รายงานวิจัยฉบับสมบูรณ์

โครงการ การสังเคราะห์และการศึกษาไอโอโนฟอร์ที่เลือกจำเพาะจากคาลิกซ์[4]เอรีน

โดย นาย มงคล สุขวัฒนาสินิทธิ์

19 กรกฎาคม 2552

สัญญาเลขที่ RMU4980024

รายงานวิจัยฉบับสมบูรณ์
ทุนเพิ่มขีดความสามารถด้านการวิจัยของอาจารย์รุ่นกลางในสถาบันอุดมศึกษา ปี 2549
โครงการ: การสังเคราะห์และการศึกษาไอโอโนฟอร์ที่เลือกจำเพาะจากคาลิกซ์[4]เอรีน

รศ.ดร.มงคล สุขวัฒนาสินิทธิ์

จุฬาลงกรณ์มหาวิทยาลัย

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย และสำนักงานคณะกรรมการการอุดมศึกษา

(ความเห็นในรายงานนี้เป็นของผู้วิจัย สกว.ไม่จำเป็นต้องเห็นด้วยเสมอไป)

กิตติกรรมประกาศ

คณะผู้วิจัยขอขอบพระคุณสำนักงานกองทุนสนับสนุนการวิจัย (สกว.) และสำนักงานคณะกรรมการอุดมศึกษา (สกอ.) เป็นอย่างสูงที่ได้ให้ทุนเพิ่มขีดความสามารถด้านการวิจัยของอาจารย์รุ่นกลางในสถาบันอุดมศึกษาปี 2549 ในโครงการ การสังเคราะห์และการศึกษาไอโอโนฟอร์ที่เลือกจำเพาะจากคาลิกซ์[4]เอรีน ในช่วงระหว่าง วันที่ 20 กรกฎาคม 2549 - 19 กรกฎาคม 2552 (3 ปี) ทำให้โครงการวิจัยนี้บรรลุตามวัตถุประสงค์ที่ตั้งไว้ คณะผู้วิจัยหวังเป็นอย่างยิ่งว่าโครงการวิจัยนี้จะเป็นประโยชน์ต่อผู้ที่สนใจต่อไป

Abstract

Project Code : RMU4980024

Project Title : Synthesis and study of calix[4]arene-based selective ionophores

Investigator : Mongkol Sukwattanasinitt, Department of Chemistry, Faculty of Science, Chulalongkorn University, Bangkok 10330.

E-mail Address : smongkol@chula.ac.th

Project Period : 20 July 2006-19 July 2009 (3 years)

This project aims to synthesize ligands from calix[4]arene which can bind with metal ions effectively and selectively. The calix[4]arene derivatives containing stilbene bridge was obtained in high yield through McMurry coupling reaction using excess $TiCl_4$ in high dilution condition. The shape of a calix[4]arene cavity is largely depended on the length of the stilbene bridge. A long bridge length squeezes the calix[4]arene basket into pinched cone conformation. On the other hand, a short bridge length leads to normal cone shape basket. The stilbene-bridged 1,3-alternate calix[4]arene crown 5 and 6 can selectively extract potassium and cesium ions, repectively. These calix[4]arene crown have higher extractability and selectivity compring to normal crown ethers. Another series of calix[4]arene derivatives containing multiple diacetylene units were synthesized in good yield through a modified Cadiot-Chodkiewicz coupling reaction of tetra(2-propynyl)-*tert*-butylcalix[4]arene with iodo-pentynol using CuI catalyst in pyrrolidine. The solid-state photopolymerization study revealed that only the calix[4]arene derivatives containing four diyne units with alkyl urethane groups were substantially polymerized upon exposure to UV and gamma irradiation to give polydiacetylenes containing calix[4]arene. The ene-yne conjugation formed through the topological 1,4-addition polymerization of the diyne units. Unfortunately, these new polymers have not showed binding property with any metal ions. Modified series of calix[4]arene derivatizatives with expected selective binding property are currently being pursued.

Keywords: calixarene, host-guest complex, ionophore, metal ion, polydiacetylene, supramolecule

บทคัดย่อ

รหัสโครงการ : RMU4980024

ชื่อโครงการ : การสังเคราะห์และศึกษาไอโอโนฟอร์ที่เลือกจำเพาะจากคาลิกซ์[4]เอรีน

ชื่อนักวิจัย และสถาบัน: นาย มงคล สุขวัฒนาสินิทธิ์ ภาควิชาเคมี คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย ถนนพญาไท เขตปทุมวัน 10330

E-mail Address : smongkol@chula.ac.th

ระยะเวลาโครงการ : 20 กรกฎาคม 2549-19 กรกฎาคม 2552 (3 ปี)

โครงการวิจัยนี้มีเป้าหมายในการสังเคราะห์ลิแกนด์จากคาลิกซ์[4]เอรีนที่เลือกจับไอออนโลหะได้อย่างมีประสิทธิภาพและจำเพาะเจาะจง ซึ่งได้อนุพันธ์ของคาลิกซ์[4]เอรีนที่มีสติลบีนเป็นสะพานเชื่อมด้วยเปอร์เซ็นต์ผลผลิตที่สูงโดยผ่านปฏิกิริยารีดักชันคู่ควบแมคเมอรี่ ภายในโมเลกุลของบิสเบนซาลดีไฮด์คาลิกซ์[4]เอรีน โดยใช้ไทเทเนียมเตตระคลอไรด์มากเกินพอ ภายใต้สภาวะที่เจือจาง โดยลิแกนด์ที่สังเคราะห์ขึ้นมีคอนฟอร์เมชันของคาลิกซ์[4]เอรีนอยู่ในรูปของโคน และพินช์โคน ขึ้นอยู่กับความยาวของสะพานสติลบีน ถ้าสะพานสติลบีนยาวจะทำให้โครงสร้างของคาลิกซ์[4]เอรีน อยู่ในรูปของพินช์โคน แต่ถ้าสะพานสติลบีนสั้นจะทำให้โครงสร้างของคาลิกซ์[4]เอรีน อยู่ในรูปของโคน อนุพันธ์คาลิกซ์[4]เอรีนที่มีสะพานสติลบีนและสลับ 1,3 กับคราวน์อีเทอร์ 5 และ 6 สามารถเลือกจับกับโพแทสเซียมไอออนและซีเซียมไอออนได้ตามลำดับ โดยอนุพันธ์ดังกล่าวแสดงความสามารถในการสกัดและมีความเลือกจำเพาะที่ดีกว่าคราวน์อีเทอร์ทั่วไป นอกจากนี้ยังได้สังเคราะห์อนุพันธ์คาลิกซ์[4]เอรีนที่มีหมู่ไดแอเซทิลีนหลายหมู่ต่ออยู่โดยอาศัยปฏิกิริยาคู่ควบระหว่างเตตระโพรพาจิลคาลิกซ์[4]เอรีนและไอโอโดแอลไคล์ในไพโรลิดีน โดยมีคอปเปอร์(I)ไอโอไดด์เป็นตัวเร่งปฏิกิริยา จะได้เตตระไดอะเซทิลีนคาลิกซ์[4]เอรีนด้วยเปอร์เซนต์ผลผลิตที่ดี ซึ่งพบว่ามีเพียงอนุพันธ์คาลิกซ์[4]เอรีนที่มีหมู่ไดอะเซทิลีนสี่หมู่และมีสายแอลคิลยูรีเทนสามารถเกิดพอลิเมอร์ไรเซชันภายใต้แสงยูวีหรือรังสีแกมมา อย่างไรก็ตามพอลิเมอร์ที่ได้ยังไม่สามารถจับไอออนของโลหะใดๆ ได้ การสังเคราะห์อนุพันธ์จากคาลิกซ์[4]เอรีนอื่นๆ ที่สามารถทำหน้าที่เป็นไอโอโนฟอร์ที่เลือกจำเพาะจึงยังคงดำเนินต่อไป

คำหลัก:คาลิกซารีน,สารประกอบเชิงซ้อนโฮสต์-เกสต์,ไอโอโนฟอร์,ซูปราโมเลกุล,ไดแอเซทิลีน

