

Synthesis of trifluoroethoxy-coated binuclear phthalocyanines with click spacers and investigation of their clamshell behaviour†

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Received 11th February 2009, Accepted 27th March 2009

First published as an Advance Article on the web 14th April 2009

DOI: 10.1039/b902905b

We disclose here the synthesis of a novel trifluoroethoxy-coated binuclear Pc **1** which is the first example of a never-closing clamshell Pc.

The suppression and control of the aggregation properties of phthalocyanines (Pcs), both in solvents and in solid films, by only their inherent specificity without any external assistance is a challenge in materials science, especially for solar cells, optical filters, sensors and photodynamic therapy.¹ Phthalocyanine (Pc) derivatives offer a very wide choice of molecular physicochemical properties, including color, photodynamics and catalytic activity by changing the nature of their aggregation states: monomer, dimer or highly aggregated. The outstanding optical and photosensitizing properties of Pcs with both a wide absorbing spectral range and high luminescence quantum yields are often perturbed in a randomly aggregated state. Freedom from molecular aggregation is particularly desirable for solar cells and photodynamic therapy, because self-association reduces the efficiency of solar cells and quenches fluorescence and interferes with the formation of singlet oxygen, respectively.² Among various Pc derivatives that have been investigated to add a new aspect to the study of Pc aggregation, the design and syntheses of novel binuclear Pc derivatives have gained much attention.³ Intermolecular aggregation can be suppressed by clamshell behaviour, *i.e.*, cofacial intramolecular self-association of binuclear Pcs wherein the two Pc rings are bridged by a spacer with a sufficient linkage length. Since the first report by Leznoff and coworkers in 1984, a series of binuclear Pcs has been synthesized to investigate clamshell behaviour with a dynamic equilibrium existing between open and closed conformations.⁴ Although intermolecular *vs* intramolecular aggregations can be controlled by the choice of bridging linkage and the concentration of the Pcs, freedom from molecular association is still a challenge (Fig. 1).



Fig. 1 Aggregation and clamshell behaviour of binuclear Pcs.

We recently synthesized trifluoroethoxy-coated binuclear Pc wherein the two Pcs are covalently linked with a conjugated *rigid*

di-yne spacer and noted its prominent avoidance of intermolecular aggregation.⁵ Fluorophobic repulsion is responsible for this behaviour, preventing its aggregation even in the 18 π -conjugation system. In order to evaluate the strength of the fluorophobic repulsion, we attempted to impede the intramolecular aggregation. Indeed, intramolecular aggregation is much more favourable than intermolecular aggregation for entropic reasons; therefore, the achievement of freedom from intramolecular aggregation in the clamshell system was the next challenge. As an extension of our work on fluorine chemistry,⁶ we disclose here the synthesis of a novel trifluoroethoxy-coated binuclear Pc **1** which is the first example of a *never-closing* clamshell Pc. The two Pc rings in **1** are covalently connected by a flexible linker using “double-click” chemistry.^{5,7} The binuclear Pc **1** is free from intra- and intermolecular aggregations independent of solvent and concentration. It is interesting to note that while sterically demanding *tert*-Bu substituents on Pc cannot stop the clamshell closing, fluorophobic repulsion can stop the clamshell from closing to any great extent without any external source of help such as coordinating solvents. Novel mononuclear Pc **2**, referred to as “single-click Pc” was also synthesized for comparison (Fig. 2).

A previously unknown trifluoroethoxy-coated binuclear Pc **1** was synthesized from 23-ethynyl-1,2,3,4,8,9,10,11,15,16,17,18-dodecakis(2,2,2-trifluoroethoxy)phthalocyaninate zinc(II) (**3**)^{5a} and 1,4-bis(azidomethyl)benzene (**4a**) by our “double-click” chemistry⁷ using CuI, Et₃N and DMSO in 95% yield. Target **1** is sufficiently soluble in any organic solvent and was characterized by reverse-phase HPLC, ¹H and ¹⁹F NMR, and the isotopic patterns of Zn in MALDI-TOF MS spectra (see experimental section and ESI†). The single-click Pc **2** was prepared in high yield by a procedure similar to that of **1** using (azidomethyl)benzene (**4b**) instead of **4a** (Scheme 1).

