



Cite this: *Org. Biomol. Chem.*, 2023, **21**, 858

Persistent azulene α -carbocations: synthesis from aldehydes, spectroscopic and crystallographic properties†

Catajina Harabaju, ^a Jodie L. Hann, ^a Lloyd C. Murfin, ^a Gabriele Kociok-Köhn ^b and Simon E. Lewis ^{*a}

The non-benzenoid aromatic system azulene is sufficiently nucleophilic at C1 that it can react with a protonated aldehyde to form an α -azulenyl alcohol. This in turn may be protonated and undergo loss of water to give an azulene α -carbocation. We report the isolation of such azulenyl cations as salts with non-coordinating anions. The salts have been characterised by NMR, UV/Vis absorption and (in certain cases) X-ray crystallography. Reduction of representative salts to afford azulenyl(aryl) methylenes has been demonstrated.

Received 16th September 2022,
 Accepted 21st December 2022

DOI: 10.1039/d2ob01695h

rsc.li/obc

Introduction

Azulene **1** is a bicyclic non-benzenoid aromatic hydrocarbon with a 10-electron π -system, which is isomeric with naphthalene **2**. Its properties differ from those of benzenoid **2** in several significant ways.¹ It is unusually polar for a molecule devoid of heteroatoms, possessing a dipole moment of 1.08 D,² which arises from the contribution to the resonance hybrid of structure **1'**, in which the two rings are both individual 6-electron aromatic systems. It also exhibits the anomalous fluorescence property of emitting as a result of the $S_0 \leftarrow S_2$ transition, in violation of Kasha's rule.³ Strikingly, whereas **2** is colourless, **1** is a deep blue colour, as a result of its HOMO–LUMO gap being in the visible region. Ring substituents that perturb the azulene chromophore give rise to derivatives of many different colours. The relationship between the electronic nature of a substituent, its point of attachment and resultant shift in the absorption maximum has been studied.⁴ Many new dyes based on azulene have been reported, and selected examples are shown in Fig. 1, such as azulenoisoidigo (**3**),⁵ azulene-fused tetracene diimide **4**,⁶ and biazulene diimides **5**.⁷ Azulene dyes such as **6** have been exploited in dye-sensitized solar cells.⁸ The changes in optical properties (both absorbance and fluorescence) that occur as a result of changes to the substituents make azulene derivatives ideal for use as chemosensors and chemodosimeters. For

example, bis(pyrrolyl)azulene **7** is a fluorescent and colorimetric sensor for fluoride,⁹ AzuFluor® 435-DPA-Zn (**8**) is a fluorescent sensor for ADP¹⁰ and AzuFluor® 483-Bpin (**9**) is a fluorescent dosimeter for peroxyxynitrite.¹¹

In any azulene **10** with a carbon substituent at the 1- or 3-position, a positive charge on that α -aryl carbon will be

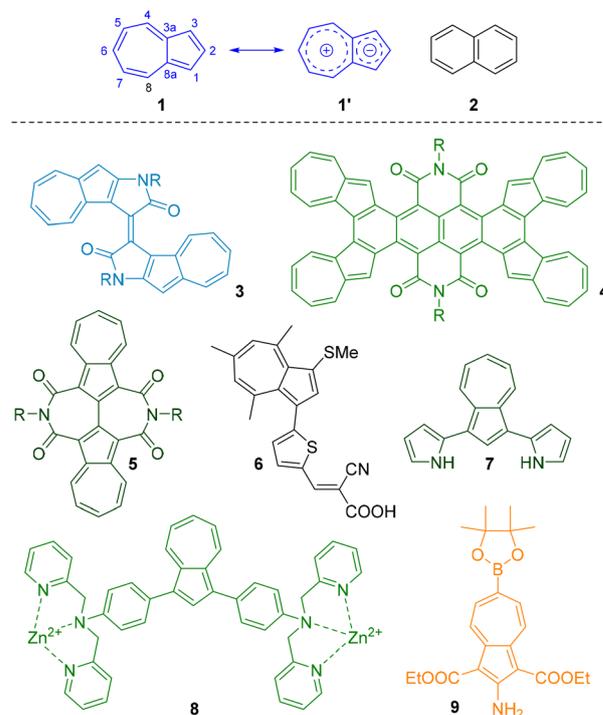


Fig. 1 Structures of azulene, naphthalene and azulene-based dyes.

^aDepartment of Chemistry, University of Bath, Bath, BA2 7AY, UK.

E-mail: S.E.Lewis@bath.ac.uk

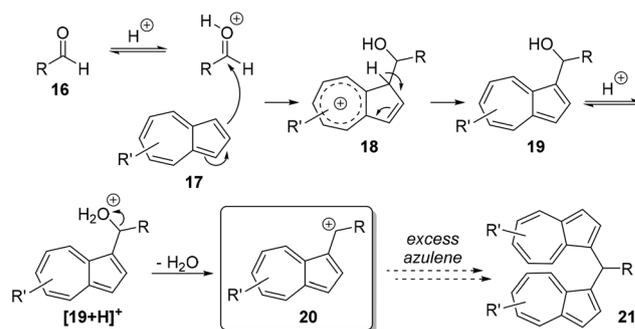
^bMaterial and Chemical Characterisation Facility (MC²), University of Bath, Bath, BA2 7AY, UK

† Electronic supplementary information (ESI) available: NMR spectra, X-ray crystallographic data. CCDC 2129310–2129315. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d2ob01695h>



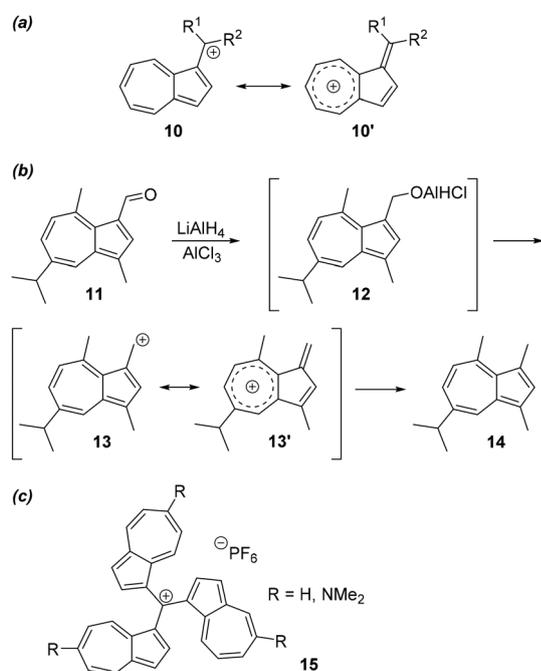
stabilised due to the existence of a resonance structure comprising a tropylium ring, **10'** (Scheme 1a). The stabilisation of such cations explains various aspects of azulene reactivity that are distinct from benzenoid aromatic systems.¹² For example, 3-formylguaiazulene (**11**) may be reduced twice (Scheme 1b), first to alkoxy intermediate **12**, and then to 3-methylguaiazulene (**14**).¹³ This second reduction is enabled by the stability of cationic intermediate **13** (Scheme 1b). The intermediacy of cations such as **10** also enables reactions such as hydration of 1-azulenylalkynes,¹⁴ formation of azuleno[2,1-*b*]thiophenes,¹⁵ formation of calix[*n*]azulenes,¹⁶ pyrrole-mediated azulene decarbonylation,¹⁷ and protection of thiols with azulene-based protecting groups.¹⁸ If cations of type **10** possess R¹ and R² substituents which are sufficiently cation-stabilising, then they may be isolable as stable salts with non-nucleophilic anions. A notable example are the tris(azulen-1-yl)cations **15**, which display exceedingly high pK_R⁺ values as a result of the stability conferred by the three cation-stabilising azulene substituents (Scheme 1c). For example, **15** (R = H)¹⁹ has pK_R⁺ = 11.3, whereas the effect of additional electron donating groups is clearly shown for **15** (R = NMe₂),²⁰ with pK_R⁺ = 24.3.