บทนำ

เคมีซูปราโมเลคิวลาร์ (supramolecular chemistry) เป็นการศึกษาเกี่ยวกับแรงกระทำระหว่างโมเลกุลโดยแรงยึดเหนี่ยวที่ไม่ใช่พันธะโคเวเลนต์ นักเคมีอินทรีย์ได้สังเคราะห์สารที่สนใจขึ้นเพื่อศึกษาทางด้านเคมีซูปราโมเลคิวลาร์ เพื่อทำความเข้าใจกลไกทางธรรมชาติ หรือสร้างโมเลกุลที่สามารถทำหน้าที่ต่างๆ ได้ตามที่ต้องการ อันเป็นพื้นฐานสำหรับการพัฒนาศาสตร์ทางด้านนาโนเทคโนโลยีแบบ “bottom up” เนื่องจากแรงกระทำแบบซุปราโมเลคิวลาร์นี้ทำให้โมเลกุลหรือไอออนสามารถจัดเรียงตัวกันเองเกิดเป็นระบบที่น่าสนใจ และมีส่วนสำคัญต่อกลไกการทำงานของสารเคมีต่างๆ ในธรรมชาติ ระบบซูปราโมเลคิวลาร์ที่เกี่ยวข้องกับแรงกระทำระหว่างไอออนหรือโมเลกลุลขนาดเล็กกับโมเลกุลขนาดใหญ่ที่เรียกว่า “host-guest complex” เป็นระบบที่ได้รับความสนใจเป็นอย่างมากเนื่องจากเป็นระบบที่อธิบายกลไกบางอย่างที่เกิดขึ้นในสิ่งมีชีวิต เช่น การเกิดกระบวนการโซเดียม/โพแทสเซียมปั๊ม และกระบวนการขนส่งและลำเลียงสารเคมีในร่างกายสิ่งมีชีวิต นอกจากนี้ระบบดังกล่าวยังมีประโยชน์ต่อการนำไปประยุต์ใช้ในงานตรวจวิเคราะห์และการแยกสารพิษจากอุตสาหกรรม[1]

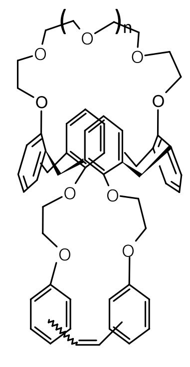
คาลิกซ์[4]เอรีนได้รับความสนใจอย่างแพร่หลายในการนำมาใช้เป็นโครงสร้างพื้นฐานสำหรับการสังเคราะห์ลิแกนด์ที่สามารถจับกับไอออนหลากหลายชนิด[2] เนื่องจากโครงสร้างของคาลิกซ์[4]เอรีนมีช่องว่างในสามมิติและมีหมู่ฟีนอล 4 หมู่ ที่วางตัวในตำแหน่งที่เหมาะสมสำหรับการปรับเปลี่ยนเป็นหมู่ฟังก์ชันอื่นที่ทำให้เกิดโพรงที่มีขนาดต่างๆกันและมีสมบัติทางอิเล็กตรอนที่เหมาะสมสำหรับการเลือกจับไอออนโลหะชนิดต่างๆ[3] คาลิกซ์[4]เอรีนคราวน์อีเธอร์เป็นอนุพันธ์ของคาลิกซ์[4]เอรีนที่มีสายโซ่พอลิอีเธอร์เชื่อมระหว่างวงแหวนฟีนอลที่อยู่ด้านตรงข้ามกัน มีรายงานว่าคาลิกซ์[4]เอรีนคราวน์อีเธอร์มีสมบัติในการเลือกจับอัลคาไลไอออออนที่ดีกว่าอนุพันธ์ของคราวน์อีเธอร์ทั่วไป[4] ความเลือกจำเพาะในการจับไอออนโลหะของ คาลิกซ์[4]เอรีนคราวน์อีเธอร์สามารถควบคุมได้โดยการปรับความยาวของสายโซ่พอลิอีเธอร์และคอนฟอร์เมชันของ คาลิกซ์[4]เอรีน[5] ได้มีการนำคาลิกซ์[4]เอรีนคราวน์อีเธอร์มาประยุกต์ใช้สำหรับเป็นระบบจำลองการเกิดโซเดียม/โพแทสเซียมปั๊ม[6] การนำส่งรูบิเดียมในการรักษาโดยการฉายรังสี[7] และการแยกซีเซียม-137 ไอออน ซึ่งเป็นสารกัมมันตรังสีจากกากนิวเคลียร์[8] นอกจากนี้ยังมีรายงานวิจัยว่าโครงสร้างของคาลิกซ์[4]เอรีนที่อยู่ในรูปของ 1,3-alternate conformation สามารถจับกับ soft ion เช่น ซีเซียมไอออนได้ดีกว่า hard ion เช่น โซเดียมและโพแทสเซียมไอออออน เนื่องจากการเกิด ion-π interaction[9]

ได้มีรายงานการสังเคราะห์คาลิกซ์[4]เอรีนที่มีลักษณะเป็นท่อเพื่อใช้เป็นลิแกนด์ที่มีสมบัติในการเลือกจับโพแทสเซียมไอออนเพื่อเป็นแบบจำลองสำหรับ potassium channel โครงสร้างแบบท่อที่มีรายงาน

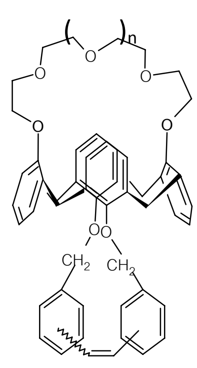
นั้นอาศัยอะตอมออกซิเจนและไนโตรเจนเป็นโดเนอร์อะตอมเพื่อจับกับไอออนของโลหะ[10] แต่ยังไม่มีการสังเคราะห์ท่อคาลิกซ์[4]เอรีนที่มีระบบ π-conjugate เป็นส่วนประกอบของส่วนท่อ ซึ่งเราเชื่อว่าการใส่ระบบ π-conjugate เข้าไปเป็นส่วนประกอบของท่อน่าจะมีผลต่อการเลือกจับไอออนขนาดใหญ่ซึ่งเป็น soft ion ได้ดียิ่งขึ้น

ตั้งแต่ปี พ.ศ. 2544 เป็นต้นมา กลุ่มวิจัยของเราได้ทำการสังเคราะห์และศึกษาอนุพันธ์ของคาลิกซ์[4]เอรีน ที่มีหมู่เอโซเบนซีน และ สติลบีน เป็นสะพานเชื่อมระหว่างหมู่ฟีนอลด้านตรงข้ามกันของวงคาลิกซ์[4]เอรีน สำหรับใช้เป็นลิแกนด์จับไอออน[11] และโมเลกุล[12] แบบสวิทช์ได้ด้วยแสง ซึ่งเราพบว่าการใช้รีจิโอไอโซเมอร์ (regioisomer) ต่างๆ กัน ของเอโซเบนซีน และ สติลบีนมีผลในการควบคุมรูปร่างของโพรงคาลิกซ์[4]เอรีน ซึ่งน่าจะนำมาใช้ประโยชน์ในการออกแบบโครงสร้างลิแกนด์จากคาลิกซ์[4]เอรีน ให้มีสมบัติในการเลือกจับไอออนได้

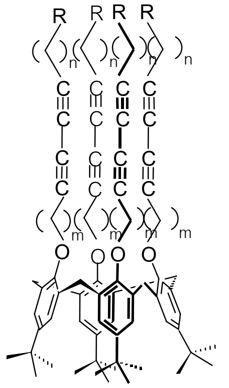
ในโครงการวิจัยนี้เราได้ตั้งเป้าหมายที่จะสังเคราะห์ลิแกนด์จากคาลิกซ์[4]เอรีนใน 2 รูปแบบ คือ รูปแบบแรกเป็นการใช้เทคนิคการสังเคราะห์ที่พัฒนาขึ้นในกลุ่มวิจัยของเราในการสร้างสะพานสติลบีนเชื่อมระหว่างหมู่ฟีนอลด้านตรงข้ามกันของวงคาลิกซ์[4]เอรีน (โครงสร้าง **1** และ **2**) โดยมีสมมติฐานว่าสะพานสติลบีนจะทำให้เกิด 1,3 alternate conformation ในขั้นตอนการทำให้เป็นคราวน์อีเธอร์ และลิแกนด์ที่สังเคราะห์ได้จะมีความจำเพาะเจาะจงต่อซีเซียมไอออนสูง รูปแบบที่ 2 เป็นคาลิกซ์[4]เอรีน คราวน์อีเธอร์ที่มีโครงสร้างลักษณะเป็นท่อโดยมีหมู่ไดแอเซทิลีนซึ่งเป็นระบบ π-conjugate เป็นส่วนประกอบของท่อ (โครงสร้าง **3**) โดยมีสมมติฐานว่าระบบ π-conjugate นี้จะสามารถทำให้ลิแกนด์สามารถเลือกจับกับ soft metal ion ได้อย่างจำเพาะเจาะจง