The aggregation behaviour of **1** was explored by ¹H and ¹⁹F NMR, UV-vis and steady-state fluorescence spectra. The ¹H and ¹⁹F NMR spectra in *d*-acetone very clearly indicate non-aggregation behaviour, while the non-fluorinated, *tert*-butyl analogue of **1** shows broad signals due to the intramolecular closed clamshell formation (see Fig. S1 and S2 in the ESI†).⁵ In the UV-vis spectra in CHCl₃, **1** exhibits strong absorption at 702 nm of the Q-band, and 360 nm of the B-band, which are indicative of a monomeric state, independent of concentration. Freedom from inter- and intramolecular aggregations, as well as the closed clamshell formation, was strictly ascertained by the addition of a metal-coordinating molecule, pyridine.⁸ Namely, the shape of the spectrum did not change even after the addition of 1% pyridine (Fig. 3a). The behaviour was next investigated thoroughly in a variety of solvents (see Fig. S3–S11 in the ESI†). The same phenomenon was observed with common

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† Electronic supplementary information (ESI) available: Experimental details and Fig. S1–21. See DOI: 10.1039/b902905b

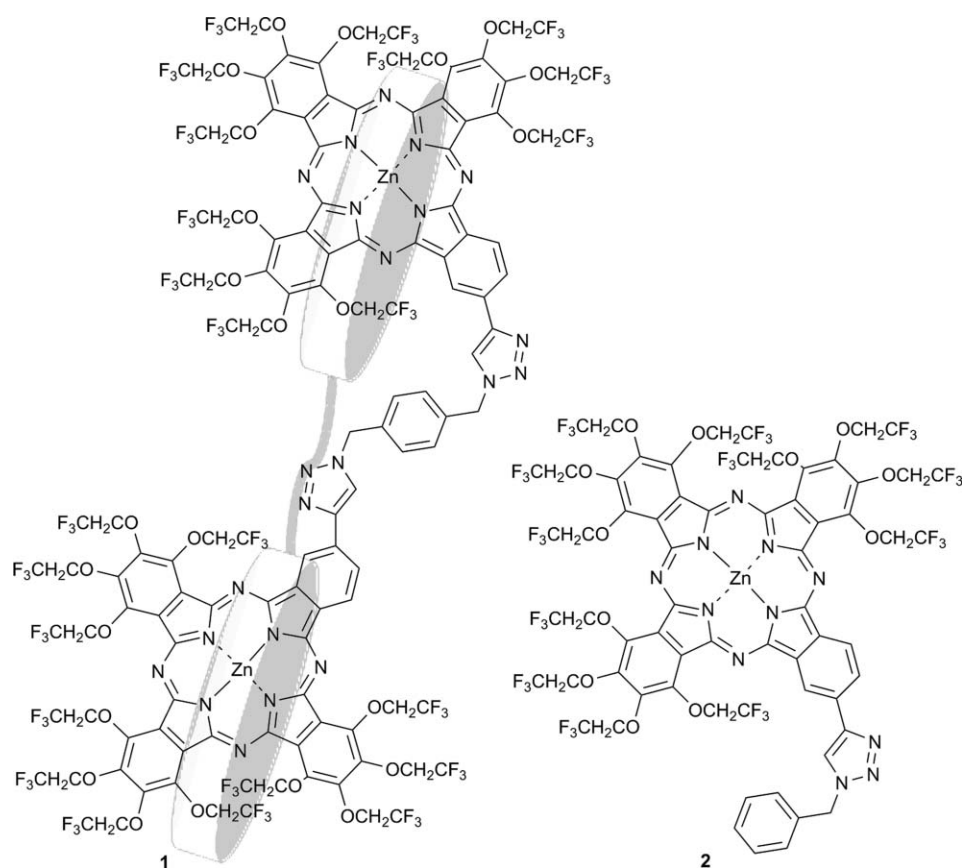
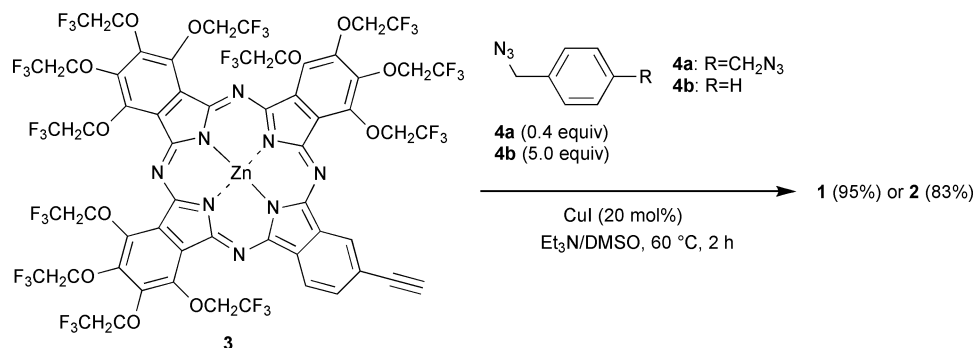


