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A 'push–pull' tropylium-fused aminoporphyrazine

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ABSTRACT

Crossover Linstead macrocyclization of cycloheptatrienylmaleonitrile and (dimethylamino)-maleonitrile gave access to an unsymmetrical (A_3B) porphyrazine bearing six peripheral amino substituents and a fused cycloheptatrienyl ring. Subsequent hydride abstraction gave a tropylium-fused aminoporphyrazine, which contains both strongly electron-donating and withdrawing groups and thus can be labelled as a 'push–pull' macrocycle. Detailed structural studies of this novel porphyrazine are described.

1. Introduction

Over the past few decades, considerable research in the field of non-linear optics (NLO) has been reported[1–3] due in part to the applicability of NLO materials in telecommunications and optical signal processing devices.[2,3] Since the mid-1980s organic NLO materials have emerged as important targets, since they exhibit large and fast nonlinearities and are, in general, easy to process and integrate into optical devices.[4–6] Of particular importance is the fact that fine-tuning of the NLO properties can be achieved by rational modification of the chemical structure. Amongst the various potential NLO chromophores, tetrapyrrolic macrocycles occupy a unique position.[7–9] Their ground state absorption is mostly confined to a few narrow regions (Soret and Q bands) allowing high transmission in the spectral window between these bands. Moreover, their optical properties can be readily varied by altering the cavity metal, its oxidation state or axial ligands, or the nature of the substituents at the periphery. While porphyrins and phthalocyanines have been extensively examined in this regard, the related tetraazaporphyrins (porphyrazines, pz) have not.

Porphyrazines are porphyrin analogues, with *meso* nitrogen atoms replacing the *meso* carbon atoms. Peripheral heteroatom functionalization of the macrocycle by thiols, amines or alcohols results in significant modulation of their physical and electronic properties.[10–13] Of particular note, porphyrazines containing peripheral amino substituents show strong electron donation into the macrocyclic π-system[11,13,14] and numerous structural analogues,[15] metallic complexes,[15c,16] charge transfer complexes,[17] and seco-porphyrazines have been prepared.[18,19] Tetrapyrrolic macrocycles bearing an electron-donating group on one side of the molecule and an electron-withdrawing group on the other have been termed 'push–pull', and such systems have received special attention, due to the need for a molecular dipole for efficient NLO properties.[8,9] We considered that amino-porphyrazines ring fused to a tropylium cation should be interesting targets with potential NLO properties (see **1**, Fig. 1).

2. Results and discussion

Our initial attempts to synthesize a 'push–pull' porphyrazine **1** bearing an unsubstituted tropylium ring (R^2=H), were largely unsuccessful. During the course of this work however, Kobayashi and co-workers published the synthesis of porphyrazine **2** (Fig. 1).[20] Subsequent oxidation of porphyrazine **2** using DDQ was accompanied by spectroscopic changes (UV–vis, MS, MCD) consistent with the formation of mono-tropylium species. In light of this precedent, we examined the synthesis of porphyrazine **1** (R^2=Ph), so as to fully characterize a porphyrazine tropylium cation. Cyclohepatrienyl maleonitrile **11** was prepared by the Kobayashi route,[20]

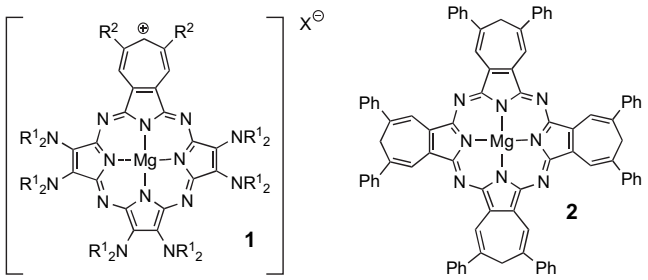

Figure 1. Generic target porphyrazine **1** and Kobayashi's system.[20]