Cations of type **10** can be stable enough to be isolated even when R¹ = H, as long as R² ≠ H. Such cations can be conveniently prepared by reaction of an azulene with the requisite aldehyde in the presence of an appropriate Brønsted acid (*i.e.* one with a non-coordinating anion, such as HBF₄, HPF₆ or HClO₄) as shown in Scheme 2. Protonation of the aldehyde **16** activates it towards an S_EAr reaction with an azulene **17** to afford alcohol **19**. This in turn undergoes a second protonation, followed by loss of water to give persistent cations **20** (Scheme 2). The outcome of the reaction is dependent on stoichiometry, since if an excess of the azulene is used, a second

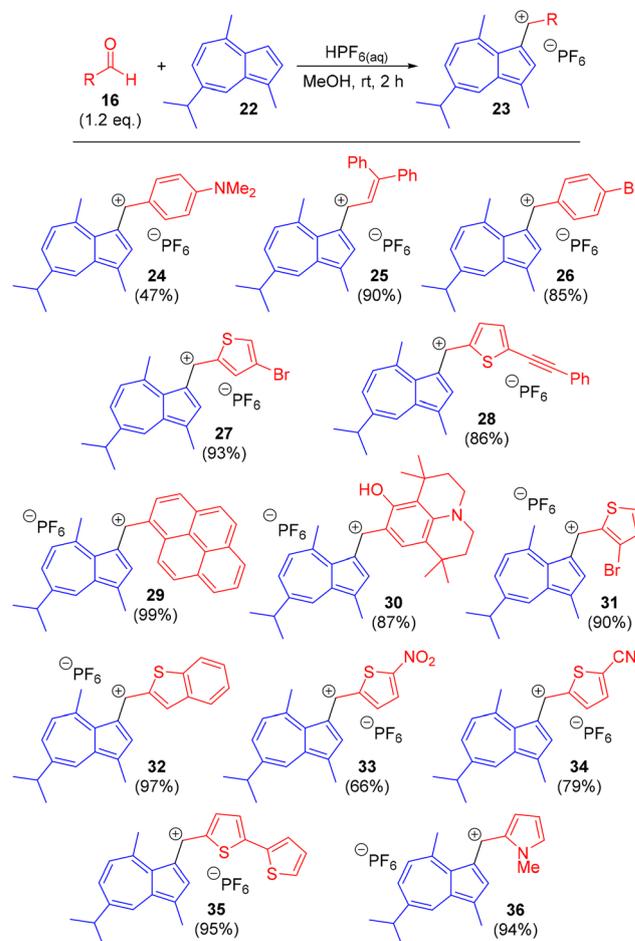


Scheme 2 Synthesis of azulene α -aryl cations from aryl aldehydes.

S_EAr reaction can occur to give bis(azulen-1-yl)methines of type **21**. Products of type **20** have been studied by Reid²¹ and by Stepanow,²² who have demonstrated the applicability of this process to various aromatic and aliphatic aldehydes. Subsequently, Takekuma also disclosed extensive studies on this class of compounds.²³ Applications of salts of type **20** have been described in the patent literature, such as in optical data storage,²⁴ in thermal-transfer printing,²⁵ in photocross-



Scheme 1 Stability of α -aryl cations at the azulene 1- or 3-position.



Scheme 3 Synthesis of arylazulenyl cations **24**–**36**.



slinkable resins,²⁶ in cancer phototherapy²⁷ and in retinal tissue staining.²⁸ These salts have also been employed for the synthesis of various heterocycles²⁹ and in chemical sensing of various anions.³⁰ The wide substrate scope of the reaction shown in Scheme 2 led us to prepare and study novel cations of type **20** derived from aldehydes that have not previously been used in this process. The results of these investigations are reported here.

Results and discussion

We chose guaiazulene **22** as the substrate for cation formation, since not only is it appreciably cheaper than **1** (as a result of the availability of **22** from natural sources³¹), but the presence of the C1-methyl substituent precludes oligomerisation reactions.³² Application of previously reported reaction conditions (HPF₆, MeOH, room temperature, 2 h) gave the expected products with a wide range of both aryl and heteroaryl aldehydes, including those bearing both electron-donating and electron-withdrawing substituents (Scheme 3). In the first instance we employed *p*-dimethylaminobenzaldehyde to prepare salt **24**. Other salt forms of **24** have been reported previously (with BF₄⁻, ClO₄⁻, or I⁻ counteranions).^{21b,23f,r} Salt **24** was comprehensively characterised by NMR spectroscopy (see ESI[†]), which

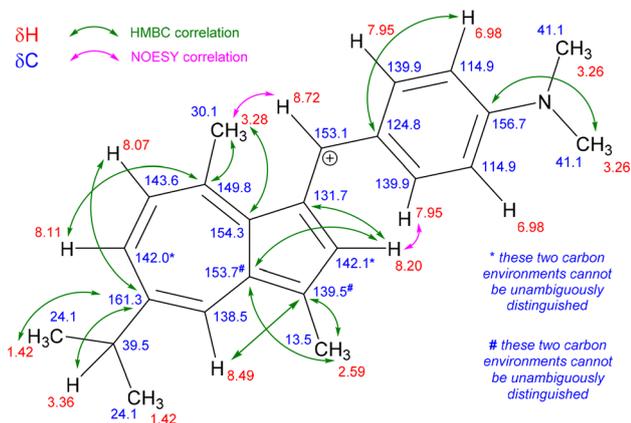


Fig. 2 Structure of **24**, with selected HMBC and NOESY interactions indicated.

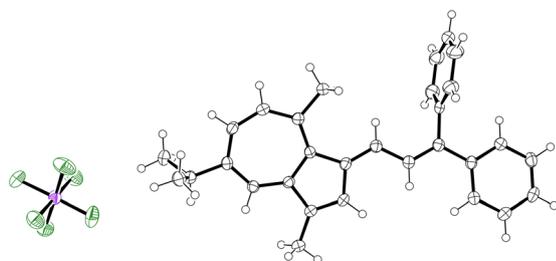


Fig. 3 ORTEP representation of the X-ray structure of **25**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. CCDC 2129313.†

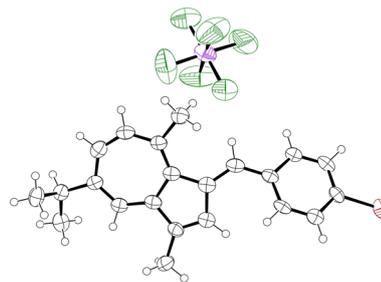


Fig. 4 ORTEP representation of the X-ray structure of **26**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Only one of 3 independent molecules in the unit cell is shown for clarity. CCDC 2129312.†

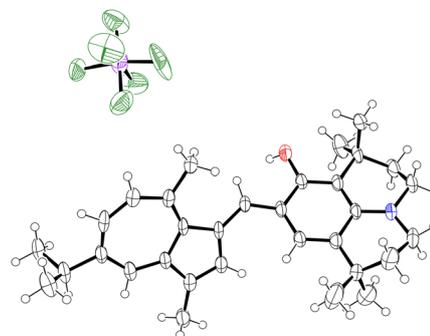


Fig. 5 ORTEP representation of the X-ray structure of **30**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Only one of 2 independent molecules in the unit cell is shown. Disordered water molecules and disorder in PF₆⁻ anion are omitted for clarity. CCDC 2129314.†

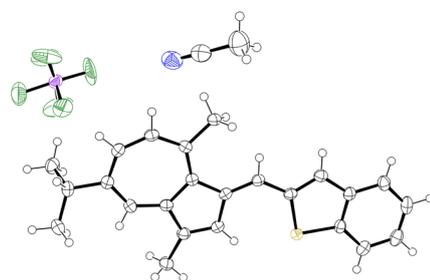


Fig. 6 ORTEP representation of the X-ray structure of **32-MeCN**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. Disorder in PF₆⁻ anion omitted for clarity. CCDC 2129315.†

Table 1 Selected parameters for X-ray structures of **25**, **26**, **30** and **32**; (X = C, S)

Salt	C ^{Az} -C ⁺ bond length [†] /Å	C ⁺ -C ^α bond length [†] /Å	C ^{Az} -C ⁺ -C ^{Ar(α)} -X ^{Ar(β)} dihedral angle [‡]
25	1.372(3)	1.430(3)	n/a
26	1.36(1)-1.39(1)	1.45(2)	28(1) ^o -30(2) ^o
30	1.385(6)-1.391(6)	1.421(4)-1.426(5)	22.1(6) ^o -24.9(6) ^o
32	1.373(3)	1.428(3)	3.5(4) ^o



