the deuterated alkyne 7 (94% deuterium incorporation). Alkyne 7 was treated with DIBAL in dichloromethane as a non-coordinating solvent that would support epoxide chelation with the aluminium centre, and allene 8 was isolated apparently as one predominant stereoisomer,$^{16}$ depicted as that expected, and confirmed retro-centre, and allene solvent that would support epoxide chelation with the aluminium

Scheme 2  Simplified SnV reaction modes of methyleneaziridine 4 with a generic nucleophile Nu$^\text{t}$.

Scheme 3  Reagents and conditions: (i) DIBAL, CH$_2$Cl$_2$, 0 °C, 1 h (53%); (ii) CDI, CH$_2$CN, RT, 24 h then add NH$_2$OH.HCl, RT, 24 h; (b) TsCl, Et$_3$N, Et$_2$O, 0 °C → RT, 18 h (9, 62%); (c) Cl$_3$CCO-NCO, CH$_2$Cl$_2$, 0 °C, 4 h then K$_2$CO$_3$, MeOH, RT, 4 h (10, 97%); (iv) from 9) K$_2$CO$_3$, Rh$_2$(esp)$_3$, CH$_2$Cl$_2$, reflux, 48 h (4–17%).

Fig. 1  NMR chemical shifts and diagnostic NOE correlations to support the assigned stereochemistry in methyleneaziridine 4.

close proximity to the CHN and =CHD protons, as seen in the NOE spectra. A simple dihedral drive calculation supports this view (ESI$^\text{†}$).$^{19}$

Two variants of the SnV reaction were carried out, both of which converted methyleneaziridine 4 into products with reasonable overall efficiency (Scheme 4). In the first, addition of lithium dimethylcuprate gave a 77% isolated yield of 4-isopropenyl oxazolidinone 11, in which the methyl group was found (see below) to be cis- to the deuterium atom. In the second, a copper-catalysed Grignard reaction with vinyl-magnesium bromide gave 4-(buta-1,3-dien-2-yl) oxazolidine 12 as the major product, again with the new C–C bond formed cis- to the deuterium atom. The azirine 13 was also isolated in this work; its formation may be explained by competing addition at the carbonyl followed by 1,4-vinylation of the so-formed $\beta$-$\beta$-unsaturated ester.$^{20}$

A combination of NMR experiments, including NOE (Fig. 2) provided support for the stereochemical assignments in SnV products 11 and 12. Notably, in 11 no NOE correlation was observed between the vinyl methyl protons and =CHD; similarly, in compound 12, there were no significant correlations between the vinyl protons and =CHD.

An invertive SnV$_\alpha$ reaction appears to be stereoelectronically accessible in methyleneaziridines 2 and 4, and the microscopic reverse of such a process is supported in the NaNH$_2$-mediated formation of simple methyleneaziridines from 2-bromoallylic amines.$^{21}$ Despite this, our results clearly rule out the SnV$_\alpha$ mode of ring-opening, the stereochemical outcome being consistent with a (retentive) SnV$_\alpha$ mode of reaction. Setting aside the extent of the involvement of the metal counterions in this process, at one simplistic mechanistic extreme, as the delivery of the methyl or vinyl ligand to the methylene group initiates and charge begins to build on the terminal carbon, the sp$^2$-C–N bond weakens, with progression along this pathway.
constituting an overall concerted process (cf. Scheme 2). At the other end of the spectrum, an initial carboxylation reaction from the exposed face of the methylene group would generate a short-lived organocopper intermediate that rapidly fragments following rotation via the lower energy pathway\textsuperscript{11c} to place the C–Cu and C–N bonds antiperiplanar to one another. Alternatively, a cross-coupling mechanism may be considered\textsuperscript{22} in which formal-Cu(i) insertion into the activated sp\textsuperscript{2}-C–N bond (→ 14, Scheme 5) and reductive elimination/ligand coupling (→ 15) would deliver the same stereochemical outcome; further research would be necessary to evaluate the viability and implications of such a mechanistic pathway.