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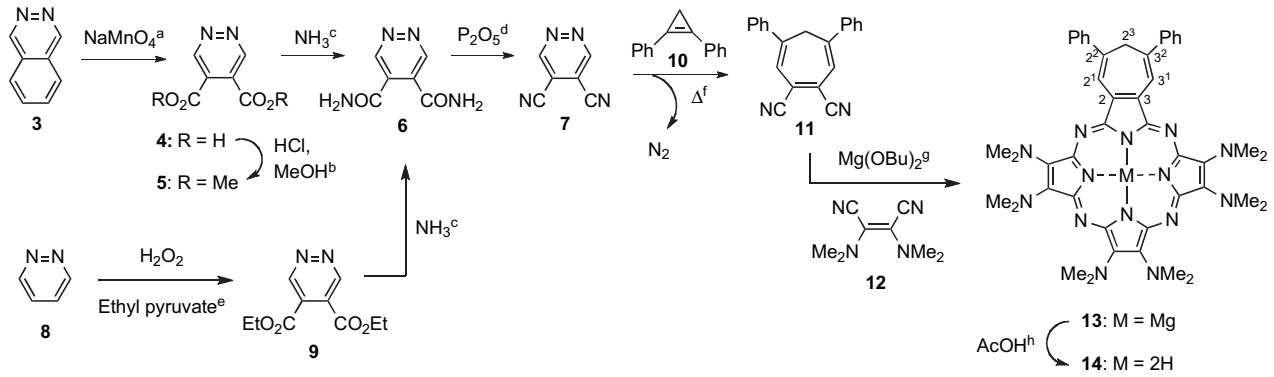


Reagents and conditions:

(a) $NaMnO_4$, NaOH, Δ, 12 h, 65%; (b) HCl, MeOH, rt, 12 h, 25%; (c) NH_3, MeOH, rt, 4 d, 75-96%; (d) P_2O_5, reflux, 5 h, 54%; (e) H_2O_2, Ethyl pyruvate, 30 min, 22%; (f) PhCl, Δ, 16 h, 36%; (g) $Mg(O^nBu)_2$, *n*-BuOH, Δ, 24 h, 9%; (h) AcOH, CH_2Cl_2, rt, 72%.

Scheme 1.

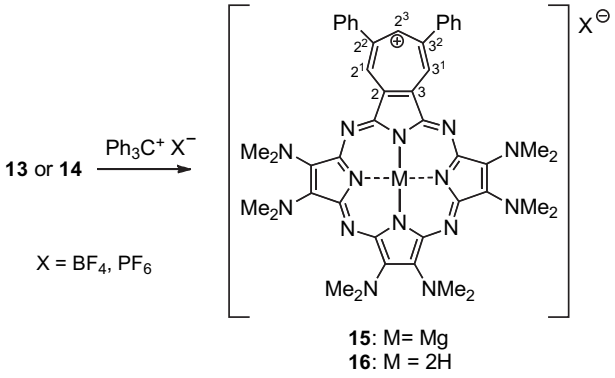
involving cycloaddition[21] of 1,2-diphenylpropene (**10**)[20,22] with 4,5-dicyanopyrazine (**7**). Oxidative cleavage of phthalazine (**3**) furnished diacid **4** in moderate yield (65%).[24] Following the procedure of Di Stefano et al.,[23] esterification of **4** in the presence of HCl and MeOH, followed by reaction with ammonia gave diamide **6**. Alternatively and more conveniently, radical carboxylation of pyridazine (**8**)[25] and amidation gave diamide **6**. Dehydration of diamide **6** using phosphorus pentaoxide gave dicyanopyrazine **7** in moderate yield (54%). Cycloaddition of dinitrile **7** with 1,2-diphenylpropene (**10**)[20,22] and nitrogen elimination[21] gave maleonitrile **11** (Scheme 1).

A statistically-biased crossover Linstead macrocyclization[11] of maleonitriles **11** and **12**[26] in a 1:7 ratio, respectively, afforded the crude target unsymmetrical (A_3B) porphyrazine, amongst a mixture of other porphyrazine constituents (A_4, A_2B_2). Purification by chromatography gave the A_3B cyclohepatrienyl fused aminoporphyrazine **13** in a relatively low yield (9%) (Scheme 1). It should be noted however that this yield is comparable to other challenging mixed macrocyclizations of the electron-rich amino maleonitriles.[11] Demetallation of porphyrazine **13** proceeded unremarkably to give free-base porphyrazine **14** in good yield (72%).

We considered that, although Kobayashi[20] and Latos–Grazynski[27] utilized DDQ for the oxidation of cycloheptatriene-porphyrazine **2** and carbocyclic porphyrin analogues to the corresponding tropylium species, respectively, hydride abstraction of porphyrazine **13** or **14** using triphenylmethyl tetrafluoroborate or hexafluorophosphate[28] would be more convenient, in that it should directly provide tropylium-fused porphyrazines with a chemically inert, non-coordinating counterion, which should aid product isolation and characterization (Scheme 2).