Fig. 2 Binuclear Pc **1** and mononuclear Pc **2** with click spacer.



Scheme 1 Synthesis of Pcs **1** and **2**.

organic solvents such as dioxane, THF, pyridine, DMF, PhCN (Fig. S4–S7 and S9). The non-aggregated state was also indicated by strong and sharp absorption bands of the UV–vis spectra in less-polar solvents as PhCF₃, CH₂Cl₂, *m*-difluorobenzene or Solkane® (CF₃CH₂CF₂CH₃), but the Q-bands in these solvents were slightly more sharpened with the addition of pyridine (Fig. S3, S8, and S10–S11†). The results implied that the effect of fluorophobic repulsion on impeding aggregation in less polar solvents, especially fluorinated solvents, is somewhat decreased compared to that in polar solvents. Although minor differences are observed in these solvents, all the UV–vis absorbances are very different from those of previously reported sterically demanding non-fluorinated binuclear Pcs in the closed clamshell conformation.^{4,7} It should also be noted that similar UV–vis spectra were observed

for the single-click Pc **2** (Fig. 3b). The absorption spectra of the binuclear Pc **1** can be superimposed on the corresponding figures of single-click Pc **2** despite its homodimeric structure. These results indicate that the binuclear Pc **1** behaves like mononuclear Pc **2**, and neither the intermolecular aggregated nor closed clamshell formation of Pc **1** are detected in organic solvents.

Steady-state fluorescence spectra in CHCl₃ were next investigated to prove the aggregation state in **1**. While the emission of closed clamshell binuclear Pcs is well-known to be self-quenched between the coupled halves of the binuclear species, a single strong λ_{em} was observed for Pc **1** at 715 nm both in a non-coordinating solvent, CHCl₃ (fluorescence quantum yield, $\Phi_{\text{f}} = 0.24$), and a coordinating solvent, dioxane ($\Phi_{\text{f}} = 0.26$). A reference, non-aggregated single-click Pc **2** also showed similarly strong

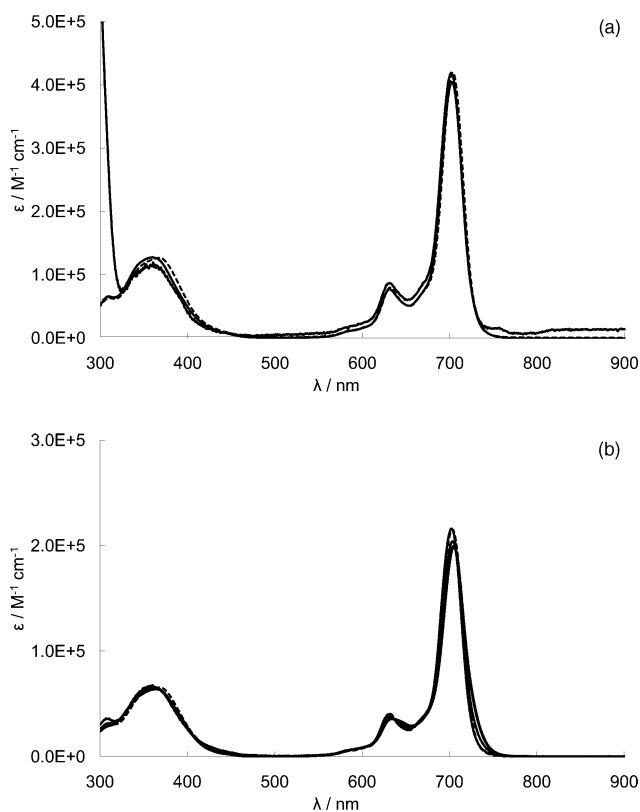


Fig. 3 UV-vis spectra of (a) Pc **1** in CHCl₃ (bold black to grey solid lines: 2.6×10^{-6} to 10^{-7} M, dotted: with 1 vol% of pyridine) and (b) Pc **2** in CHCl₃ (bold black to gray solid lines: 1.0×10^{-4} to 10^{-6} M, dotted line: with 1 vol% of pyridine).

fluorescence at 715 nm ($\Phi_f = 0.27$ in CHCl₃; $\Phi_f = 0.30$ in dioxane). These results strongly support the fact that Pc **1** exists free of aggregations (see Fig. S12–S13 in the ESI†).