1



2

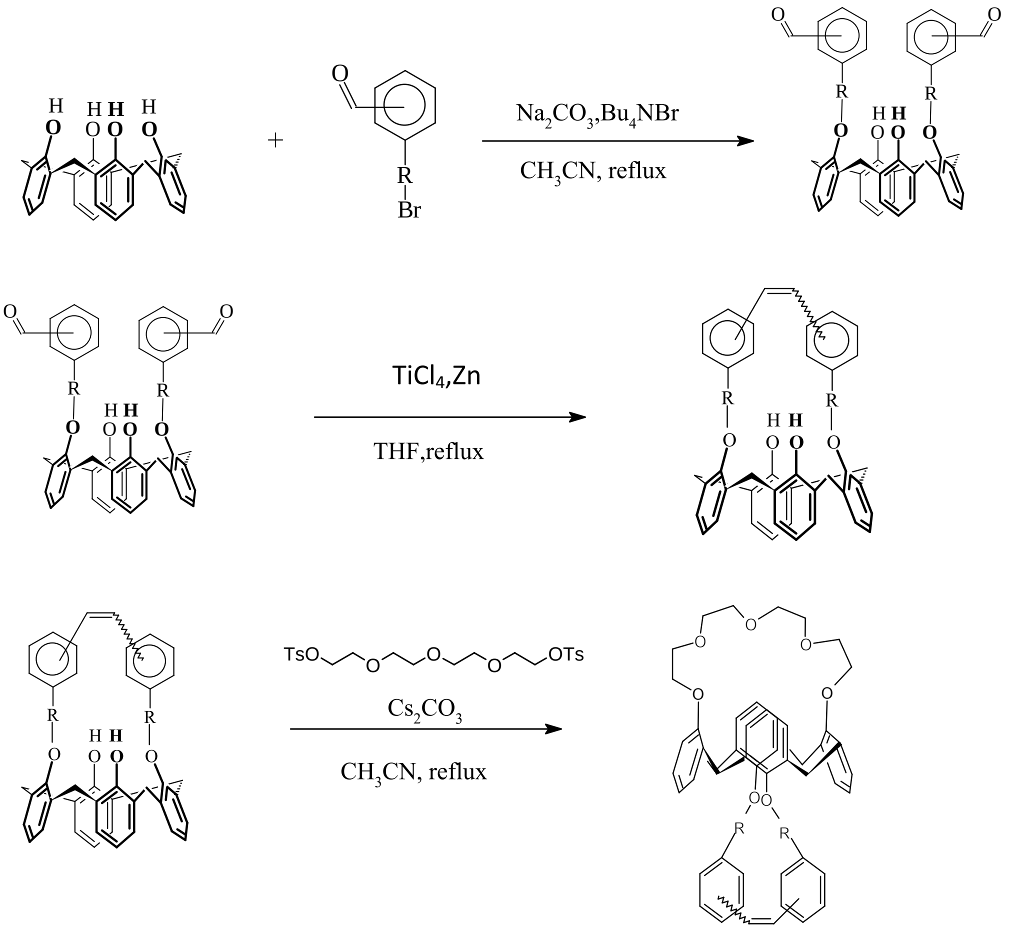


3

วิธีการทดลอง

1. ทำการสังเคราะห์สารขั้นกลางของลิแกนด์แบบที่ **1,2** และ **3** โดยได้สังเคราะห์ลิแกนด์ตามวิธีต่อไปนี้

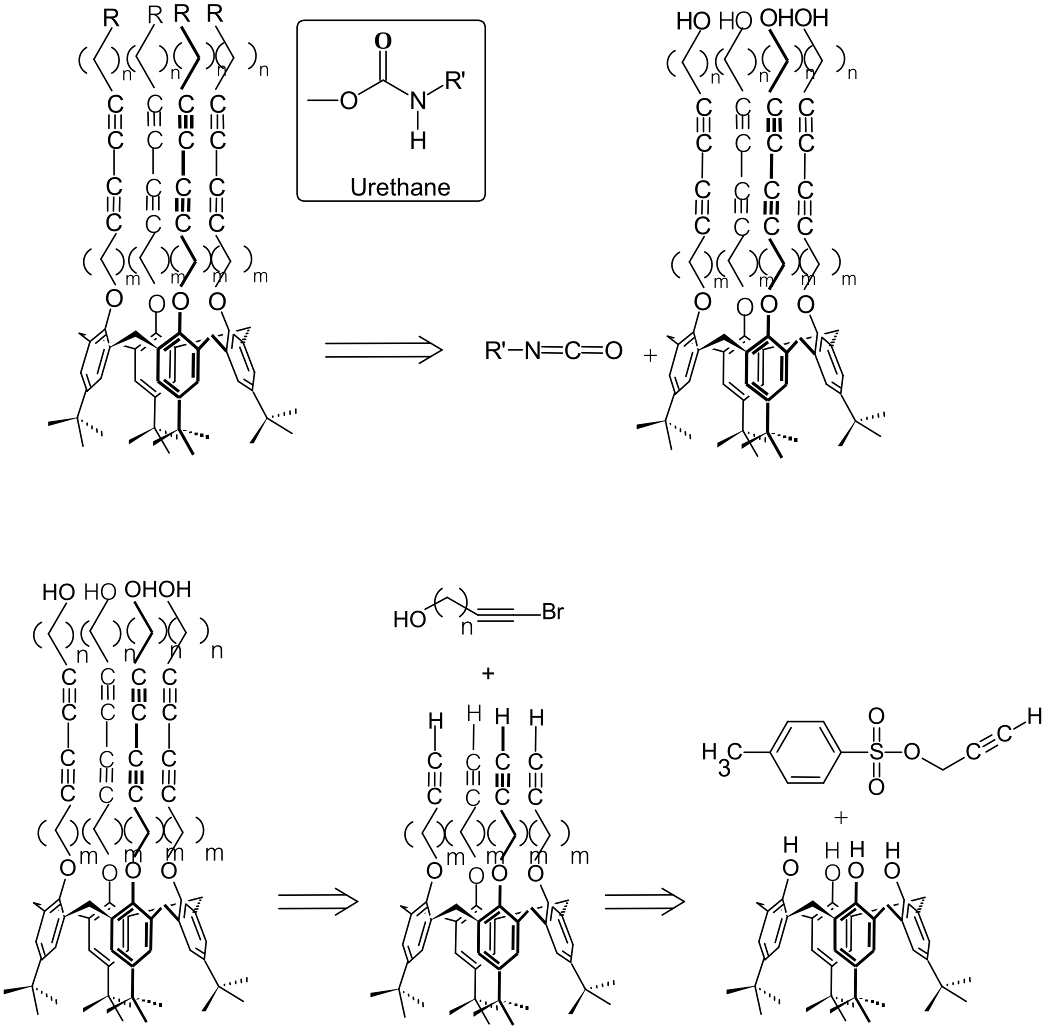
แนวทางการสังเคราะห์ (synthetic pathway) สำหรับลิแกนด์แบบที่ 1 และ 2



$R = OCH_2CH_2$

$R = CH_2$

แนวทางการสังเคราะห์แบบย้อนกลับ (retro-synthetic pathway) สำหรับลิแกนด์แบบที่ 3



2. พิสูจน์ทราบโครงสร้างของสารที่สังเคราะห์ด้วยวิธีทางสเปกโทรสโกปี
3. ศึกษาการจับไอออนโลหะด้วยวิธีทางสเปกโทรสโกปี
4. เขียนผลงานวิจัยเพื่อตีพิมพ์