Titration of porphyrazine **13** in dichloromethane and methanol with Ph_3CX (X=BF_4, PF_6) resulted in notable changes in the UV–vis spectrum (Fig. 2). The broad Q band centred around 710 nm[11] undergoes further broadening with a decrease in intensity. In addition, the small band at 550 nm, attributed to n–π^* transitions of the nitrogen lone pairs,[11] disappears and the Soret band undergoes a blue shift with a decrease in intensity. Of particular importance is the development of a new peak around 811 nm that overlaps with the Q band. In the DDQ oxidation of porphyrazine **2** by Kobayashi and co-workers,[20] a new peak was observed at 820 nm, and attributed to expansion of the π-system. Despite containing significantly less conjugation than **2**, the new peak of **13** is only slightly blue-shifted in comparison. This is a result of the previously reported influence of the strongly electron-donating peripheral amino substituents, which strongly modulate the Q band shift.[11] Analogous titration studies performed on H_2[pz(A_3B)] **14** (see Supplementary data) reveal a slight blue shift and broadening of the Soret band, with a decrease in intensity of the bands at 539 nm and 719 nm and a new peak emerging at 820 nm.

While our titration studies compared favourably with Kobayashi's result, we were keen to unequivocally characterize tropylium porphyrazines instead of just relying upon UV–vis, MS, and MCD studies.[20] Slow evaporation of a THF and dichloromethane (1:1) solution of porphyrazine **13** with triphenylmethyl hexafluorophosphate under anhydrous, anaerobic conditions, provided crystals suitable for an X-ray crystallographic study (Fig. 3). This is the first example an X-ray crystallographic structure of a tropylium cation fused to any macrocycle of the porphyrin/phthalocyanine/porphyrazine class. Curiously the structure revealed the free-base



15: M= Mg
16: M = 2H

Scheme 2.

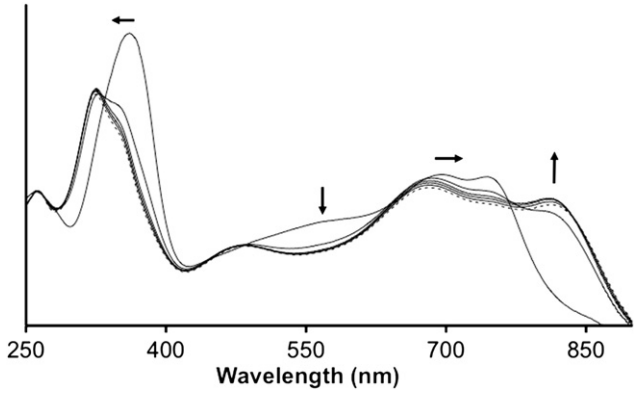


Figure 2. UV–vis changes upon Ph_3CBF_4 addition to porphyrazine **13**.