Cyclic voltammograms (CV) and differential-pulse voltammograms (DPV) of binuclear Pc **1** and single-click Pc **2** in THF are summarized in Fig. 4/Table 1 and Fig. 5/Table 2. The voltammograms of **1** and **2** show quite similar features that may be

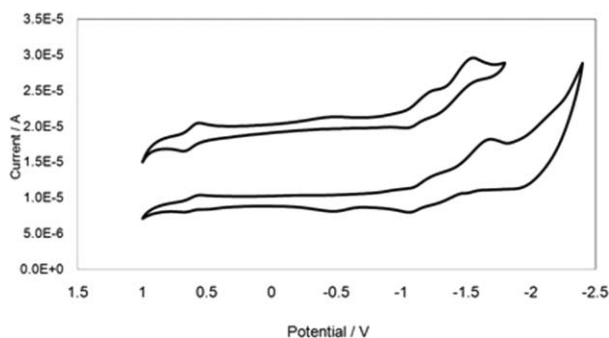


Fig. 4 Cyclic voltammograms of **1** (top) and **2** (bottom).

Table 1 Half-wave redox potentials of **1** and **2** (V vs Ag/AgNO₃) in THF containing 0.1 M of TBAPF

Pc	$E_{1/2}^{\text{ox1}}$	$E_{1/2}^{\text{red1}}$	$E_{1/2}^{\text{red2}}$
1	0.605	-1.199	-1.434
2	0.610	-1.152	-1.534

Table 2 DPV peak potentials of **1** and **2** (V vs Ag/AgNO₃) in THF containing 0.1 M of TBAPF

Pc	$E_{1/2}^{\text{ox1}}$	$E_{1/2}^{\text{red1}}$	$E_{1/2}^{\text{red2}}$
1	0.640	-1.160	-1.435
2	0.635	-1.155	-1.595

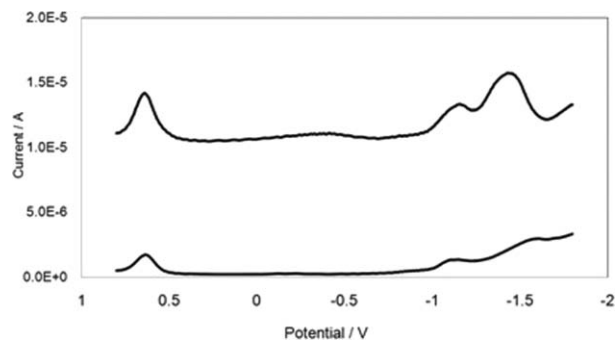


Fig. 5 Differential pulse voltammograms of **1** (top) and **2** (bottom).