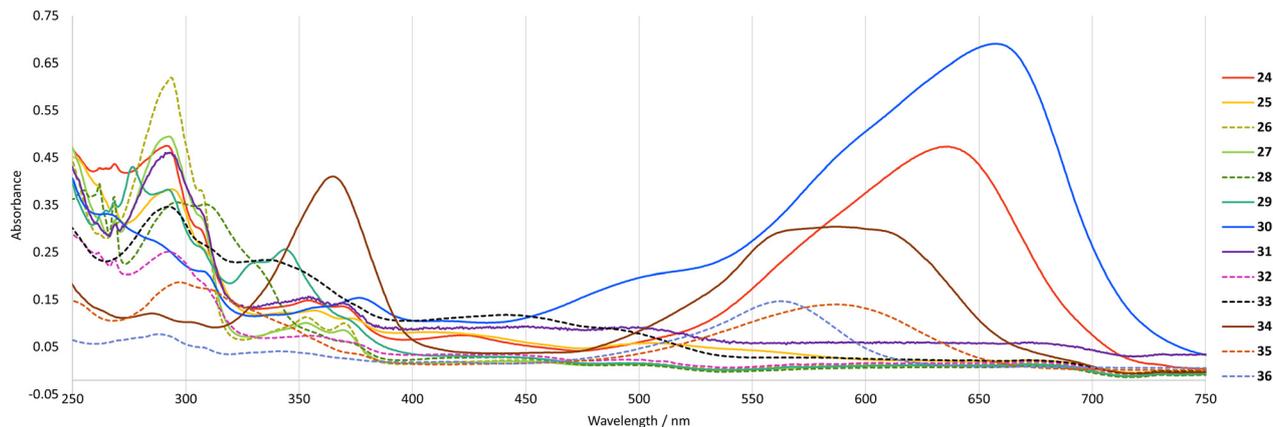


Fig. 7 UV/vis absorption spectra for salts 24–36 (15 μM) in MeCN.

allowed for assignment of each proton and carbon resonance in the structure (Fig. 2).

We next applied the reaction conditions to a selection of (hetero)aromatic aldehydes to synthesise novel salts 25–36. These were isolated as air-stable crystalline solids in good yields (79–99%), with the exception of 33, for which the yield was moderate (66%). This lower yield may be attributable to the presence of the highly electron-withdrawing nitro substituent. There are few reports of α -aryl cations in conjugation with nitro groups, but such salts can be isolable when other electron-donating groups are also present.³³ We next sought to characterise the novel salts crystallographically and were able to obtain X-ray structures for 25 (Fig. 3), 26 (Fig. 4), 30 (Fig. 5) and 32 (Fig. 6).

The structure of 25 reveals that in the solid state the π -system is not planar. Rather, the (*Z*)-phenyl substituent is oriented almost perpendicular to the propenyl chain; the $\text{C}=\text{C}-\text{C}^{\text{ipso}}-\text{C}^{\text{ortho}}$ dihedral angle is $85.1(3)^\circ$. This is in keeping with the trend observed for all 1,1-diphenylethenes for which X-ray crystallographic data have been reported, *i.e.* there are no examples in which this motif has the two phenyl rings oriented coplanar. Such an orientation would of course lead to the occlusion of the two *ortho*-hydrogen atoms, but it is nevertheless surprising that the deviation from planarity in 25 is as significant as it is.

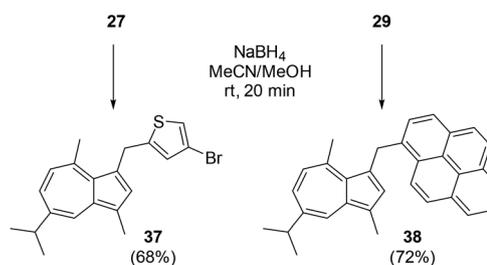
As per 25, the structures of 26 and 30 also adopt conformations in the solid state where the π -system exhibits a degree of deviation from planarity (Table 1); the $\text{C}^{\text{Az}}-\text{C}^+-\text{C}^{\text{Ar}(\alpha)}-\text{C}^{\text{Ar}(\beta)}$ dihedral angle being between $28(1)^\circ$ and $30(2)^\circ$ for 26 and between $22.1(6)^\circ$ and $24.9(6)^\circ$ for 30.[‡] In both cases, this deviation from planarity can again be explained through occlusion of hydrogen atoms, in this case the phenyl *ortho*-hydrogen and the hydrogen at the azulene 2-position. In contrast, the π -system is close to fully planar for 32, the $\text{C}^{\text{Az}}-\text{C}^+-\text{C}^{\text{Ar}(\alpha)}-\text{S}$ dihedral angle being $3.5(4)^\circ$. We suggest such a planar conformation is now more favourable as the sulfur atom lacks a substituent to occlude the azulene 2-position hydrogen.

[‡] Ranges are given for these dihedral angles since for 26 and 30 the unit cells comprise multiple independent molecules.

We next characterised novel salts 24–36 by UV-vis absorption spectroscopy (Fig. 7 and Table 2). The diverse array of colours exhibited by 24–36 is reflected by the variation in absorption maxima that were observed. Notably, the two salts exhibiting the highest extinction coefficients in the visible region were 24 and 30, which are the two salts bearing the most electron-donating substituents, *i.e.* amino groups. The difference in absorption maxima may be ascribable to the fact that 30 bears an additional conjugated electron-donating substituent, *i.e.* a hydroxyl group.

Table 2 Absorption maxima and extinction coefficients for salts 24–36 in MeCN

Compound	$\lambda_{\text{max}}/\text{nm}$ ($\log \epsilon$)
24	640 (4.50), 421 (3.70), 354 (4.00)
25	506 (3.59), 409 (3.74), 357 (3.93)
26	669 (3.02), 447 (3.16), 370 (3.82)
27	676 (2.89), 445 (3.11), 370 (3.76)
28	670 (2.79), 439 (3.28)
29	669 (2.94), 490 (3.01)
30	657 (4.66), 377 (4.01)
31	656 (3.59), 499 (3.79), 355 (4.02)
32	674 (3.10), 492 (3.19), 353 (3.69)
33	672 (3.17), 441 (3.90)
34	586 (4.31), 365 (4.44)
35	587 (3.97), 298 (4.10)
36	563 (3.99), 289 (3.71)



Scheme 4 Reduction of salts 27 and 29.



We investigated the reduction of salts of type **23** with a hydridic reducing agent. Thus, two representative example salts (**27** and **29**) were treated with sodium borohydride to afford the corresponding methylene compounds **37** and **38** (Scheme 4). In both cases the desired reduction occurred rapidly at room temperature, with the product precipitating from solution in sufficient purity that after filtration, no further purification was necessary. Both **37** and **38** were blue in the solid state, as a consequence of the azulene motif no longer being conjugated to the other aromatic system. We were able to obtain an X-ray structure for **38** (Fig. 8).

The protons on the C4-methyl group of guaiazulene are acidic,³⁴ and in cations **24–36** they would be expected to be even more acidic due to the presence of the conjugated cation. However, deprotonation at the C4-methyl group of **24–36** would give an azulenoquinone dimethide system **39**, which would be expected to be unstable with respect to self-reaction³⁵ or other decomposition pathways (Scheme 5a). Of the salts **24–36**, julolidine derivative **30** is unique in possessing an alternative site of deprotonation, namely the hydroxyl group. In this case, deprotonation of **30** would lead to neutral *ortho*-quinone methide **40**, in which aromaticity of the azulene motif is retained (Scheme 5b). In the event treatment of a solution of **30** in CH₂Cl₂

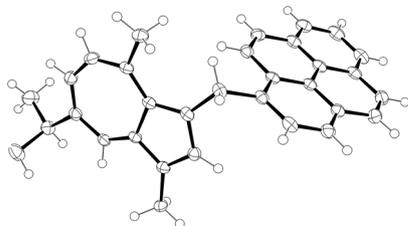
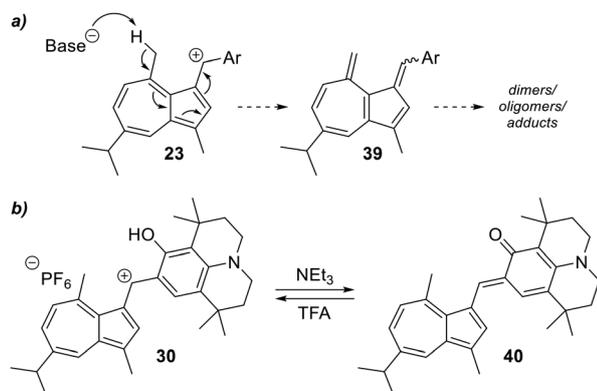


Fig. 8 ORTEP representation of the X-ray structure of **38**. Ellipsoids are shown at 50% probability. Hydrogens are shown as spheres of arbitrary radius. CCDC 2129310.†



Scheme 5 (a) Deprotonation at C4-methyl group leading to **39**, anticipated to be unstable. (b) Deprotonation of **30** at the hydroxyl group, leading to *o*-quinone methide **40**.