ผลการทดลองและบทวิจารณ์

สามารถสังเคราะห์ลิแกนด์ที่ **1** ได้สำเร็จโดยพบว่า โครงสร้างของสารขั้นกลางลิแกนด์แบบที่ **1** *o-cis, o-trans, m-cis* มีคอนฟอร์เมชันของคาลิกซ์[4]เอรีนอยู่ในรูปของโคน ส่วน *m-trans*, *p-cis* อยู่ในรูปของพินช์โคน จากการทดลองนี้ทำให้สามารถสรุปได้ว่า ถ้าความยาวโมเลกุลของสติลบีนที่ใช้เป็น

สะพานเชื่อมยาวจะทำให้โครงสร้างของคาลิกซ์[4]เอรีน อยู่ในรูปของพินซ์โคนเนื่องจากความแข็งเกร็งของโครงสร้าง นอกจากนี้โครงสร้างของสารขั้นกลางของลิแกนด์แบบที่**1** ยังส่งผลในการสังเคราะห์ลิแกนด์แบบที่ **1** โดยพบว่า สามารถสังเคราะห์ลิแกนด์แบบที่ **1** ได้จากทุกไอโซเมอร์ยกเว้น *m-trans* ที่ไม่สามารถสังเคราะห์เป็นลิแกนด์แบบที่ **1** ได้ ซึ่งมาจากที่สารขั้นกลางของลิแกนด์แบบที่ **1** ของ m-trans ไอโซเมอร์อยู่ในรูปของพินซ์โคนที่มีริมไฮดรอกซีที่แคบเกินไปทำให้ไม่สามารถพลิกเป็น 1,3 อัลเทอเนตคอนฟอร์เมชันได้ ส่วนความสามารถในการสกัดไอออนโลหะของลิแกนด์แบบที่ **1** พบว่าสามารถสกัดโพแทสเซียมไอออนและซีเซียมไอออนได้ดีกว่าคราวน์อีเทอร์โดยทั่วไป

ลิแกนด์แบบที่ 2 ไม่สามารถสังเคราะห์ได้จึงไม่สามารถศึกษาความสามารถในการจับไอออนโลหะชนิดต่างๆได้

สามารถสังเคราะห์ลิแกนด์แบบที่ **3** ได้สำเร็จ และจากการศึกษาสมบัติการเกิดโฟโตพอลิเมอไรเซชันของลิแกนด์ พบว่าความสามารถในการเกิดพอลิเมอไรเซชันขึ้นกับจำนวนหมู่ไดแอเซทิลีนที่ติดอยู่บนคาลิกซ์[4]เอรีน และชนิดของหมู่ฟังก์ชันที่ปลายสายของไดแอเซทิลีน โดยเกิดปฏิกิริยาการเติมที่ตำแหน่ง 1 และ 4 ขึ้นภายในโมเลกุลของหมู่ไดแอเซทีลีนที่ติดอยู่บนคาลิกซ์[4]เอรีน แต่เมื่อศึกษาความสามารถในการจับไอออนโลหะชนิดต่างๆ พบว่าพอลิเมอร์ยังไม่สามารถจับไอออนของโลหะใดๆได้

การทดลองและผลการทดลองได้นำมาเขียนในรูปแบบของบทความวิจัยตีพิมพ์ไปแล้ว 2 บทความ และอยู่ระหว่างการแก้ไขต้นฉบับเพื่อส่งตีพิมพ์อีก 1 บทความ ตามรายละเอียดแสดงในเอกสารแนบ

เอกสารอ้างอิง

1. (a) Lehn, J.-M. *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 89. (b) Vogtle, F. *Supramolecular Chemistry*; John Wiley & Sons, 1991. (c) Lehn, J.-M. *Supramolecular Chemistry, Concepts and Perspectives*; VCH, 1995. (d) Stix, G. *Scientific American* **1996**, 78. (e) Steed, J. W.; Atwood, J. L. *Supramolecular Chemistry***,** Wiley & Sons: New York, 2000**.** (f)Nguyen, S. T.; Gin, D. L.; Hupp, J. T.; Zhang, X. "Supramolecular Chemistry: Functional Structures on the mesoscale" *Proc. Natl. Acad. Sci. USA.* **2001**, *98*, 11849.

2. (a) Gutsche C. D. *Acc. Chem. Res.* **1983**, *16***,** 161-170. (b) Gutsche, C. D. *Calixarenes*Revisitrd, Monograph in Supramolecular Chemistry, Stoddart, J. F., Ed.; The Royal Society of Chemistry: Cambridge, 1989. (c) Böhmer, V. *Angew. Chem., Ine. Ed. Engl*. **1995**, 34, 713-745. (d) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713-1734. (e) Gutsche, C. D. *Calixarenes*Revisited, Monograph in Supramolecular Chemistry, Stoddart, J. F., Ed.; The Royal Society of Chemistry: London, 1998. (f) *Calixarenes 2001*; Asfari, Z.; Böhmer, V.; Harrowfield, J.; Vicens, J.Kluwer Academic Publishers: Dordrecht, Holland, 2001.

3. (a) Casnati, A.; Pochini, A.; Ungaro, R.; Ugozzoli, F.; Arnaud, F.; Fanni, S.; Schwing, M.-J.; Egberink, R. J. M.; de Jong, F.; Reinhoudt, D. N. *J. Am. Chem. Soc*. **1995**, *117*, 2767-2777. (b) Matsumoto, H; Shinkai, S. *Tetrahedron Lett.* **1996**, *37*, 77-80. (c) Arduini, A.; Domiano, L.; Pochini, A.; Secchi, A.; Ungarro, R.; Ugozzoli, F.; Struck, O.; Verboom, W.; Reinhoudt, D. N. *Tetrahedron* **1997**, *53*, 3767-3776. (d) Bodenant, B.; Weil, T.; Businelli-Pourcel,M.; Fages, F.; Barbe, B.; Pianet, I.; Laguerre, M. *J. Org. Chem.* **1999**, *64*, 7034-7039. (e) Beer, P. D.; Hopkins, P. K.; McKinny, J. D. *Chem. Commun.* **1999**,1253-1254. (f) Guillon, J.; Leger, J.-M.; Sonnet, P.; Jarry, C.; Robba, M. *J. Org. Chem.* **2000**; *65*, 8283-8289. (g) Tuntulani, T.; Poompradub, S; Thavornyutikarn, P; Jaiboon, N.; Ruangpornvisuti, V; Chaichit, N; Asfari, Z; Vicens, J. *Tetrahedron Lett.* **2001**, *42*, 5541-5544. (h) Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 486-516. (i) Liu, J.-M.; Zheng, Q.-Y.; Yang, J. L.; Chen, C.-F.; Huang, Z.-T. *Tetrahedron Lett.* **2002**, *43*, 9209-9212. (j) Yilmaz, A.; Memon, S.; Yilmaz, M.

Tetrahedron **2002**, 7735-7740. (k) Cao, Y.-D.; Zheng, Q.-Y.; Chen, C.-F.; Huang, Z.-T. *Tetrahedron Lett.* **2003**, *44*, 4751-4755.