Conclusions

To the best of our knowledge, the direct nucleophilic sp\textsuperscript{2} C–N bond cleavage reactions that we reported in 2010 remain the only examples in methyleneaziridine chemistry. In this work, we have demonstrated that the substitution is stereoretentive, ruling out an SnV\texttextsubscript{α} pathway, but the detailed mechanism of these reactions remains open to speculation and further work is intended to close this particular chapter of methyleneaziridine reactivity.\textsuperscript{23}

Experimental

General information

All solvents for anhydrous reactions were obtained dry from Grubbs solvent dispenser units after being passed through an activated alumina column under argon. THF was additionally distilled from sodium/benzophenone ketyl under argon. Commercially available reagents were used as supplied unless otherwise specified. Triethylamine was distilled from CaH\textsubscript{2} and stored over KOH pellets under argon. ‘Petrol’ refers to the fraction of light petroleum ether boiling between 30 and 40 °C; ‘ether’ refers to diethyl ether. All reactions were carried out in oven-dried glassware and under an atmosphere of argon unless otherwise specified. Thin layer chromatography (TLC) was carried out using Merck aluminium backed DC60 F254 0.2 mm precoated plates. Spots were then visualised by the quenching of ultraviolet light fluorescence (λ\textsubscript{max} 254 nm) and then stained and heated with either anisaldehyde or KMnO\textsubscript{4} solutions as appropriate. Retention factors (R\textsubscript{f}) are reported along with the solvent system used in parentheses. Flash column chromatography was performed using Merck 60 silica gel (particle size 40–63 μm) and the solvent system used is reported in parentheses. Infrared spectra were recorded using a Bruker Tensor 27 FT-IR fitted with a diamond ATR module. Absorption maxima (ν\textsubscript{max}) are reported in wavenumbers (cm\textsuperscript{-1}) and are described as strong (s), medium (m), weak (w) or broad (br). Proton (\textsuperscript{1}H) and carbon-13 (\textsuperscript{13}C) spectra were referenced (in MestReNova) to the appropriate solvent peak: CDCl\textsubscript{3}, 7.26/77.16; acetone-d\textsubscript{6}, 2.05/29.84. Peak multiplicities are described as singlet (s), doublet (d), triplet (t), quartet (q), septet (sept), octet (oct), multiplet (m), and broad (br) or a combination thereof. Coupling constants (J) are rounded to the nearest 0.5 Hz. Assignments are made on the basis of chemical shifts, integrations, and coupling constants, using COSY, HSQC, and NOE experiments where appropriate. High Resolution Mass Spectra (HRMS) were recorded by the staff at the Chemistry Research Laboratory (University of Oxford) using a Waters GCTOF spectrometer (EI/FI). Melting points were recorded on a Griffin melting point apparatus and are uncorrected.

Trans-2-(deuterioethynyl)-3-isopropylxirane (7)

Trans-2-ethylxyl-3-isopropylxirane (2.03 g, 18.4 mmol) was added to a stirring solution of K\textsubscript{2}CO\textsubscript{3} (3.76 g, 27.2 mmol) in acetonitrile (42 mL). After 30 min, D\textsubscript{2}O (20 mL) was added and stirring was continued for 5 h. The product was extracted from the reaction mixture into petrol (5 × 100 mL). The combined
extracts were dried (MgSO4) and the solvent was removed in vacuo [CARE: the product is volatile] to afford the title compound as a pale yellow oil (1.50 g, 73%, 94% deuterium incorporation). Rf 0.58 (petrol/ether, 3:1); νmax/cm⁻¹ (thin film): 2966, 2589, 1980, 1469; δH (400 MHz, CDCl3) 0.97 (3H, d, J = 7.0 Hz), 0.99 (3H, d, J = 7.0 Hz), 1.52 (1H, oct, J = 7.0 Hz), 2.29 (0.1H, d, J = 1.5 Hz, residual CH2), 2.89 (1H, dd, J = 7.0, 2.0 Hz), 3.11 (1H, d, J = 2.0 Hz); δC (100 MHz, CDCl3) 18.1, 18.7, 30.4, 43.9, 65.4, 71.5 (t, J = 38.5 Hz), 80.3 (t, J = 7.5 Hz).