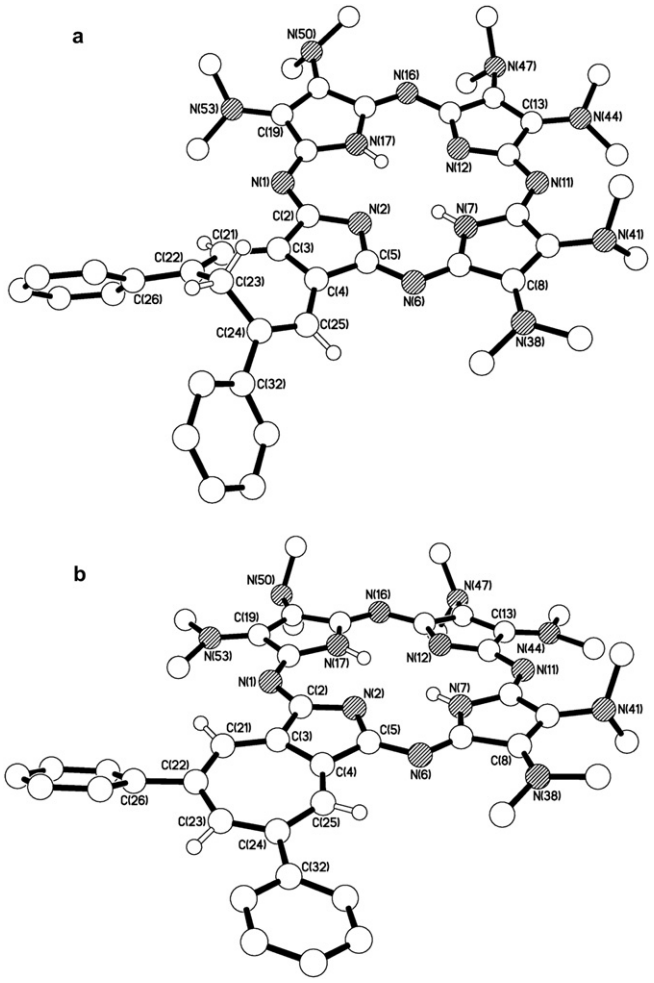


Figure 3. The molecular structure of porphyrazines (a) 14 and (b) 16^{+}.

(not magnesium) tropylium porphyrazine salt **16** crystallized from the mixture. Further isolation studies (vide infra) confirmed that exposure of magnesium porphyrazine **13** to triphenyl carbonium salts results in partial demetallation and subsequent decomposition of the macrocycle. As a point of comparison, we also determined the X-ray crystal structure of the neutral porphyrazine **14** (Fig. 3).

On oxidation of the porphyrazine **14** to the tropylium porphyrazine **16**, the change in the fused seven- and five-membered ring system is clearly visible (Fig. 3). The C(23) methylene group in **14** has become a methine in **16**,[29] resulting in a near planar geometry for the 10-membered ring in **16**, with C(22), C(23) and C(24) lying only ca. 0.07, 0.18 and 0.11 Å, respectively, out of the plane of the other seven atoms. This contrasts with the significantly folded geometry seen for the 10-membered ring in **14**, where C(22), C(23) and C(24) lie ca. 0.43, 1.27 and 0.40 Å out of the plane of the remaining seven atoms. Whilst the pattern of bonding within the 10-membered ring system of both structures possess approximate C_2 symmetry about the N(2)···C(23) axis, the effect of the change in the bonding at C(23) between **14** and **16** can be seen almost throughout the 10-membered ring. The overall effect on going from **14** to **16** is one of increasing delocalization; the C(2)–C(3)/C(5)–C(4) bonds become ca. 0.02 Å shorter, the C(3)–C(21)/C(4)–C(25) bonds become ca. 0.06 Å shorter, the C(21)–C(22)/C(24)–C(25) bonds become ca. 0.05 Å longer, and the C(22)–C(23)/C(25)–C(23) bonds become ca. 0.10 Å shorter (see Table S1 in Supplementary data). The C(3)–C(4) bond, common to the seven- and five-membered ring systems that are fused together, is ca. 0.05 Å longer, whilst the bonds to N(2) are unchanged.

Since tropylium porphyrazine **16** was designed as a 'push–pull' system, it is reasonable to expect to see shortening of the *N*–C(pz) bond lengths, corresponding to a slight increase in bond order, due to the electron density from the nitrogen (NMe_2) lone pairs 'pushing' into the ring. Indeed, statistically significant shortening of the C(pz)–N bond lengths (0.016–0.042 Å) are visible for three of the six dimethylamino groups (Table S1): N(53)–C(19), N(44)–C(13), and N(38)–C(8). This effect is partially reflected in changes throughout the porphyrazine skeleton. As can be seen in Figure 3, the N(38), N(44) and N(53)-bound NMe_2 units of **16** are approximately co-planar with respect to their parent pyrrole, whilst the others are significantly inclined. It is therefore possible to correlate the bond shortening, and thus electron donation, to the dimethylamino groups whose lone pairs are co-planar with the π system. We have previously demonstrated, that due to conflicting non-bonding interactions, both dimethylamino groups on a single pyrrole unit cannot be co-planar and thus both efficiently donate electron density simultaneously.[30] It is therefore not surprising that in structure **16** (Fig. 3b), only three of the possible six amino substituents appear to be involved in electron donation.