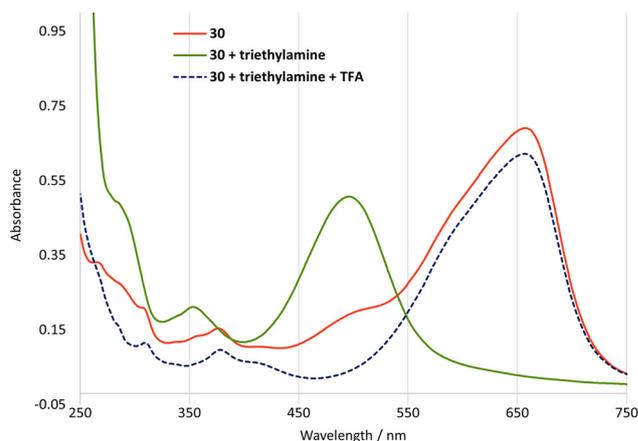


Fig. 9 UV/vis absorption spectra for salts **30** (15 μM) upon treatment with base and subsequent acid in MeCN.

with triethylamine led from a rapid colour change from blue to red, which we ascribe to formation of **40**. The red colour of the solution remained unchanged upon prolonged standing under air, and the halochromic behaviour was shown to be reversible, with addition of trifluoroacetic acid leading to regeneration of the blue colour of **30** (Fig. 9). This process could be repeated multiple times. Azulenes directly conjugated to *para*-quinone methides have been reported,³⁶ but to our knowledge **40** constitutes the first example of an azulene directly conjugated to an *ortho*-quinone methide.

Conclusions

We have reported the synthesis and characterisation of highly conjugated azulene-substituted cations, which are readily isolated as hexafluorophosphate salts. They are stable in the solid state, with no decomposition observed after being stored on the bench >1 year (with no protection from air/light). The cations persist in both protic (MeOH) and aprotic (MeCN, CH₂Cl₂) solvents. The synthesis of these salts requires only one step and employs a cheap, naturally-occurring azulene starting material. Furthermore, salts with high extinction coefficients and different absorption maxima in the visible region (and hence different colours) are accessible by varying the aldehyde starting material. As such salts of the type described here may find applications as low-cost dyestuffs. Salts such as **30**, with an appropriate acidic proton, can display halochromic behaviour as a result of deprotonation to form neutral quinoidal systems, such as **40**. Further studies on salts of this type are ongoing in our laboratory and the results will be reported in due course.

Experimental

Materials and methods

See the ESI† for general details of the materials and methods used.



Synthetic procedures

General procedure A for synthesis of compounds 24–36. To a solution of guaiazulene **22** (100 mg, 0.50 mmol, 1 eq.) in MeOH (2 mL) was added a solution of aldehyde (0.61 mmol, 1.2 eq.) in MeOH (4 mL) containing HPF₆ (55% aqueous solution, 0.12 mL, 2.7 eq.). The reaction mixture was stirred at room temperature under air until the starting material was consumed, as shown by TLC (EtOAc/petrol 1 : 4). The reaction mixture was diluted with diethyl ether (10 mL), then cooled to 0 °C for the specified time. Precipitated material was isolated by filtration, dried under vacuum and then purified as specified.

[4-(Dimethylamino)phenyl]-3-guaiazulenylmethylum hexafluorophosphate 24. *General procedure A* was used with *p*-diaminobenzaldehyde (90 mg); reaction time 1.5 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **24** as green crystals (113 mg, 47% yield). M.pt 181 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 8.72 (s, 1H), 8.49 (d, *J* = 2.1 Hz, 1H), 8.20 (s, 1H), 8.11 (dd, *J* = 11.1, 2.1 Hz, 1H), 8.07 (d, *J* = 11.1 Hz, 1H), 7.95 (d, *J* = 9.3 Hz, 2H), 6.98 (d, *J* = 9.3 Hz, 2H), 3.36 (hept, *J* = 6.9, 1H), 3.28 (s, 3H, 14), 3.26 (s, 6H), 2.59 (d, *J* = 1.0 Hz, 3H), 1.42 (d, *J* = 6.8 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 161.3, 156.7, 154.3, 153.7, 153.1, 149.8, 143.6, 142.0, 142.1, 139.8, 139.4, 138.5, 124.8, 114.9, 41.0, 39.4, 30.0, 24.0, 13.4 ppm. NMR data in agreement with those previously reported for the tetrafluoroborate salt.^{23f}

(2,2-Diphenylethenyl)-3-guaiazulenylmethylum hexafluorophosphate 25. *General procedure A* was used with β-phenylcinnamaldehyde (126 mg); reaction time 3 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **25** as red crystals (244 mg, 90% yield). M.pt 199 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 8.56 (s, 1H), 8.34–8.26 (m, 4H), 7.92 (d, *J* = 12.0 Hz, 1H), 7.65–7.47 (m, 8H), 7.43–7.39 (m, 2H), 3.45 (hept, *J* = 6.9 Hz, 1H), 2.86 (s, 3H), 2.56 (s, 3H), 1.43 (d, *J* = 6.8 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 169.4, 163.5, 160.3, 156.6, 152.4, 149.4, 148.1, 144.4, 143.9, 141.3, 140.1, 139.8, 139.5, 139.0, 132.3, 131.9, 131.0, 130.6, 129.9, 129.7, 126.6, 40.1, 28.8, 23.8, 13.9 ppm. IR ν_{max} 2967, 1553, 1397, 1339, 1295, 1255, 1210, 1109, 1046, 985, 825, 780, 705, 596, 555 cm⁻¹. HRMS (ESI⁺): calc. for C₃₀H₂₉ [M]⁺ 389.2264, found 389.2264.

(4-Bromophenyl)-3-guaiazulenylmethylum hexafluorophosphate 26. *General procedure A* was used with 4-bromobenzaldehyde (112 mg); reaction time 4 h; cooling time 10 min. **26** was obtained as orange crystals (219 mg, 85% yield); no further purification was necessary. M.pt 173 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 8.69 (s, 1H), 8.59 (d, *J* = 2.2 Hz, 1H), 8.56 (d, *J* = 11.3 Hz, 1H), 8.45 (dd, *J* = 11.3, 2.2 Hz, 1H), 7.93 (s, 1H, 7), 7.80–7.77 (m, 2H), 7.72–7.69 (m, 2H), 3.51 (hept, *J* = 6.9 Hz, 1H), 3.36 (s, 3H), 2.51 (s, 3H), 1.46 (d, *J* = 6.9 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 172.6, 162.0, 158.4, 153.8, 151.3, 148.8, 146.8, 145.4, 141.0, 140.1, 135.6, 135.1, 133.5, 127.3, 40.4, 29.7, 23.8, 13.9 ppm. One aromatic carbon was not observed. IR ν_{max} 2974, 1573, 1552, 1454, 1403, 1344, 1313, 1195, 1071, 1047, 1005, 983, 826, 743, 662, 635, 555, 502 cm⁻¹.

HRMS (ESI⁺): calc. for C₂₂H₂₂⁷⁹Br [M]⁺ 365.0900, found 365.0901.