(3R*,5R*)-6-Deutero-2-methylhexa-4,5-dien-3-ol (8)

A solution of epoxyalkyne (1.00 mL) was added dropwise to a stirred solution of DitBuO (500 mg, 1.82 mmol) in THF (1 mL) at RT under Ar. The mixture was stirred at RT until the reaction was complete by TLC (25 mL). The product was purified by flash chromatography (petrol/ether, 3:1) affording the title compound as a pale yellow oil (1.93 g, 73%, 94% deuterium incorporation). Rf 0.58 (petrol/ether, 3:1); νmax/cm⁻¹ (thin film): 2966, 2589, 1980, 1469; δH (400 MHz, CDCl3) 0.89 (3H, d, J = 7.0 Hz), 1.52 (1H, oct, J = 7.0 Hz), 2.29 (0.1H, d, J = 1.5 Hz, residual CH2), 2.89 (1H, dd, J = 7.0, 2.0 Hz), 3.11 (1H, d, J = 2.0 Hz); δC (100 MHz, CDCl3) 18.1, 18.7, 30.4, 43.9, 65.4, 71.5 (t, J = 38.5 Hz), 80.3 (t, J = 7.5 Hz).

(4R*,5S*,Z)-4-Isopropyl-6-(methylene-d)-3-oxa-1-azabicyclo[3.1.0]hexane-2-one (4)

Rh2(OAc)4 (6.8 mg, 15.4 µmol) and K2CO3 (127 mg, 0.919 mmol) were added to a stirred solution of acetone (3 mL) at 25 °C. The reaction mixture was stirred vigorously for 90 min then diluted with acetone, filtered, and concentrated in vacuo at RT to give the crude product. Purification by flash chromatography (petrol/ether, 7:1) afforded the title compound as a pale yellow oil (12 mg, 25%). Rf 0.49 (petrol/ether 1:1); νmax/cm⁻¹ (thin film) 2966, 1793s, 1761w, 1176m, 1116w, 1072m, 1031s; δH (500 MHz, CDCl3) 1.02 (3H, d, J = 7.0 Hz), 1.08 (3H, d, J = 7.0 Hz), 1.81 (1H, d, J = 9.5, 7.0 Hz), 3.62 (1H, t, J = 5.5 Hz), 4.35 (1H, d, J = 9.5, 5.5 Hz), 5.16 (1H, s); δC (100 MHz, CDCl3) 17.6, 18.0, 21.9, 32.4, ~76.6 (from HSQC; obscured by solvent peak in 1D spectrum), 80.3, 88.2, 129.8, 129.9, 130.5, 146.2, 155.0, 209.1; HRMS (ESI) m/z: [M + Na]+ calcd for C15H18DNNaO5S, 349.0939; found, 349.0932.

(4S*,5R*)-5-Isopropyl-4-[(E)-propen-2-yl-1-d]oxazolidin-2-one (11)