4. (a) Gbidini, E.; Ugozzoli, F.; Ungaro, R.; Harkema, S.; El-Fadl, A.; Reinhoudt D. *J. Am. Chem. Soc.* **1990**, *112,* 6979-6985. (b) Nijenhuis, W. F.; Buitenhuis, E. G.; de Jong, F.; Sudholter, E. J. R.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1991**, *113*, 7963-7968. (c) Yamamoto, H.; Shinkai, S. *Chem. Lett.* **1994**, 1115-1118. (d) Asfari, Z.; Bressot, C.; Vicens, J.; Hill, C.; Dozol, J.; Rouquette, H.; Eymard, S.; Lamare, V.; Toumois, B. *Anal. Chem.* **1995***, 67,* 3133-3139. (e) Geraci, C.; Chessari, G.; Piattelli, M.; Neri, P*. J. Chem. Soc., Chem. Commun*. **1997**, 921. (f) Kim, J.; Lee, W.; Suh, I.; Kim, .J;; Yoon, I.; Lee J. *J. Org. Chem.* **2000,** *65,* 7215-7217.
5. (a) Bocchi. C.; Careri. M.; Casnati. A.; Mori. G. *Anal. Chem.* **1995**; *67*, 4234-4238. (b) Asfari. Z.; Bressot. C.; Vicens. J.; Hill. C.; Dozol. J.; Rouquette. H.; Eymard. S.; Lamare. V.; Tournois. B. *Anal. Chem.* **1995**; *67*, 3133-3139. (c) Arnaud-Neu, F.; Caccamese, S.; Fuangswasdi, S.; Pappalardo, S.; Parisi, M. F.; Petringa, A.; Principato, G. *J. Org. Chem.* **1997**; *62*, 8041-8048. (d) Kim, J. S.; Pang, J. H.; Yu, I. Y.; Lee, W. K.; Suh, I. H.; Kim, J. K.; Cho, M. H.; Kim, E. T.; D. Y. Ra. *J. Chem. Soc., Perkin Trans. 2* **1999***, 837-840.* (e) Casnati, A.; Ca, N. D.; Sansone, F.; Ugozzoli, F.; Ungaro, R. *Tetrahedron* **2004**, *60*, 7869-7876. (f) Luo, H.; Dai, S.; Bonnesen, P. V.; Buchanan, A. C., III; Holbrey, J. D.; Bridges, N. J.; Rogers, R. D. *Anal. Chem.* **2004**; *76*, 3078-3083. (g) van Leeuwen, F. W. B.; Beijleveld, H.; Miermans, C. J. H.; Huskens, J.; Verboom, W.; Reinhoudt, D. N.*Anal. Chem.* **2005**; *77*, 4611-4617.
6. (a) Reinhoudt, D. N.; Dijkstra, P. J.; in 't Veld, **P.** J. A.; Bugge, K.-E.;Harkema, **S.;** Ungaro. R.; Ghidini, E. *J. Am. Chem.* Soc. **1987**, *109,* 4761-4762. (b) Dijkstra, P. J.; Brunink, J. A. J.; Bugge, K.-E.; Reinhoudt, D. N.; Harkema, **S.;** Ungaro, R.; Ugozzoli, F.; Ghidini, E. *J. Am. Chem.* Soc. **1989**, *111*, 7567-7575. (c) Beer, P. D.; Gale, P. A.; Chen, Z.; Drew, M. G. B.; Heath, J. A.; Ogden, M. I.; Powell, H. R. *Inorg. Chem*. **1997**, *36*, 5880-5893. (d) Bourgeois, J.-P.; Echegoyen, L.; Fibboli, M.; Pretsch, E.; Diederich, F. *Angew. Chem.*, *Int. Ed.* **1998**, *37*, 2118-2121.
7. (a) Brewer, K. *J. Am. Chem.* Soc. **1938**, *60,* 691. (b) Anderson, C. J.; Welch, M. J. *Chem. Re*v. **1999**, *99*, 2219-2234.
8. (a) *Radioactive Waste Management and Disposal*; Cecille, L., Ed.; Elsevier: New York, **1991**. (b) Asfari, Z.; Pulpoka, B.; Saadioui, M.; Wenger, S.; Nierlich, M.; Thuery, P.; Reynier, N.; Dozol, J.-F.; Vencens, *J. Mol. Recognit. Inclusion, Proc. 9th Int. Symp*. **1998**, 173-178. (c) Hill, C.;

Dozol, J.-F.; Lamare, V.; Rouquette, H.; Eymard, S.; Tournois, B.; Vincens, J.; Asfari, Z.; Bressot, C. *J. Inclusion Phenom. Mol. Recognit. Chem*. **1994**, *19*, 399-408. (d) McDowell, W. J.; Case, G. N.; McDonough, **J. A.;** Bartsch, R. A. *Anal. Chem.* **1992,** *64,* 3013-3017.

9. (a) Lamare, V.; Dozol, J. F.; Ugozzoli, F.; Casnati, A.; Ungaro, R. *Eur. J. Org. Chem.* 1998, *8*, 1559-1568. (b) Kim, J. S.; Ohki, A.; Ueki, R; Ishizuka, T.; Shimotashiro, T.; Maeda, S. *Talanta* 1999, *48*, 705-710.
10. (a) Schmitt, P.; Beer, P. D.; Drew, M. G. B.; Sheen, P. D. *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1839. (b) Sidorov, V.; Dotch, F. W.; El-Kouedi, M.; Davis, J. T. *Chem. Commun*. **2000**, 2369. (c) Matthews, S. E.; Schmitt, P.; Felix V.; Drew, M. G. B.; Beer, P. D. *J. Am. Chem. Soc.* **2002**, *124,* 1341.
11. (a) Pipoosananakaton, B.; Sukwattanasinitt, M.; Jaiboon, N.; Chaichit, N.; Tuntulani, T. *Tetrahedron Lett.* **2000**, *41*, 9095-9100. (b) Sukwattanasinitt, M.; Rojanathanes, R.; Tuntulani, T.; Sritana-anant, Y.; Ruangpornvisuti, V. *Tetrahedron Lett.* **2001**, *42*, 5291-5293. (c) Rojanathanes, R.; Pipoosananakaton, B.; Tuntulani, T.; Bhanthumnavin, W.; Orton, J. B.; Cole, S. J.; Hursthouse, M. B.; Grossel, M. C.; Sukwattanasinitt, M. *Tetrahedron* **2005**, *61*, 1317-1324.
12. Rojanathanes, R.; Tutulani, T. ; Bhabthumnavin, W., Sukwattanasinitt, M. *Org. Lett.*, **2005**, *7*, 3401-3404.

Output จากโครงการวิจัยที่ได้รับทุนจาก สกว.

1. ผลงานตีพิมพ์ในวารสารวิชาการนานาชาติ
    1.1 Jaiyu, A.; Rojanathanes, R.; **Sukwattanasinitt, M.** “Stilbene-bridged 1,3-alternate calix[4]arene crown ether for selective alkali ion extraction“ *Tetrahedron Lett.* **2007**, *48*, 1817-1821. (Impact factor 2008 = 2.538)
    1.2 Lim, C.; Sandman, D.J.; **Sukwattasinitt, M.** “Topological Polymerization of tert-Butylcalix[4]arenes Containing Diynes” *Macromolecules* **2008**, *41*, 675-681. (Impact factor 2008 = 4.407)
    1.3 ต้นฉบับบทความที่ 3 เรื่อง “X-ray guided ^{1}H NMR analysis of pinched cone calix[4]arenes” อยู่ระหว่างการแก้ไขปรับปรุงต้นฉบับเพื่อส่งตีพิมพ์ในวารสารที่เหมาะสมต่อไป

1.4 Niamnont N.; Siripornnoppakhun W.; Rashatasakhon, P.; **Sukwattanasinitt M.** "A polyanionic dendritic fluorophore for selective detection of Hg^{2+} in Triton X-100 aqueous media" *Org. Lett.* **2009,** *11*, 2768-2771. (Impact factor 2008 = 5.128) เป็นผลงานที่ใช้เงินทุนวิจัยบางส่วนจากทุนที่ได้รับในโครงการนี้ทำวิจัย

2. การนำผลงานวิจัยไปใช้ประโยชน์

   2.1 เชิงพาณิชย์ ยังไม่มี

   2.2 เชิงนโยบาย ยังไม่มี

   2.3 เชิงสาธารณะ ยังไม่มี

   2.4 เชิงวิชาการ ได้ผลิตบัณฑิตปริญญาเอก 2 คนจากโครงการวิจัยนี้

3. อื่นๆ

   รางวัลที่ได้รับ

   3.1 SYNFACTS editorial board selection of the article "Topological Polymerization of tert-Butylcalix[4]arenes Containing Diynes" for its important insights **in 2008**

   3.2 The Wiley-CST Award for Outstanding Publication **2008** from Global publisher John Wiley & Sons, Inc.

   3.3 Outstanding Publication Award from Ratchadaphiseksomphot Endowment Fund for the article "Temperature Indicators from Nanoaggregate of Diacetylenes" **in 2009**

ภาคผนวก

Available online at www.sciencedirect.com

ScienceDirect

Tetrahedron Letters 48 (2007) 1817–1821

Tetrahedron Letters

Stilbene-bridged 1,3-alternate calix[4]arene crown ether for selective alkali ion extraction

Arisa Jaiyu, Rojrit Rojanathanes and Mongkol Sukwattanasinitt*

Department of Chemistry, Faculty of Science, Chulalongkorn University, Phyathai Road, Pathumwan, Bangkok 10330, Thailand

Received 4 December 2006; revised 3 January 2007; accepted 4 January 2007

Available online 9 January 2007

Abstract—A series of stilbene-bridged calix[4]arenes was synthesized through an intramolecular reductive McMurry coupling of bis-benzaldehyde calix[4]arene in high yields. Tetra- and pentaethylene glycol chains were tethered to the phenolic groups of calix[4]-arene to form stilbene-bridged calix[4]arene crown-5 and crown-6, respectively. The presence of stilbene bridge over the calix[4]arene rim effectively prevented the connection of the polyether chains in the cone conformation resulting in the exclusive formation of 1,3-alternate stilbene-bridged calix[4]arene crown product. Compared to the cone analogues, the 1,3-alternate calix[4]-arene crown ethers showed a greater extraction ability and selectivity toward Cs^+.