An analytically pure sample of porphyrazine **16** was isolated by chromatography and characterized by NMR spectroscopy. Comparison of the ^{1}H NMR spectra of porphyrazines **13** and **16** demonstrated a downfield shift of the olefinic protons (2^1, 3^1, see Schemes 1 or 2 for numbering) from 9.26 ppm in **13** to 10.09 ppm in **16**, supporting an increase in π-conjugation. While the methylene protons (2^3, see Schemes 1 or 2 for numbering, 4.21 ppm) in **13** were absent in the spectrum of **16**, the location of the corresponding methine proton was not immediately apparent but shown to be at 8.8 ppm in a 1D TOCSY experiment (see Supplementary data).

In conclusion, a method for the synthesis of a tropylium-fused aminoporphyrazine **15** has been described. An X-ray crystallographic study and NMR spectroscopy of the free-base derivative **16**, as compared to the starting material from which it is derived, gave unambiguous confirmation of the proposed structure, and also indicated electron donation from three of the six peripheral amino substituents. This confirms the proposition of porphyrazine **15** as a 'push–pull' macrocycle.

3. Experimental

3.1. General

*3.1.1. Mg[pz(A$_3$B)] (**13**).* A slurry of Mg (180 mg, 7.4 mmol) and I_2 (ca. 2 crystals) in *n*-BuOH (20 mL) was heated to reflux for 24 h. The mixture was allowed to cool to room temperature when dinitriles **12** (492 mg, 3.0 mmol) and **11** (126 mg, 0.43 mmol) in *n*-BuOH (12 mL) were added and the mixture heated to reflux for a further 24 h. The mixture was filtered through Celite and the solids washed with CH_2Cl_2. The mixture was purified by triple chromatography ($MeOH:CHCl_3:Et_2O$ 0.3:70:70); ($MeOH:CH_2Cl_2$ 1:30); ($MeOH:Et_2O:CH_2Cl_2$ 1:4:30) to give porphyrazine **13** (30 mg,) as a blue solid: R_f 0.33 ($MeOH:CH_2Cl_2$ 1:10); IR (neat) 3583, 3355, 3195, 1662, 1580, 1449, 1378, 1308, 1260, 1208, 1003 cm^{-1}; UV–vis (CH_2Cl_2) λ_{max} (log ε) 356 (4.53), 690 (4.30); ^{1}H NMR (500 MHz, py-d_5) δ 3.82 (s, 12H), 3.97 (s, 12H), 4.13, (s, 12H), 4.21 (s, 2H), 7.44 (m, 2H), 7.58 (m, 4H), 8.23 (d, J=7.5 Hz, 4H), 9.26 (s, 2H); ^{13}C NMR (125 MHz, py-d_5) δ 35.0, 43.0, 44.9, 45.5, 55.1, 122.4, 127.6, 127.9, 129.4, 131.7, 132.3, 138.0, 138.8, 142.4, 152.6, 152.7, 156.8, 157.8; MS (MALDI) *m*/*z* 812 $[M+H]^+$; HRMS (MALDI) calcd for $C_{45}H_{51}MgN_{14}$: $[M+H]^+$, 812.28, found: $[M+H]^+$, 812.96. Anal. Calcd for $C_{45}H_{50}MgN_{14}$: C, 66.62; H, 6.21; N, 24.17. Found: C, 66.70; H, 6.30; N, 24.05.

*3.1.2. H$_2$[pz(A$_3$B)] (**14**).* AcOH (0.26 mL, 4.6 mmol) was added at 0 °C to Mg-porphyrazine **13** (37 mg, 46 μmol) in CH_2Cl_2 (11 mL). The mixture stirred at room temperature for 16 h, poured into