Methyl lithium (0.16 mL, 1.6 M solution in ether, 0.256 mmol) was added dropwise to a stirred suspension of CuI (25 mg, 0.111 mmol) in THF (1 mL) in a pear-shaped flask at ~20 °C. After 15 min, a solution of methyleneaziridine (20 mg, 0.130 mmol) in THF (1 mL) was added. The mixture was stirred for 30 min, quenched with satd. NH4Cl, and concentrated in vacuo. The residue was purified by flash chromatography (petrol/ether, 7:1) then stirred with (MgSO4) and the solvent was removed in vacuo. Purification by flash chromatography (petrol/ether, 5:1) afforded the title compound as a pale yellow oil (0.131 mmol) in THF (1 mL) was added. The mixture was stirred at RT until the reaction was complete by TLC (12 mL, 1.0 M). Purification of the crude product was then allowed to warm to RT. The organic components were then diluted with ether (30 mL), washed with brine (2 mL), dried (Na2SO4), and the solvent removed in vacuo. The crude product was purified by flash chromatography (petrol/ether, 5:1 → pure ether) to afford the title compound as a pale yellow oil (983 mg, 85%). Rf 0.50 (petrol/ether, 1:1); νmax/cm⁻¹ (thin film) 3284br, 2967m, 1770s, 1598m, 1467m, 1379s, 1192s, 1179s, 1019m, 742m; δH (400 MHz, CDCl3) 0.82 (3H, d, J = 7.0 Hz), 0.84 (3H, d, J = 7.0 Hz), 1.80 (1H, oct, J = 7.0 Hz), 2.46 (3H, s), 4.77 (1H, d, J = 6.0 Hz), 4.85–4.95 (2H, m), 7.35 (2H, d, J = 8.0 Hz), 7.76 (1H, s), 7.82 (2H, d, J = 8.0 Hz); δC (100 MHz, CDCl3) 17.8, 18.0, 21.9, 32.4, 76.7 (from HSQC; obscured by solvent peak in 1D spectrum), 80.3, 88.2, 129.8, 129.9, 130.5, 146.2, 155.0, 209.1; HRMS (ESI) m/z: [M + Na]+ calcd for C15H18DNNaO5S, 349.0939; found, 349.0932.
Vinylmagnesium bromide (0.25 mL, 1.0 M solution in THF, /C0 6.5 Hz), 4.44 (1H, dd, J = 4.97 (1H, br s), 5.19 (1H, d, J = 6.5 Hz), 0.12 (3H, d, J = 6.5 Hz), 1.01 (3H, d, J = 6.5 Hz), 1.90 (1H, apparent oct, J = 6.5 Hz), 4.44 (1H, dd, J = 8.0, 7.0 Hz), 4.64 (1H, d, J = 8.0 Hz), 4.97 (1H, br s), 5.19 (1H, d, J = 11.0 Hz), 5.27 (1H, s), 5.31 (1H, d, J = 17.5 Hz), 6.37 (1H, dd, J = 17.5, 11.0 Hz); δH (500 MHz, acetone-d6) 0.89 (3H, d, J = 6.5 Hz), 0.95 (3H, d, J = 6.5 Hz), 1.85 (1H, oct, J = 6.5 Hz), 4.48 (1H, dd, J = 8.0, 6.5 Hz), 4.78 (1H, d, J = 8.0 Hz), 5.17 (1H, d, J = 11.0 Hz), 5.32 (1H, s), 5.44 (1H, d, J = 17.5 Hz), 6.44 (1H, dd, J = 17.5, 11.0 Hz), 6.68 (1H, br s); δC (125 MHz, acetone-d6) 18.0, 20.3, 29.3 (from HSQC; partially obscured by solvent peak), 57.6, 84.2, 115.5, 117.6 (t, J = 24.5 Hz), 137.5, 143.8, 159.5; HRMS (ESI) m/z: [M + Na]+ calcd for C12H18DNNaO2, 205.1058; found, 205.1052. Also obtained was azirene 13, a colourless oil (6.0 mg, 23%). Rf 0.74 (petrol/ether, 1:1).

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are grateful to The Ministry of Education and Science of Ukraine (VP) and the University of Oxford (PD) for funding.