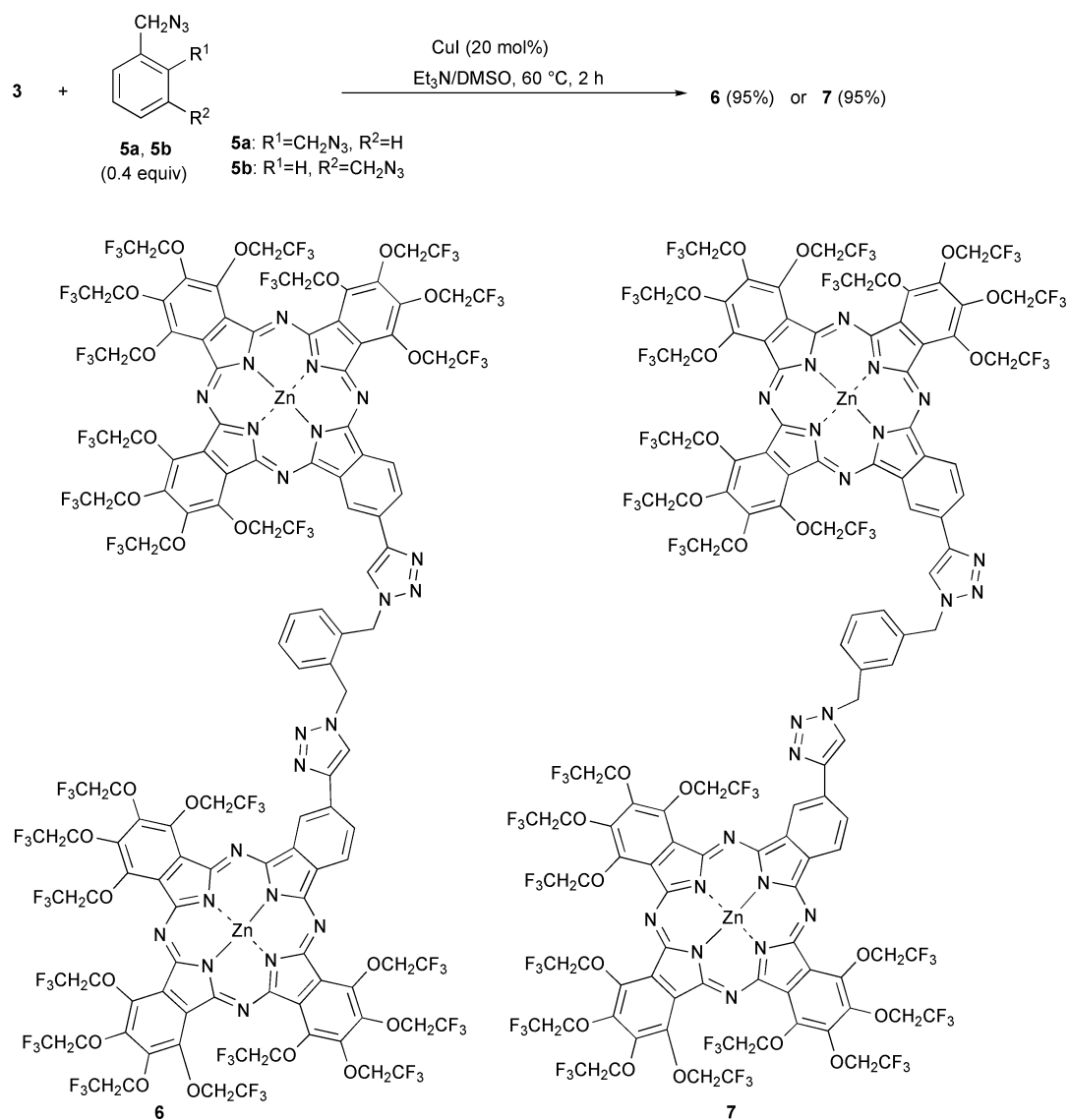
attributed to the mononuclear Pc moiety. The voltammograms of mono-click Pc **2** do not differ considerably from those of Pc **1**, and lead to the following explanations: the two Pc units in binuclear **1** are oxidized at the same potential, and no splitting of the Pc-based oxidation process is observed. This indicates that the two Pc moieties in the dyad **1** are electrochemically equivalent. In the cathodic scan, dyad **1** showed two reduction processes at -1.199 and -1.434 V, and Pc **2** showed the same processes at -1.152 and -1.534 V. A similar speculation was done in DPV.

Finally, regioisomeric binuclear Pcs **6** and **7** with *ortho*- and *meta*-double click spacers were synthesized in a manner similar to that of Pc **1** from **3** using 1,2- or 1,3-bis(azidomethyl)benzene (**5a** or **5b**) instead of **4a** (Scheme 2). UV-vis and steady-state fluorescence spectra similar to those of Pc **1** were observed for binuclear Pcs **6** and **7**, which clearly revealed their non-aggregation behaviour (see Fig. S14–S21 in the ESI†).