aqueous NaOH (1 M; 20 mL) and extracted with CH_2Cl_2 (3×10 mL) until the aqueous layer was colourless. The combined organic extracts were dried ($MgSO_4$), filtered and rotary evaporated. Chromatography (MeOH:CH_2Cl_2 1:40) gave porphyrazine **14** (26 mg, 72%) as a purple solid: R_f 0.87 (MeOH:CH_2Cl_2 1:20); IR (neat) 3583, 3356, 3193, 1658, 1631, 1596, 1424, 1379, 1311, 1207, 1081, 874 cm^{-1}; UV–vis (CH_2Cl_2) λ_{max} (log ε) 341 (4.44), 539 (4.25), 719 (4.20) nm; ^1H NMR (500 MHz, py-d_5) δ 3.73 (s, 12H), 3.90 (s, 12H), 4.07 (s, 12H), 4.20 (s, 2H), 7.44 (m, 2H), 7.58 (m, 4H), 8.23 (d, J=7.4 Hz, 4H), 9.12 (s, 2H); ^{13}C NMR (125 MHz, py-d_5) δ 14.3, 23.0, 29.6, 30.0, 32.1, 35.1, 43.4, 45.0, 121.8, 127.7, 128.2, 129.3, 129.4, 131.7, 132.1, 139.0, 141.9, 142.1, 155.4; MS (MALDI) m/z 790 $[M+H]^+$; HRMS (MALDI) calcd for $C_{45}H_{53}N_{14}$: $[M+H]^+$, 789.99, found: $[M+H]^+$, 789.88. $C_{45}H_{52}N_{14}$. Crystal data for **14**: $C_{45}H_{52}N_{14}\cdot MeCN$, M=830.06, triclinic, $P\bar{1}$ (no. 2), a=12.9108(4), b=13.4537(5), c=13.6153(4) Å, α=89.983(3), β=68.104(3), γ=86.542(3)°, V=2189.72(13) $Å^3$, Z=2, D_c=1.259 g cm^{-3}, μ(Cu-Kα)=0.626 mm^{-1}, T=173 K, deep purple blocks, Oxford Diffraction Xcalibur PX Ultra diffractometer; 8355 independent measured reflections (R_{int}=0.0361), F^2 refinement, R_1(obs)=0.047, wR_2(all)=0.131, 5174 independent observed absorption-corrected reflections [$|F_o|>4\sigma(|F_o|)$, $2\theta_{max}$=143°], 621 parameters. CCDC 7,37,182.

*3.1.3. {2H[pz(A$_3$B)]}PF$_6$ (**16**).* Ph_3CPF_6 (9.57 mg, 1 equiv) in CH_2Cl_2 (1 mL) was added to Mg[pz(A_3B)] **13** (20 mg, 0.024 mmol) in CH_2Cl_2 (1 mL) and the reaction mixture was stirred at ambient temperature for 1 h in the dark (N_2). After rotary evaporation, the residue was triturated with dry hexane (5×1 mL). Double chromatography (CH_2Cl_2:MeOH 30:1), ($CHCl_3$:MeOH 30:1) gave $H_2[pz(A_3B)]^+PF_6^-$ **16** (5 mg, 22%) as a blue solid: R_f 0.45 (MeOH:$CHCl_3$ 110); UV–vis (CH_2Cl_2) λ_{max} 316, 544, 660, 744, 820 nm; ^1H NMR (500 MHz, py-d_5) δ 3.35 (s, 12H), 3.62 (s, 12H), 3.95 (s, 12H), 7.65 (m, 2H), 7.75 (m, 4H), 8.11 (d, J=7.5 Hz, 4H), 8.88 (s, 1H), 10.09 (s, 2H); ^{13}C NMR (125 MHz, py-d_5) δ 30.0, 43.1, 44.3, 44.9, 45.2, 79.0, 128.0, 128.2, 128.4, 128.9, 130.1; MS (MALDI) m/z 788 $[M]^+$. Crystal data for **16**: $(C_{45}H_{51}N_{14})(PF_6)\cdot C_4H_8O$, M=1005.07, triclinic, $P\bar{1}$ (no. 2), a=9.4257(2), b=15.8772(5), c=16.4032(5) Å, α=79.931(2), β=78.654(2), γ=86.405(2)°, V=2368.74(12) $Å^3$, Z=2, D_c=1.409 g cm^{-3}, μ(Cu-Kα)=1.185 mm^{-1}, T=173 K, very dark platy needles, Oxford Diffraction Xcalibur PX Ultra diffractometer; 9067 independent measured reflections (R_{int}=0.0603), F^2 refinement, R_1(obs)=0.044, wR_2(all)=0.117, 4764 independent observed absorption-corrected reflections [$|F_o|>4\sigma(|F_o|)$, $2\theta_{max}$=143°], 678 parameters. CCDC 7,37,183.

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Supplementary data

General experimental methods, additional experimental procedures, compound characterization data, copies of spectra and chromatograms, and crystallographic information files (CIFs) are available. Supplementary data associated with this article can be found in the online version at doi:10.1016/j.tet.2009.09.105.

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