References

1. G. C. Feast, L. W. Page and J. Robertson, Chem. Commun., 2010, 46, 2835–2837.
2. A. H. Stoll and S. B. Blakey, J. Am. Chem. Soc., 2010, 132, 2108–2109.
3. See also: R. Liu, PhD Thesis, Brigham Young University, 2007.
4. J. Robertson, G. C. Feast, L. V. White, V. A. Steadman and T. D. W. Claridge, Org. Biomol. Chem., 2010, 8, 3060–3063.
5. H. Lebel, K. Huard and S. Lectard, J. Am. Chem. Soc., 2005, 127, 14198–14199.
6. C. G. Espino and J. Du Bois, Angew. Chem., Int. Ed., 2001, 40, 598–600.
7. Selected papers: (a) L. A. Boralsky, D. Marston, R. D. Grigg, J. C. Hershberger and J. M. Schomaker, Org. Lett., 2011, 13, 1924–1927; (b) R. D. Grigg, J. M. Schomaker and V. Timokhin, Tetrahedron, 2011, 67, 4318–4326; (c) C. D. Weatherly, J. W. Rigoli and J. M. Schomaker, Org. Lett., 2012, 14, 1704–1707; (d) S. C. Schmid, I. A. Guzei, I. Fernández and J. M. Schomaker, ACS Catal., 2018, 8, 7907–7914.
8. M. Shipman, Synlett, 2006, 3205–3217.
9. (a) H. Alper and N. Hamel, Tetrahedron Lett., 1987, 28, 3237–3240; (b) B. H. Oh, I. Nakamura and Y. Yamamoto, J. Org. Chem., 2004, 69, 2856–2858; (c) A. I. Siriwandana, K. K. A. D. S. Kathriarachchi, I. Nakamura, I. D. Gridnev and Y. Yamamoto, J. Am. Chem. Soc., 2004, 126, 13898–13899; (d) K. K. A. D. S. Kathriarachchi, A. I. Siriwandana, I. Nakamura and Y. Yamamoto, Tetrahedron Lett., 2007, 48, 2267–2270.
10. (a) N. Prévoist and M. Shipman, Org. Lett., 2001, 3, 2383–2385; (b) N. Prévoist and M. Shipman, Tetrahedron, 2002, 58, 7165–7175.
11. Recent reviews: (a) C. F. Bernasconi and Z. Rappoport, Acc. Chem. Res., 2009, 42, 993–1003; (b) S. Chiba, K. Ando and K. Narasaka, Synlett, 2009, 2549–2564; see also: (c) Y. Apeloig and Z. Rappoport, J. Am. Chem. Soc., 1979, 101, 5095–5098; (d) D. Cohen, R. Bar and S. S. Shaik, J. Am. Chem. Soc., 1986, 108, 231–240; (e) I. Fernández, F. M. Bickelhaupt and E. Uggerud, J. Org. Chem., 2013, 78, 8574–8584.
12. An example was published subsequent to the completion of this work: C. Jarava-Barrera, A. Parra, L. Amenós, A. Arroyo and M. Tortosa, Chem. – Eur. J., 2017, 23, 17478–17481.
13. For example: (a) M. Ito, Y. Hirata, K. Tsukida, N. Tanaka, K. Hamada, R. Hino and T. Fujiwara, Chem. Pharm. Bull., 1988, 36, 3328–3340; (b) A. Baumeler, W. Brade, A. Haag and C. H. Eugster, Helv. Chim. Acta, 1990, 73, 700–715.
14. (a) J. X. Wang, Y. Li and C. X. Zhang, J. Chin. Chem. Soc., 2003, 50, 1183–1187; (b) H. Jiang, N. Holub, M. W. Paixão, C. Tiberi, A. Falciacchio and K. A. Jørgensen, Chem. – Eur. J., 2009, 15, 9638–9641.
15. S. P. Bew, G. D. Hiatt-Gipson, J. A. Lovell and C. Poullain, Org. Lett., 2012, 14, 456–459.
16. The NMR data for allene 8 showed no doubling in any of the 1H or 13C resonances; cf. J. A. Marshall and G. S. Bartley, J. Org. Chem., 1994, 59, 7169–7171.
17. S.-I. Hashimoto, N. Watanabe and S. Ikegami, Tetrahedron Lett., 1992, 33, 2709–2712.
18 C. G. Espino, K. W. Fiori, M. Kim and J. Du Bois, J. Am. Chem. Soc., 2004, 126, 15378–15379.
19 The DFT equilibrium geometry of methyleneaziridine 4 was obtained in Spartan '18 (B3LYP/6-31+G*), then semi-empirical (PM3) relative energies were calculated for constrained conformations in which the H–C–C–H dihedral angle varied from –180° to +180° over 36 steps.
20 Comparison ¹H NMR (CDCl₃) data are available for azirine 16, below, which is compound 4f in H. Alper and J. E. Prickett, Inorg. Chem., 1977, 16, 67–71.
21 J. J. Shiers, M. Shipman, J. F. Hayes and A. M. Z. Slawin, J. Am. Chem. Soc., 2004, 126, 6868–6869.
22 (a) C. V. Maffeo, G. Marchese, F. Naso and L. Ronzini, J. Chem. Soc., Perkin Trans. 1, 1979, 92–97; (b) A. S. E. Karlström, M. Rönö, A. Thorarensen and J.-E. Bäckvall, J. Org. Chem., 1998, 63, 2517–2522; (c) I. P. Beletskaya and A. V. Cheprakov, Coord. Chem. Rev., 2004, 248, 2337–2364; (d) J. E. Ney and J. P. Wolfe, J. Am. Chem. Soc., 2006, 128, 15415–15422; (e) C.-Y. Huang and A. G. Doyle, Chem. Rev., 2014, 114, 8153–8198.
23 (a) B. Pan, F. Li and Y. Zhao, RSC Adv., 2020, 10, 39304–39322; (b) K. A. Tehrani and N. De Kimpe, Curr. Org. Chem., 2009, 13, 854–877.