In summary, we synthesized trifluoroethoxy-coated binuclear Pcs showing a powerful non-aggregation property. The ¹H and ¹⁹F NMR, UV-vis and steady-state fluorescence spectra, CV and DPV data strongly support that, for the first time, the trifluoroethoxy-coating can ideally prevent binuclear Pc clamshells from closing, independent of the solvent concentration and substitution pattern of the spacers (*ortho*-, *meta*- and *para*-). Although the fluorophobic repulsion in the binuclear Pcs slightly diminishes in fluorinated solvents as well as CH₂Cl₂, the non-aggregation effect is clearly superior to that of sterically demanding *tert*-Bu substituents on Pcs. The net effect of fluorophobic repulsion in the dyad under a variety of solvents is now under investigations.^{5a}

Experimental section

Synthesis of 1: a mixture of 23-ethynyl-1,2,3,4,8,9,10,11,15,16,17, 18-dodecakis(2,2,2-trifluoroethoxy)phthalocyaninate zinc(II) (**3**) (44.9 mg, 0.025 mmol), 1,4-bis(azidomethyl)benzene (**4a**) (1.9 mg, 0.010 mmol), CuI (1.0 mg, 0.005 mmol), Et₃N (0.05 ml) and DMSO (1.0 ml) was freeze dried to remove oxygen. Then the solution was filled with Ar and stirred at 60 °C for 2 h. After cooling it to rt, water and dil. sulfuric acid were added.



Scheme 2 Synthesis of regioisomeric Pcs **6** and **7** with *ortho*- and *meta*-double click spacers.

The precipitates were filtered. Purification by silica gel column chromatography (hexane : acetone = 70:30 to 60 : 40) gave green solids (36.0 mg, 95%). C₁₂₄H₆₄F₇₂N₂₂O₂₄Zn₂; M.W.: 3744.63, ¹H-NMR (acetone-*d*₆, 400 MHz): δ 5.06–5.19 (m, 24H), 5.72–5.85 (m, 24H), 5.96 (s, 4H), 7.72 (s, 4H), 8.82 (d, *J* = 8.4 Hz, 2H), 8.87 (s, 2H), 9.45 (d, *J* = 8.4 Hz, 2H), 9.87 (s, 2H); ¹⁹F-NMR (acetone-*d*₆, 376 MHz): δ -74.1– -74.0, -73.7, -73.1, -72.8; IR (KBr): 2975, 1488, 1456, 1275, 1159, 1068, 1008, 970, 860, 762, 670 cm⁻¹; UV-vis (2.6 × 10⁻⁶ M in CHCl₃): λ_{max} (log ε) = 702 (5.61), 631 (4.89), 360 (5.11) nm; (0.5 × 10⁻⁶ M in PhCF₃): λ_{max} (log ε) = 695 (5.44), 644 (4.92), 358 (4.99) nm; (0.5 × 10⁻⁶ M in dioxane): λ_{max} (log ε) = 703 (5.62), 632 (4.90), 368 (5.10) nm; (0.5 × 10⁻⁶ M in THF): λ_{max} (log ε) = 700 (5.68), 630 (4.95), 358 (5.16) nm; (0.5 × 10⁻⁶ M in pyridine): λ_{max} (log ε) = 704 (5.66), 632 (4.99), 370 (5.18) nm; (0.5 × 10⁻⁶ M in DMF): λ_{max} (log ε) = 699 (5.62), 630 (4.93), 368 (5.12) nm; (0.5 × 10⁻⁶ M in CH₂Cl₂): λ_{max} (log ε) = 702 (5.46), 643 (4.85), 365 (5.02) nm; (0.5 × 10⁻⁶ M in PhCN): λ_{max} (log ε) = 699 (5.56), 633 (4.86), 369 (5.01) nm; (0.5 × 10⁻⁶ M in *m*-PhF₂): λ_{max} (log ε) = 699 (5.62), 630 (4.92), 364

(5.11) nm; (0.5 × 10⁻⁶ M in Solkane): λ_{max} (log ε) = 692 (5.27), 640 (4.73), 361 (4.91) nm; Fluorescence (CHCl₃): λ_{em} = 715 nm, Φ_f = 0.24, (dioxane): λ_{em} = 715 nm, Φ_f = 0.26.; MALDI-TOF MS (dithranol): *m/z* = 3740.8–3749.8 ([M⁺], isotopic pattern); HPLC: (H₂O:MeCN:THF = 8:42:50, 0.3 ml/min), t_R = 14.0 min.

Acknowledgements

Support was provided by KAKENHI (19390029), by a Grant-in-Aid for Scientific Research on Priority Areas “Advanced Molecular Transformations of Carbon Resources” from the Ministry of Education, Culture, Sports, Science and Technology Japan (19020024), and Nagase Science and Technology Foundation.

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