(4-Bromothiophen-2-yl)-3-guaiazulenylmethylum hexafluorophosphate 27. *General procedure A* was used with 4-bromo-2-thiophenecarboxaldehyde (116 mg); reaction time 4 h; cooling time 10 min. **27** was obtained as orange crystals (246 mg, 93% yield); no further purification was necessary. M.pt 178 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 8.63 (s, 1H), 8.57 (d, *J* = 2.2 Hz, 1H), 8.49 (d, *J* = 11.2 Hz), 8.40 (dd, *J* = 11.2, 2.2 Hz, 1H), 8.16 (br s, 1H), 8.01–8.00 (m, 1H), 7.85 (br s, 1H), 3.49 (hept, *J* = 6.8 Hz, 1H), 3.32 (s, 3H), 2.56 (s, 3H), 1.45 (d, *J* = 6.8 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 171.4, 160.8, 157.7, 154.0, 150.7, 146.7, 145.2, 142.2, 141.3, 140.2, 139.1, 137.7, 136.1, 113.6, 40.2, 29.7, 23.8, 14.0 ppm. One aromatic carbon was not observed. IR ν_{max} 3115, 2963, 1568, 1398, 1344, 1294, 1168, 1118, 1045, 825, 742, 585, 555 cm⁻¹. HRMS (ESI⁺): calc. for C₂₀H₂₀⁸¹BrS [M]⁺ 373.0444, found 373.0445.

3-Guaiazulenyl-(5-(phenylethynyl)thiophen-2-yl)methylum hexafluorophosphate 28. *General procedure A* was used with 5-(2-phenyleth-1-ynyl)thiophene-2-carbaldehyde (116 mg); reaction time 4 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **28** as dark green lustrous crystals in two batches (148 mg and 87 mg; 86% total yield). M.pt 198 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 8.74 (s, 1H), 8.57 (d, *J* = 2.2 Hz, 1H), 8.43 (d, *J* = 11.2 Hz, 1H), 8.36 (dd, *J* = 11.2, 2.2 Hz, 1H), 8.21 (br s, 1H), 7.91 (d, *J* = 4.2 Hz, 1H), 7.61–7.59 (m, 2H), 7.50 (d, *J* = 4.2 Hz, 1H), 7.50–7.45 (m, 3H), 3.47 (hept, *J* = 6.9 Hz, 1H), 3.34 (s, 3H), 2.58 (s, 3H), 1.45 (d, *J* = 6.9 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 170.1, 160.0, 157.3, 153.7, 149.8, 146.1, 144.8, 143.4, 141.6, 140.2, 140.1, 139.2, 136.7, 136.4, 135.2, 132.6, 131.1, 130.0, 122.4, 101.8, 83.1, 40.1, 29.8, 23.8, 14.0 ppm. IR ν_{max} 2965, 2198, 1980, 1601, 1565, 1400, 1377, 1343, 1175, 1101, 1042, 837, 822, 806, 747, 688, 665, 551, 517 cm⁻¹. HRMS (ESI⁺): calc. for C₂₈H₂₅S [M]⁺ 393.1672, found 393.1672.

3-Guaiazulenyl-(1-pyrenyl)methylum hexafluorophosphate 29. *General procedure A* was used with pyrene-1-carbaldehyde (139 mg); reaction time 4 h; cooling time 10 min. Recrystallisation from MeCN/diethyl ether gave **29** as burgundy crystals (279 mg, 99% yield). M.pt 187 °C; ¹H-NMR (500 MHz, CD₃CN) δ = 9.65 (s, 1H), 8.55–8.49 (m, 3H), 8.44–8.37 (m, 5H), 8.33–8.30 (m, 2H), 8.24 (d, *J* = 8.9 Hz, 1H), 8.16 (app t, *J* = 7.7 Hz, 1H), 7.89 (s, 1H), 3.51 (hept, *J* = 6.9 Hz, 1H), 3.48 (s, 3H), 2.48 (s, 3H), 1.49 (d, *J* = 6.9 Hz, 6H) ppm; ¹³C-NMR (126 MHz, CD₃CN) δ = 171.7, 161.2, 157.9, 150.5, 148.3, 146.2, 145.0, 142.6, 141.5, 139.8, 135.2, 132.7, 132.2, 131.7, 131.5, 131.0, 130.7, 128.40, 128.36, 128.20, 128.17, 126.5, 125.4, 124.6, 40.3, 29.9, 23.8, 13.9 ppm. IR ν_{max} 2972, 1560, 1532, 1431, 1387, 1340, 1318, 1258, 1235, 1208, 1113, 1043, 829, 718, 681, 658, 629, 598, 556 cm⁻¹. HRMS (ESI⁺): calc. for C₃₂H₂₇ [M]⁺ 411.2108, found 411.2112.

3-Guaiazulenyl-(8-hydroxy-1,1,7,7-tetramethyl-2,3,6,7-tetrahydro-1*H*,5*H*-pyrido[3,2,1-*ij*]quinolin-9-yl)methylum hexafluorophosphate 30. *General procedure A* was used with 8-hydroxy-1,1,7,7-tetramethyljulolidine-9-carboxaldehyde (165 mg); reaction time 4 h; cooling time 10 min. **30** was obtained as lus-



trous green-gold crystals (262 mg, 87% yield); no further purification was necessary. M.pt 170 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.82 (s, 1H), 8.40 (d, J = 2.2 Hz, 1H), 7.91 (s, 1H), 7.88 (dd, J = 10.9, 2.2 Hz, 1H), 7.72 (d, J = 10.9 Hz, 1H), 7.64 (br s, 1H), 7.61 (s, 1H), 3.65–3.62 (m, 2H), 3.55–3.53 (m, 2H), 3.27 (hept, J = 6.9 Hz, 1H), 3.17 (s, 3H), 2.61 (s, 3H), 1.84–1.79 (m, 4H), 1.46 (s, 6H), 1.40 (d, J = 6.9 Hz, 6H), 1.29 (s, 6H) ppm; $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 160.9, 155.3, 154.3, 151.8, 148.6, 145.3, 145.0, 142.3, 140.3, 138.1, 137.5, 134.5, 132.8, 131.5, 127.7, 119.8, 118.0, 50.0, 49.1, 39.1, 38.6, 35.0, 32.9, 32.7, 29.7, 28.8, 27.9, 24.3, 13.3 ppm. IR ν_{max} 3574, 2957, 1611, 1528, 1500, 1462, 1312, 1257, 1089, 1046, 904, 824, 777, 648, 592, 554 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{32}\text{H}_{40}\text{NO}$ $[\text{M}]^+$ 454.3105, found 454.3107.

(3-Bromothiophen-2-yl)-3-guaiazulenylmethylum hexafluorophosphate 31. *General procedure A* was used with 3-bromothiophene-2-carboxaldehyde (116 mg); reaction time 4 h; cooling time 10 min. **31** was obtained as burgundy crystals (235 mg, 90% yield); no further purification was necessary. M.pt 169 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.83 (s, 1H), 8.59 (d, J = 2.2 Hz, 1H), 8.51 (d, J = 11.2 Hz, 1H), 8.41 (dd, J = 11.2, 2.2 Hz, 1H), 8.23 (s, 1H), 8.16 (d, J = 5.4 Hz, 1H), 7.41 (d, J = 5.4 Hz, 1H), 3.49 (hept, J = 6.9 Hz, 1H), 3.39 (s, 3H), 2.57 (s, 3H), 1.46 (d, J = 6.9 Hz, 6H) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 171.1, 160.5, 157.3, 154.2, 150.6, 146.9, 145.1, 140.3, 139.7, 138.6, 138.3, 137.1, 135.1, 133.6, 127.3, 40.2, 29.8, 23.8, 14.1 ppm. IR ν_{max} 3121, 2967, 1599, 1563, 1447, 1398, 1377, 1296, 1211, 1158, 1103, 1042, 979, 819, 738, 659, 608, 554 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{20}\text{H}_{20}^{81}\text{BrS}$ $[\text{M}]^+$ 373.0444, found 373.0443.

(Benzothiophen-2-yl)-3-guaiazulenylmethylum hexafluorophosphate 32. *General procedure A* was used with benzothiophene-2-carboxaldehyde (98 mg); reaction time 4 h; cooling time 10 min. **32** was obtained as red crystals (238 mg, 97% yield); no further purification was necessary. M.pt 192 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.80 (s, 1H), 8.52 (d, J = 2.2 Hz, 1H), 8.43 (d, J = 11.2 Hz, 1H), 8.36 (dd, J = 11.2, 2.2 Hz, 1H), 8.23 (s, 1H), 8.19 (s, 1H), 7.92 (d, J = 7.4 Hz, 1H), 7.91 (d, J = 8.2 Hz, 1H), 7.47–7.44 (m, 1H), 7.37 (app t, J = 7.6 Hz, 1H), 3.48 (hept, J = 6.9 Hz, 1H), 3.33 (s, 3H), 2.57 (s, 3H), 1.47 (d, J = 6.9 Hz, 6H) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 170.8, 160.4, 157.6, 153.6, 150.3, 146.2, 145.6, 145.0, 141.5, 141.2, 140.2, 140.0, 139.6, 139.3, 137.8, 130.1, 127.3, 127.1, 123.7, 40.2, 29.8, 23.8, 14.1 ppm. IR ν_{max} 2972, 1605, 1568, 1494, 1308, 1342, 1299, 1173, 1160, 1120, 1042, 825, 765, 658, 556 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{24}\text{H}_{23}\text{S}$ $[\text{M}]^+$ 343.1515, found 343.1517.