© 2007 Published by Elsevier Ltd.

1. Introduction

Since its discovery, calix[4]arene has been extensively used as a molecular platform to construct artificial ionophores.[1] Thanks to its preorganized basket structure and readily functionalizable phenolic groups, calix[4]-arene-based ionophores with variety of cavity shapes and sizes were readily synthesized.[2] Calix[4]arene crown ethers, a class of calix[4]arene derivatives containing polyether chain tethered across opposite phenolic rings, are known to be more selective alkali ionophores than their crown ethers counterparts.[3] Both crown ether chain length and calixarene conformation play important roles in regulating the complextion with metal ions.[4] The applications of calix[4]arene crown ethers for Na^+/K^+ pump mimicking,[5] Rb^+ transportation in radiopharmaceutical treatments,[6] and the removal of Cs^+ radioactive wastes were reported.[7]

We have recently synthesized and studied a series of azobenzene-bridged and stilbene-bridged *tert*-butylcalix-[4]arenes as photoswitchable ionophores[8] and molecular receptors.[9] We found that the incorporation of different isomers of rigid azobenzene or stilbene bridge on the narrow phenolic rim can regulate the calix[4]arene cavity shape. In this work, we would like to report the use of stilbene bridge to direct the synthesis of calix[4]arene crown ethers in a 1,3-alternate conformation for selective alkali ion extraction.

2. Results and discussion

Using reductive McMurry intramolecular coupling of bis-benzaldehyde calix[4]arenes **1** followed by condensation with the ditosylate ester of tetra- and pentaethylene glycol, stilbene-bridged calix[4]arene crown-5 and crown-6 were synthesized (Scheme 1). The reductive coupling yielded stereoisomeric mixtures of *cis* and *trans* stilbene **2** of which the cis isomer was predominant. By using a high dilution condition (7 mM of bisbenzaldehydes) and a large excess of $TiCl_4$ and Zn (20 equiv), the yields of stilbene products were markedly improved from our previous work.[9] The mixtures of *cis* and *trans* stilbene-bridged calix[4]arene were separated by column chromatography and used in the next condensation step. Only cis form of the final products from the condensation were successfully synthesized except for *o*-**3** that the trans isomer was also obtained. The characteristic singlet NMR signal of the calix[4]arene methylene protons observed in the spectra of **3** and **4** indicated that the stilbene-bridged calix[4]arene crowns were formed in the 1,3-alternate conformation.[10]

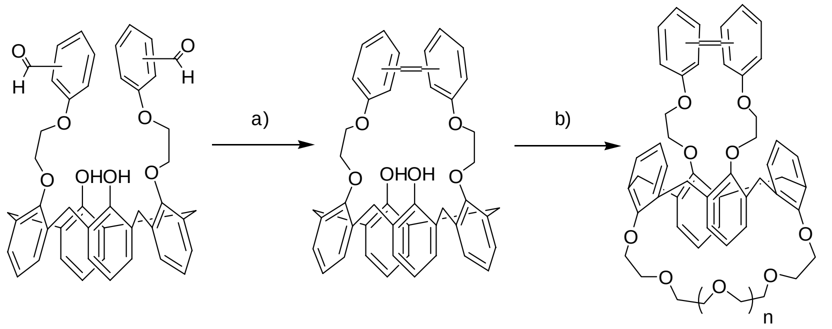
To our surprise, the attempts to prepare *m*-*trans*-**3** and *m*-*trans*-**4** from *m*-*trans*-**2** by the same approach have

---

Keywords: Crown ether; Extraction; Calix[4]arene; Alkali ion.

* Corresponding author. Tel.: +66 2 2187620; fax: +66 2 2187598; e-mail: smongkol@chula.ac.th

0040-4039/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.tetlet.2007.01.026



1

o-**2** *cis* 62% *trans* 15%
m-**2** *cis* 37% *trans* 37%
p-**2** *cis* 87%

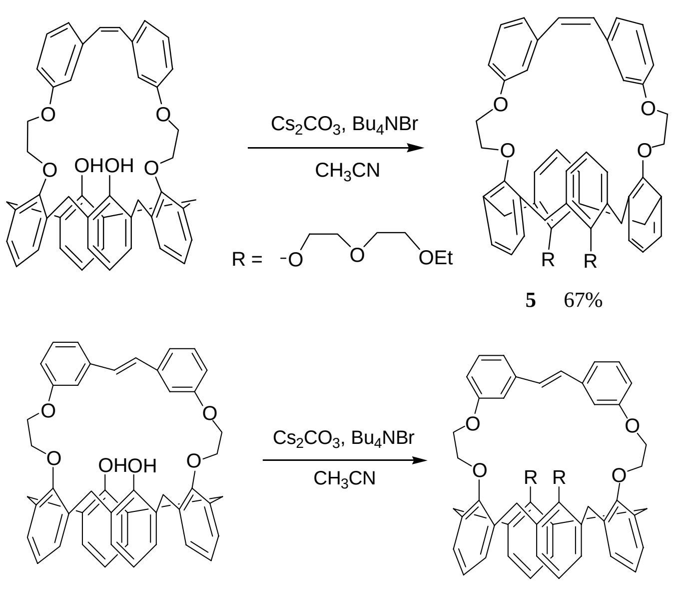
n=1	*o-cis*-**3**	80%
	o-trans-**3**	67%
	m-cis-**3**	84%
	p-cis-**3**	80%
n=2	*o-cis*-**4**	75%
	m-cis-**4**	68%
	p-cis-**4**	70%

Scheme 1. Synthesis of stilbene calix[4]arene crown ether **3**, **4**.[11] Reagents: (a) $TiCl_4$, Zn, THF; (b) $TsO(CH_2CH_2O)_{(3+n)}Ts$, Cs_2CO_3, Bu_4NBr, CH_3CN.

been so far fruitless, yielding only intractable materials. To clarify these puzzling results, both *cis*- and *trans*-*m*-**2** were condensed with 2 equiv of *p*-toluenesulfonate ester of diethyleneglycol monoethylether (Scheme 2). The products from *m*-*cis*-**2** was the expected 1,3-alternate *m*-*cis*-**5** but the reaction of *m*-*trans*-**2** gave only a poor yield of the unexpected cone *m*-*trans*-**6**. The cone conformation was assigned according to the characteristic NMR signals of the doublet pairs of the calix[4]arene methylene protons. The results suggested that the phenol ring flipping process required for the conversion of the conformation from cone to 1,3-alternate was somehow disallowed in *m*-*trans*-**2**. Although our previous work has predicted that the calix[4]arene rims in *m*-*trans*-**2** were distorted from the normal circular shape into an oval shape[9] we have never thought that this distortion would totally prevent the ring flipping process.

For comparison in the extraction study, calix[4]arene crowns without the stilbene bridge (**7** and **8**) containing the same crown sizes as **3** and **4** were also synthesized (Scheme 3). Without the stilbene bridge, calix[4]arene crowns were obtained in the cone conformation exclusively.