3-Guaiazulenyl-(5-nitrothiophen-2-yl)methylum hexafluorophosphate 33. *General procedure A* was used with 5-nitrothiophene-2-carboxaldehyde (95 mg); reaction time 4 h; cooling time 10 min. **33** was obtained as burgundy crystals (162 mg, 66% yield); no further purification was necessary. M.pt 189 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.59 (s, 1H), 8.57 (d, J = 11.2 Hz, 1H), 8.46 (dd, J = 11.2, 2.2 Hz, 1H), 8.15–8.11 (m, 1H), 8.07 (d, J = 4.4 Hz, 1H), 7.80 (dd, J = 4.4, 0.9 Hz, 1H), 3.51 (hept, J = 6.9 Hz, 1H), 3.34 (s, 3H), 2.57 (s, 3H), 1.46 (d, J = 6.8 Hz, 6H) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 173.7, 162.1, 158.6,

154.3, 152.1, 149.0, 145.9, 144.8, 140.9, 140.5, 138.7, 138.4, 137.9, 130.6, 40.5, 29.6, 23.7, 14.1 ppm. One aromatic carbon was not observed. IR ν_{max} 3105, 2980, 1605, 1574, 1522, 1494, 1455, 1419, 1404, 1334, 1319, 1250, 1200, 1109, 1048, 985, 814, 730, 653, 523, 555 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{20}\text{H}_{20}\text{NO}_2\text{S}$ $[\text{M}]^+$ 338.1210, found 338.1210.

3-Guaiazulenyl-(5-cyanothiophen-2-yl)methylum hexafluorophosphate 34. *General procedure A* was used with 5-cyanothiophene-2-carboxaldehyde (83 mg); reaction time 4 h; cooling time 10 min. **34** was obtained as orange-red crystals (185 mg, 79% yield); no further purification was necessary. M.pt 194 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.66 (s, 1H), 8.59 (d, J = 2.2 Hz, 1H), 8.55 (d, J = 11.2 Hz, 1H), 8.44 (dd, J = 11.2, 2.2 Hz, 1H), 8.11 (s, 1H), 7.89 (d, J = 4.1 Hz, 1H), 7.86 (d, J = 4.1 Hz, 1H), 3.50 (hept, J = 6.6 Hz, 1H), 3.33 (s, 3H), 2.56 (s, 3H), 1.46 (d, J = 6.9 Hz, 6H) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 173.1, 161.8, 158.4, 154.3, 151.7, 148.4, 145.7, 145.6, 140.4, 140.1, 140.0, 139.4, 138.6, 137.7, 114.2, 40.4, 29.7, 23.7, 14.1 ppm. One aromatic carbon was not observed. IR ν_{max} 3640, 3570, 3084, 2962, 2286, 2165, 1626, 1548, 1517, 1417, 1362, 1330, 1197, 1022, 811, 750, 669, 558 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{21}\text{H}_{20}\text{NS}$ $[\text{M}]^+$ 318.1311, found 318.1312.

3-Guaiazulenyl-((2,2'-bithiophen)-5-yl)methylum hexafluorophosphate 35. *General procedure A* was used with 5-cyanothiophene-2-carboxaldehyde (116 mg); reaction time 3 h; cooling time 10 min. **35** was obtained as dark green powder (247 mg, 95% yield); no further purification was necessary. M.pt 194–196 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.80 (1H, s), 8.56 (1H, d, J = 2.2 Hz), 8.37 (1H, d, J = 11.2 Hz), 8.32 (1H, dd, J = 11.2, 2.2 Hz), 8.31 (1H, br s), 7.93 (1H, d, J = 4.2 Hz), 7.65–7.62 (2H, m), 7.52 (1H, d, J = 4.1 Hz), 7.21 (1H, dd, J = 5.0, 3.7 Hz), 3.45 (1H, hept, J = 6.9 Hz), 3.34 (3H, s), 2.60 (3H, s), 1.45 (6H, d, J = 6.9 Hz) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 168.1, 158.5, 156.4, 152.7, 152.6, 148.6, 146.0, 144.5, 144.2, 141.1, 139.6, 139.3, 139.0, 136.3, 134.7, 130.7, 130.2, 128.7, 126.8, 39.9, 29.8, 23.9, 14.0 ppm. IR ν_{max} 3129, 2967, 1376, 1497, 1223, 1040, 734, 611 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{24}\text{H}_{23}\text{S}_2$ $[\text{M}]^+$ 375.1236, found 375.1241.

3-Guaiazulenyl-(*N*-methylpyrrol-2-yl)methylum hexafluorophosphate 36. *General procedure A* was used with *N*-methylpyrrole-2-carboxaldehyde (65 mg); reaction time 3 h; cooling time 10 min. **36** was obtained as dark purple crystals (218 mg, 94% yield); no further purification was necessary. M.pt 168–171 °C; $^1\text{H-NMR}$ (500 MHz, CD_3CN) δ = 8.60 (1H, s), 8.53 (1H, s), 8.27 (1H, br s), 8.19 (2H, br s), 7.61 (1H, d, J = 4.5 Hz), 7.55 (1H, br s), 6.65 (1H, ddd, J = 4.5, 2.2, 0.9 Hz), 3.92 (3H, s), 3.40 (1H, hept, J = 6.9 Hz), 3.33 (3H, s), 2.59 (3H, s), 1.43 (6H, d, J = 6.9 Hz) ppm. $^{13}\text{C-NMR}$ (126 MHz, CD_3CN) δ = 163.6, 154.5, 151.2, 145.4, 142.8, 141.4, 140.8, 139.9, 139.1, 136.5, 136.4, 133.9, 130.8, 127.1, 117.1, 39.6, 35.6, 29.8, 24.0, 13.6 ppm. IR ν_{max} 3129, 2967, 1583, 1377, 1225, 1041, 828, 651 cm^{-1} . HRMS (ESI^+): calc. for $\text{C}_{21}\text{H}_{24}\text{N}$ $[\text{M}]^+$ 290.1903, found 290.1896.

General procedure B for synthesis of compounds 37–38. To a solution of the relevant guaiazulenyl carbocation (0.008 mmol, 1 eq.) in MeCN (2.0 mL) was added a solution of NaBH_4 (7 mg, 0.17 mmol, 2.1 eq.) in EtOH (2 mL). The mixture



was stirred at room temperature under air until the starting material was consumed, as shown by TLC (EtOAc/petrol 1 : 4), approximately 20 min. Precipitation of solid was observed, which was isolated by filtration, then dried under vacuum to afford the desired product; no further purification was necessary.

4-Bromo-2-((5-isopropyl-3,8-dimethylazulen-1-yl)methyl)thiophene 37. General procedure B was used with cation 27. Product 37 was obtained as a navy blue solid (21 mg, 68% yield). M.pt 104 °C; ¹H-NMR (500 MHz, CDCl₃) δ = 8.12 (d, J = 2.1 Hz, 1H), 7.47 (s, 1H), 7.30 (dd, J = 10.8, 2.1 Hz, 1H, 6), 7.01 (d, J = 1.4 Hz, 1H), 6.86 (d, J = 10.7 Hz, 1H), 6.51 (d, J = 1.3 Hz, 1H), 4.67 (s, 2H), 3.04 (hept, J = 6.9 Hz, 1H), 2.87 (s, 3H), 2.62 (s, 3H), 1.35 (d, J = 6.9 Hz, 6H) ppm. ¹³C-NMR (126 MHz, CDCl₃) δ = 149.2, 145.3, 140.7, 139.7, 138.1, 135.1, 133.9, 132.9, 126.95, 126.93, 124.5, 123.8, 121.0, 109.3, 37.9, 31.9, 26.7, 24.7, 13.0 ppm. IR ν_{max} 3084, 2962, 1626, 1548, 1517, 1417, 1362, 1330, 1197, 1022, 811, 750, 667, 558 cm⁻¹. HRMS (ESI⁺): calc. for C₂₀H₂₁⁸¹BrS [M + H]⁺ 375.0600, found 375.0593.

1-((5-Iso-propyl-3,8-dimethylazulen-1-yl)methyl)pyrene 38. General procedure B was used with cation 29. Product 38 was obtained as a light blue solid (27 mg, 72% yield). M.pt 149 °C; ¹H-NMR (500 MHz, CDCl₃) δ = 8.36 (d, J = 9.2 Hz, 1H), 8.18 (d, J = 7.6 Hz, 2H), 8.12 (d, J = 2.2 Hz, 1H), 8.11 (d, J = 9.2 Hz, 1H), 8.04 (d, J = 7.7 Hz, 1H), 8.03 (s, 2H), 8.00 (app t, J = 7.6 Hz, 1H), 7.55 (d, J = 8.0 Hz, 1H), 7.30 (dd, J = 10.8, 2.2 Hz, 1H), 7.19 (s, 1H), 6.85 (d, J = 10.7 Hz, 1H), 5.36 (s, 2H), 3.05 (hept, J = 7.0 Hz, 1H), 2.92 (s, 3H), 2.54 (s, 3H), 1.54 (s, 2H), 1.37 (d, J = 6.8 Hz, 6H); ppm. ¹³C-NMR (126 MHz, CDCl₃) δ = 145.8, 141.0, 139.1, 137.9, 136.9, 135.1, 133.7, 133.5, 131.6, 131.1, 129.9, 128.7, 127.75, 127.74, 127.6, 126.8, 126.5, 126.0, 125.8, 125.14, 125.13, 125.10, 125.08, 124.96, 124.5, 123.7, 37.9, 35.4, 26.9, 24.8, 13.0 ppm. IR ν_{max} 3035, 2952, 2859, 1588, 1547, 1517, 1444, 1312, 1244, 1181, 1098, 1055, 1003, 774, 843, 753, 706, 690, 644 cm⁻¹. HRMS (ESI⁺): calc. for C₃₂H₂₈ [M + H]⁺ 413.2264, found 413.2250.

Author contributions

SEL conceived the project and acquired funding; CH, JLH and LCM carried out synthesis and spectroscopic characterisation. GKK acquired and interpreted X-ray crystallographic data. SEL wrote the manuscript with input from all authors.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank EPSRC for IAA funding (EP/R51164X/1) and for DTG PhD studentships to L. C. M. and J. L. H. The authors acknowledge the Material and Chemical Characterisation

Facility (MC²) at University of Bath (<https://doi.org/10.15125/mx6j-3r54>).

References

- R. S. H. Liu, *J. Chem. Educ.*, 2002, **79**, 183.
- A. G. Anderson, Jr. and B. M. Steckler, *J. Am. Chem. Soc.*, 1959, **81**, 4941.
- (a) M. Beer and H. C. Longuet-Higgins, *J. Chem. Phys.*, 1955, **23**, 1390; (b) B. D. Wagner, D. Tittelbach-Helmrich and R. P. Steer, *J. Phys. Chem.*, 1992, **96**, 7904; (c) K. Veys and D. Escudero, *J. Phys. Chem. A*, 2020, **124**, 7228.
- R. S. H. Liu, R. S. Muthyala, X.-S. Wang and A. E. Asato, *Org. Lett.*, 2000, **2**, 269–271.
- (a) B. Hou, J. Li, X. Yang, J. Zhang, H. Xin, C. Ge and X. Gao, *Chin. Chem. Lett.*, 2022, **33**, 2147; (b) X. Gao, B. Hou, J. Li and C. Ge, *Chin. Pat.*, CN113402442, 2021.
- T. Koide, M. Takesue, T. Murafuji, K. Satomi, Y. Suzuki, J. Kawamata, K. Terai, M. Suzuki, H. Yamada, Y. Shiota, K. Yoshizawa and F. Tani, *ChemPlusChem*, 2017, **82**, 1010.
- H. Xin, C. Ge, X. Yang, H. Gao, X. Yang and X. Gao, *Chem. Sci.*, 2016, **7**, 6701.
- P. Cowper, A. Pockett, G. Kociok-Köhn, P. J. Cameron and S. E. Lewis, *Tetrahedron*, 2018, **74**, 2775.
- H. Salman, Y. Abraham, S. Tal, S. Meltzman, M. Kapon, N. Tessler, S. Speiser and Y. Eichen, *Eur. J. Org. Chem.*, 2005, 2207.
- C. M. López-Alled, S. J. Park, D. J. Lee, L. C. Murfin, G. Kociok-Köhn, J. L. Hann, J. Wenk, T. D. James, H. M. Kim and S. E. Lewis, *Chem. Commun.*, 2021, **57**, 10608.
- L. C. Murfin, M. Weber, S. J. Park, W. T. Kim, C. M. López-Alled, C. L. McMullin, F. Pradaux-Caggiano, C. L. Lyall, G. Kociok-Köhn, J. Wenk, S. D. Bull, J. Yoon, H. M. Kim, T. D. James and S. E. Lewis, *J. Am. Chem. Soc.*, 2019, **141**, 19389.
- For reviews, see: (a) A. C. Razus, *Symmetry*, 2021, **13**, 526; (b) S. Ito and N. Morita, *Eur. J. Org. Chem.*, 2009, 4567.
- (a) K. Satoh, I. Ogura and M. Yamaguchi, *Nippon Kagaku Kaishi*, 1982, **1982**, 1206, DOI: [10.1246/nikkashi.1982.1199](https://doi.org/10.1246/nikkashi.1982.1199); (b) P. Uebelhart and H.-J. Hansen, *Helv. Chim. Acta*, 1992, **75**, 2493.
- T. Shoji, M. Tanaka, T. Araki, S. Takagaki, R. Sekiguchi and S. Ito, *RSC Adv.*, 2016, **6**, 78303.
- T. Shoji, K. Miura, A. Ohta, R. Sekiguchi, S. Ito, Y. Endo, T. Nagahata, S. Mori and T. Okujima, *Org. Chem. Front.*, 2019, **6**, 2801.
- (a) D. A. Colby and T. D. Lash, *J. Org. Chem.*, 2002, **67**, 1031; (b) Y. Jin, K. Akagawa, T. Mutai, I. Yoshikawa and K. Kudo, *Tetrahedron*, 2021, **84**, 132146.
- S. Ito, N. Morita and T. Asao, *Bull. Chem. Soc. Jpn.*, 1999, **72**, 2543.
- Y. Jin, K. Akagawa and K. Kudo, *Tetrahedron*, 2021, **84**, 131998.
- S. Ito, N. Morita and T. Asao, *Bull. Chem. Soc. Jpn.*, 1995, **68**, 1409.