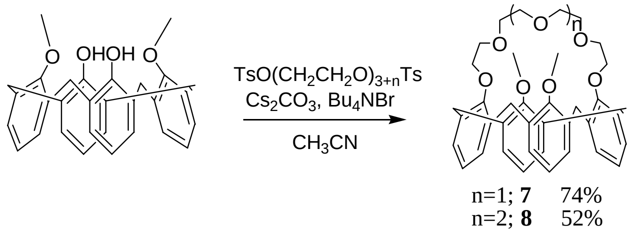
The alkali metal ion extraction at the aqueous $CHCl_3$ interface by stilbene-bridged calix[4]arene crowns **3** and **4** were investigated in comparison with compounds **5**, **7**, **8**, and 18-crown-6. The extraction was carried out by thorough mixing a chloroform solution (5 mM, 1 mL) of the ligand with an aqueous solution of the metal picrate (5 mM, 1 mL) for 24 h. After centrifugation, the aqueous phase (35 μL) was pipetted out and diluted to 5 mL. The concentration of the remaining metal ion in the aqueous phase was determined from



5 67%

6 20%

Scheme 2. Synthesis of stilbene calix[4]arene crown ether **5**, **6**.



Scheme 3. Synthesis of calix[4]arene crown ether **7**, **8**.

the UV absorbance of picrate ion at 354 nm in the diluted solution. The % extraction was calculated from $([A_0 - A]/[A_0]) \times 100$, whereas A_0 and A were the absorbance of the aqueous metal picrate solutions before and after extraction, respectively.

Calix[4]arene crowns (**3**, **4**, and **7**) and 18-crown-6 generally showed a good extractability toward alkali ions larger than Na^+ (Fig. 1). While the calix[4]arene crown-5 such as **3** and **7** showed a significantly greater K^+/Cs^+ selectivity than that of 18-crown-6, the calix[4]arene crown-6 (compound **4**) displayed impressively high Cs^+/K^+ selectivity. Stilbene-bridged calix[4]arene **5** in which structure contains two linear diethylene glycol chains has poor extractability toward all alkali ions. The result indicated that neither the six oxygen atoms present in the diethylene glycol chains nor in the crown oxygens on the same side with the stilbene bridge are suitable for hosting the alkali ions. The cone calix[4]arene crown **8** has relatively much lower Cs^+ extractability compared to the 1,3-alternate stilbene-bridged calix[4]arene crown **4**. The 1,3-alternate calix[4]arene crown was reported to have a suitable orientation of aromatic rings for cation/π interaction participating in the binding of Cs^+.[11]

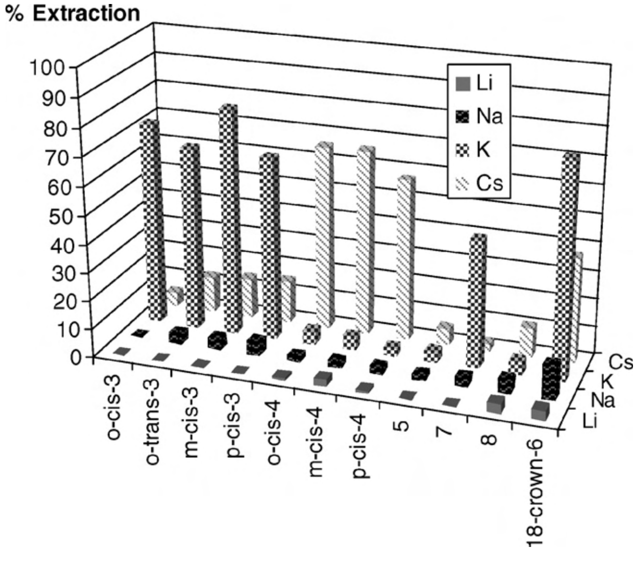


Figure 1. Extraction percentage of alkali metal picrates from water to chloroform by calix[4]arene derivatives and 18-crown-6 at room temperature.

Having a high extracting ability, ligands **3** and **4** were also tested for solid–liquid extraction. An excess amount of potassium picrate was added into a solution of **3** or **4** in $CDCl_3$ and the mixture was sonicated. The color of the solution gradually changed from colorless to yellow indicating the dissolution of metal picrate into $CDCl_3$, which is normally nonsolvent for picrate salts. The changes in ^1H NMR spectra were used to justify the nature of complexation. For example, a new set of proton signals was clearly observed after 1 h of sonication *p-cis*-**3** with potassium picrate salt (compare Fig. 2a and b) suggesting a partial association of the ligand to K^+, to form the expecting host–guest complex, in the slow exchange process. This new set of signals became stronger with the expenses of the original set of signals as the sonication prolonged. The original signals *p-cis*-**3** were completely replaced by the signals of the complex after 3 h of sonication (Fig. 2c) signifying a full complexation of the host molecules to K^+ in the solid–liquid extraction.

Upon complexation with K^+, the signals of the methylene protons in the crown ether moiety of *p-cis*-**3** were shifted significantly downfield while the other signals were shifted only slightly (Fig. 3a) indicating that K^+ situated mostly within the crown ether loop. For the complexation between *p-cis*-**4** and Cs^+, significant shifts of various signals including the calixarene aromatic protons were observed (Fig. 3b) suggesting the possibility of cation–π interaction involving in the complexation.

In summary, the incorporation of stilbene bridge to calix[4]arenes provided a sensible approach to synthesize calix[4]arene crown-5 and crown-6 in 1,3-alternate conformation. These 1,3-alternate calix[4]arene crowns have a greater extractability and selectivity than those of the corresponding cone calix[4]arene crowns. The stilbene-bridged calix[4]arene crown-5 has an excellent K^+/Cs^+ selectivity while the stilbene-bridged calix[4]arene

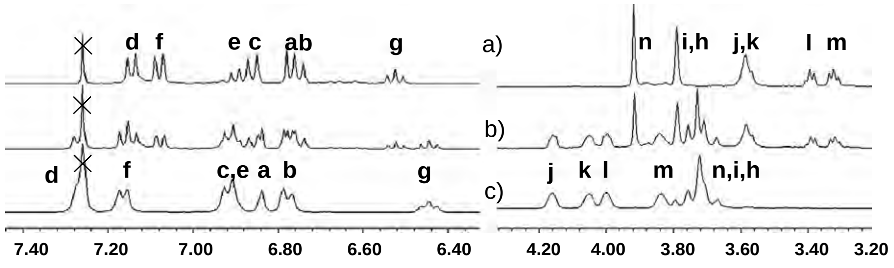


Figure 2. The ^1H NMR spectra of (a) *p-cis*-**3**, (b) partial complexation between *p-cis*-**3** and potassium picrate, and (c) full complexation between *p-cis*-**3** and potassium picrate.

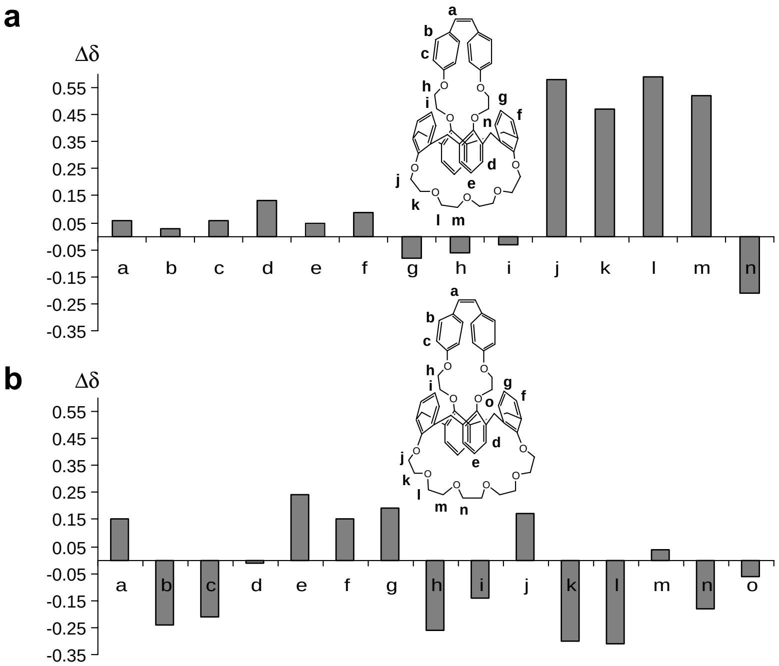


Figure 3. (a) Δ*δ* of *p-cis*-**3** complexed with potassium picrate and (b) Δ*δ* of *p-cis*-**4** complexed with cesium picrate.

crown-6 has an excellent Cs^+/K^+ selectivity in the aqueous chloroform extraction. The metal selectivities of 1,3-alternate calix[4]arene crowns also significantly outperform 18-crown-6.