- 20 S. Ito, S. Kikuchi, N. Morita and T. Asao, *J. Org. Chem.*, 1999, **64**, 5815.
- 21 (a) D. H. Reid, W. H. Stafford, W. L. Stafford, G. McLennan and A. Voigt, *J. Chem. Soc.*, 1958, 1110; (b) E. C. Kirby and D. H. Reid, *J. Chem. Soc.*, 1960, 494; (c) E. C. Kirby and D. H. Reid, *J. Chem. Soc.*, 1961, 1724; (d) E. C. Kirby and D. H. Reid, *J. Chem. Soc.*, 1961, 3579; (e) M. Fraser and D. H. Reid, *J. Chem. Soc.*, 1963, 1421.
- 22 (a) F. N. Stepanow and N. A. Aldanowa, *Russ. J. Gen. Chem.*, 1959, **29**, 344; (b) F. N. Stepanow and N. A. Aldanowa, *Angew. Chem.*, 1959, **71**, 125.
- 23 (a) S.-i. Takekuma, H. Takekuma, Y. Matsubara, A. Hirai, H. Yamamoto and T. Nozoe, *Nippon Kagaku Kaishi*, 1996, **1996**, 419, DOI: [10.1246/nikkashi.1996.419](https://doi.org/10.1246/nikkashi.1996.419); (b) S.-i. Takekuma, H. Takekuma, Y. Hanaoka and H. Yamamoto, *Nippon Kagaku Kaishi*, 1996, **1996**, 659, DOI: [10.1246/nikkashi.1996.659](https://doi.org/10.1246/nikkashi.1996.659); (c) S.-i. Takekuma, H. Takekuma, Y. Hatanaka, J. Kawaguchi and H. Yamamoto, *Nippon Kagaku Kaishi*, 1998, **1998**, 275, DOI: [10.1246/nikkashi.1998.275](https://doi.org/10.1246/nikkashi.1998.275); (d) S.-i. Takekuma, M. Sasaki, H. Takekuma and H. Yamamoto, *Chem. Lett.*, 1999, **28**, 999; (e) S.-i. Takekuma, M. Sasaki, H. Takekuma and H. Yamamoto, *Nippon Kagaku Kaishi*, 2000, **2000**, 107, DOI: [10.1246/nikkashi.2000.107](https://doi.org/10.1246/nikkashi.2000.107); (f) M. Sasaki, M. Nakamura, T. Uriu, H. Takekuma, T. Minematsu, M. Yoshihara and S.-i. Takekuma, *Tetrahedron*, 2003, **59**, 505; (g) M. Nakamura, M. Sasaki, H. Takekuma, T. Minematsu and S.-i. Takekuma, *Bull. Chem. Soc. Jpn.*, 2003, **76**, 2051; (h) M. Sasaki, M. Nakamura, G. Hannita, H. Takekuma, T. Minematsu, M. Yoshihara and S.-i. Takekuma, *Tetrahedron Lett.*, 2003, **44**, 275; (i) S.-i. Takekuma, K. Sasaki, M. Nakatsuji, M. Sasaki, T. Minematsu and H. Takekuma, *Bull. Chem. Soc. Jpn.*, 2004, **77**, 379; (j) M. Nakatsuji, Y. Hata, T. Fujihara, K. Yamamoto, M. Sasaki, H. Takekuma, M. Yoshihara, T. Minematsu and S.-i. Takekuma, *Tetrahedron*, 2004, **60**, 5983; (k) S.-i. Takekuma, Y. Hata, T. Nishimoto, E. Nomura, M. Sasaki, T. Minematsu and H. Takekuma, *Tetrahedron*, 2005, **61**, 6892; (l) S.-i. Takekuma, K. Takahashi, A. Sakaguchi, Y. Shibata, M. Sasaki, T. Minematsu and H. Takekuma, *Tetrahedron*, 2005, **61**, 10349; (m) S.-i. Takekuma, K. Sonoda, C. Fukuhara and T. Minematsu, *Tetrahedron*, 2007, **63**, 2472; (n) S.-i. Takekuma, K. Tone, M. Sasaki, T. Minematsu and H. Takekuma, *Tetrahedron*, 2007, **63**, 2490; (o) S.-i. Takekuma, K. Mizutani, K. Inoue, M. Nakamura, M. Sasaki, T. Minematsu, K. Sugimoto and H. Takekuma, *Tetrahedron*, 2007, **63**, 3882; (p) S.-i. Takekuma, M. Tamura, T. Minematsu and H. Takekuma, *Tetrahedron*, 2007, **63**, 12058; (q) S.-i. Takekuma, K. Sonoda, T. Minematsu and H. Takekuma, *Tetrahedron*, 2008, **64**, 3802; (r) S.-i. Takekuma, N. Ijibata, T. Minematsu and H. Takekuma, *Bull. Chem. Soc. Jpn.*, 2009, **82**, 585; (s) S.-i. Takekuma, K. Fukuda, Y. Kawase, T. Minematsu and H. Takekuma, *Bull. Chem. Soc. Jpn.*, 2009, **82**, 879; (t) S.-i. Takekuma, K. Fukuda, T. Minematsu and H. Takekuma, *Bull. Chem. Soc. Jpn.*, 2009, **82**, 1398; (u) S.-i. Takekuma, M. Kaibara, T. Minematsu and H. Takekuma, *Tetrahedron*, 2011, **67**, 4780; (v) S.-i. Takekuma, I. Miyamoto, A. Hamasaki and T. Minematsu, *Tetrahedron*, 2011, **67**, 9719; (w) S.-i. Takekuma, M. Yamamoto, A. Nakagawa, T. Iwata, T. Minematsu and H. Takekuma, *Tetrahedron*, 2012, **68**, 8318; (x) S.-i. Takekuma, N. Kobayashi, T. Minematsu and H. Takekuma, *Bull. Chem. Soc. Jpn.*, 2013, **86**, 968; (y) S.-i. Takekuma, A. Seki and T. Minematsu, *Bull. Chem. Soc. Jpn.*, 2014, **87**, 511.
- 24 (a) Y. Ogawa, *Jpn. Pat.*, JP08187940, 1996; (b) T. Santo and C. Hioki, *Jpn. Pat.*, JP01071791, 1989; (c) K. Takano, *Jpn. Pat.*, JP63252791, 1988.
- 25 S. Kawakami and Y. Kojima, *Jpn. Pat.*, JP04153086, 1992.
- 26 Y. Oguchi and K. Katagiri, *Jpn. Pat.*, JP61262737, 1986.
- 27 T. Okamoto, N. Yamamoto and M. Kawaguchi, *Eur. Pat.*, EP659407, 1995.
- 28 K. Watanabe, T. Shintou, T. Nomoto, T. Miyazaki, T. Tanaka, Y. Nishimura, Y. Shimada and N. Nishimura, *US Pat.*, US20110236310, 2011.
- 29 S. Yang, X.-S. Xiong and D.-L. Wang, *Heterocycles*, 2021, **102**, 2179.
- 30 S. H. Kim, Y. A. Son, J. S. Bae and D. H. Lee, *Korea Pat.*, KR2014078467, 2014.
- 31 See: D. Chen, S. Yu, L. van Ofwegen, P. Proksch and W. Lin, *J. Agric. Food Chem.*, 2012, **60**, 112 and references therein.
- 32 S. Takekuma, Z. Zhao, Y. Matsubara, D. Makihara, H. Yamamoto and T. Nozoe, *Nippon Kagaku Kaishi*, 1994, **1994**, 399, DOI: [10.1246/nikkashi.1994.399](https://doi.org/10.1246/nikkashi.1994.399).
- 33 (a) S. Ito, R. Sekiguchi, A. Mizushima, K. Kudo, J. Kawakami and T. Shoji, *ARKIVOC*, 2018, **2018**(2), 145, DOI: [10.2482/ark.5550190.p010.163](https://doi.org/10.2482/ark.5550190.p010.163); (b) H. Noguchi, T. Hirose, S. Yokoyama and K. Matsuda, *CrystEngComm*, 2016, **18**, 7377; (c) S. Nakatsuji, H. Nakazumi, K. Nakashima and S. Akiyama, *Nippon Kagaku Kaishi*, 1992, **1992**, 1279, DOI: [10.1246/nikkashi.1992.1279](https://doi.org/10.1246/nikkashi.1992.1279); (d) S. Nakatsuji, N. Okamoto, K. Nakashima and S. Akiyama, *Chem. Lett.*, 1986, **15**, 329; (e) J. R. Gandler, *J. Am. Chem. Soc.*, 1985, **107**, 8218.
- 34 G. E. Williams, G. Kociok-Köhn, T. D. James and S. E. Lewis, *Org. Biomol. Chem.*, 2021, **19**, 2502.
- 35 (a) R. Lohwy and P. M. Keehn, *Tetrahedron Lett.*, 1976, **17**, 1043; (b) N. Kato, Y. Fukazawa and S. Itô, *Tetrahedron Lett.*, 1976, **17**, 2045; (c) R. Lohwy and P. M. Keehn, *J. Am. Chem. Soc.*, 1977, **99**, 3797; (d) N. Kato, H. Matsunaga, S. Oeda, Y. Fukazawa and S. Itô, *Tetrahedron Lett.*, 1979, **20**, 2419; (e) T. Koenig, K. Rudolf, R. Chadwick, H. Geiselmann, T. Patapoff and C. E. Klopfenstein, *J. Am. Chem. Soc.*, 1986, **108**, 5024.
- 36 (a) G. Laus, H. Schottenberger, K. Wurst, J. Schütz, K.-H. Ongania, U. E. I. Horvath and A. Schwärzler, *Org. Biomol. Chem.*, 2003, **1**, 1409; (b) S. Ito, S. Kikuchi, H. Kobayashi, N. Morita and T. Asao, *J. Org. Chem.*, 1997, **62**, 2423.