Acknowledgments

This work was financially cosupported by the Thailand Research Fund (TRF) and the Commission of Higher Education under the contract code: RMU4980024.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2007.01.026.

References and notes

1. (a) Gutsche, C. D. *Acc. Chem. Res.* **1983**, *16*, 161–170; (b) Gutsche, C. D. *Calixarenes* Revisited. In *Monograph in Supramolecular Chemistry*; Stoddart, J. F., Ed.; The Royal Society of Chemistry: Cambridge, 1989; (c) Böhmer, V. *Angew. Chem., In. Ed. Engl.* **1995**, *34*, 713–745; (d) Ikeda, A.; Shinkai, S. *Chem. Rev.* **1997**, *97*, 1713–1734; (e) Gutsche, C. D. *Calixarenes* Revisited. In *Monograph in Supramolecular Chemistry*; Stoddart, J. F., Ed.; The Royal Society of Chemistry: London, 1998; (f) Asfari, Z.; Böhmer, V.; Harrowfield, J.; Vicens, J. *Calixarenes 2001*; Kluwer Academic: Dordrecht, Holland, 2001.
2. (a) Casnati, A.; Pochini, A.; Ungaro, R.; Ugozzoli, F.; Arnaud, F.; Fanni, S.; Schwing, M.-J.; Egberink, R. J. M.; de Jong, F.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1995**, *117*, 2767–2777; (b) Matsumoto, H.; Shinkai, S. *Tetrahedron Lett.* **1996**, *37*, 77–80; (c) Arduini, A.; Domiano, L.; Pochini, A.; Secchi, A.; Ungarro, R.; Ugozzoli, F.; Struck, O.; Verboom, W.; Reinhoudt, D. N. *Tetrahedron* **1997**, *53*, 3767–3776; (d) Bodenant, B.; Weil, T.; Businelli-Pourcel, M.; Fages, F.; Barbe, B.; Pianet, I.; Laguerre, M. *J. Org. Chem.* **1999**, *64*, 7034–7039; (e) Beer, P. D.; Hopkins, P. K.; McKinny, J. D. *Chem. Commun.* **1999**, 1253–1254; (f) Guillon, J.; Leger, J.-M.; Sonnet, P.; Jarry, C.; Robba, M. *J. Org. Chem.* **2000**, *65*, 8283–8289; (g) Tuntulani, T.; Poompradub, S.; Thavornyutikarn, P.; Jaiboon, N.; Ruangpornvisuti, V.; Chaichit, N.; Asfari, Z.; Vicens, J. *Tetrahedron Lett.* **2001**, *42*, 5541–5544; (h) Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 486–516; (i) Liu, J.-M.; Zheng, Q.-Y.; Yang, J. L.; Chen, C.-F.; Huang, Z.-T. *Tetrahedron Lett.* **2002**, *43*, 9209–9212; (j) Yilmaz, A.; Memon, S.; Yilmaz, M. *Tetrahedron* **2002**, 7735–7740; (k) Cao, Y.-D.; Zheng, Q.-Y.; Chen, C.-F.; Huang, Z.-T. *Tetrahedron Lett.* **2003**, *44*, 4751–4755.
3. (a) Gbidini, E.; Ugozzoli, F.; Ungaro, R.; Harkema, S.; El-Fadl, A.; Reinhoudt, D. *J. Am. Chem. Soc.* **1990**, *112*, 6979–6985; (b) Nijenhuis, W. F.; Buitenhuis, E. G.; de Jong, F.; Sudholter, E. J. R.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1991**, *113*, 7963–7968; (c) Yamamoto, H.; Shinkai, S. *Chem. Lett.* **1994**, 1115–1118; (d) Asfari, Z.; Bressot, C.; Vicens, J.; Hill, C.; Dozol, J.; Rouquette, H.; Eymard, S.; Lamare, V.; Toumois, B. *Anal. Chem.* **1995**, *67*, 3133–3139; (e) Geraci, C.; Chessari, G.; Piattelli, M.; Neri, P. *Chem. Commun.* **1997**, 921; (f) Kim, J.; Lee, W.; Suh, I.; Kim, J.; Yoon, I.; Lee, J. *J. Org. Chem.* **2000**, *65*, 7215–7217.
4. (a) Bocchi, C.; Careri, M.; Casnati, A.; Mori, G. *Anal. Chem.* **1995**, *67*, 4234–4238; (b) Asfari, Z.; Bressot, C.; Vicens, J.; Hill, C.; Dozol, J.; Rouquette, H.; Eymard, S.; Lamare, V.; Tournois, B. *Anal. Chem.* **1995**, *67*, 3133–3139; (c) Arnaud-Neu, F.; Caccamese, S.; Fuangswasdi, S.; Pappalardo, S.; Parisi, M. F.; Petringa, A.; Principato, G. *J. Org. Chem.* **1997**, *62*, 8041–8048; (d) Kim, J. S.; Pang, J. H.; Yu, I. Y.; Lee, W. K.; Suh, I. H.; Kim, J. K.; Cho, M. H.; Kim, E. T.; Ra, D. Y. *J. Chem. Soc., Perkin Trans. 2* **1999**, 837–840; (e) Casnati, A.; Ca, N. D.; Sansone, F.; Ugozzoli, F.; Ungaro, R. *Tetrahedron* **2004**, *60*, 7869–7876; (f) Luo, H.; Dai, S.; Bonnesen, P. V.;

Buchanan, A. C.; Holbrey, J. D.; Bridges, N. J.; Rogers, R. D. *Anal. Chem.* **2004**, *76*, 3078–3083; (g) van Leeuwen, F. W. B.; Beijleveld, H.; Miermans, C. J. H.; Huskens, J.; Verboom, W.; Reinhoudt, D. N. *Anal. Chem.* **2005**, *77*, 4611–4617.

5. (a) Reinhoudt, D. N.; Dijkstra, P. J.; in't Veld, P. J. A.; Bugge, K.-E.; Harkema, S.; Ungaro, R.; Ghidini, E. *J. Am. Chem. Soc.* **1987**, *109*, 4761–4762; (b) Dijkstra, P. J.; Brunink, J. A. J.; Bugge, K.-E.; Reinhoudt, D. N.; Harkema, S.; Ungaro, R.; Ugozzoli, F.; Ghidini, E. *J. Am. Chem. Soc.* **1989**, *111*, 7567–7575; (c) Beer, P. D.; Gale, P. A.; Chen, Z.; Drew, M. G. B.; Heath, J. A.; Ogden, M. I.; Powell, H. R. *Inorg. Chem.* **1997**, *36*, 5880–5893; (d) Bourgeois, J.-P.; Echegoyen, L.; Fibboli, M.; Pretsch, E.; Diederich, F. *Angew. Chem., Int. Ed.* **1998**, *37*, 2118–2121.
6. (a) Brewer, K. *J. Am. Chem. Soc.* **1938**, *60*, 691; (b) Anderson, C. J.; Welch, M. J. *Chem. Rev.* **1999**, *99*, 2219–2234.
7. (a) *Radioactive Waste Management and Disposal*; Cecille, L., Ed.; Elsevier: New York, 1991; (b) Asfari, Z.; Pulpoka, B.; Saadioui, M.; Wenger, S.; Nierlich, M.; Thuery, P.; Reynier, N.; Dozol, J.-F.; Vincens, J. In *J. Mol. Recognit. Inclusion, Proc. 9th Int. Symp.*; 1998; pp 173–178; (c) Hill, C.; Dozol, J.-F.; Lamare, V.; Rouquette, H.; Eymard, S.; Tournois, B.; Vincens, J.; Asfari, Z.; Bressot, C. *J. Inclusion Phenom. Mol. Recognit. Chem.* **1994**, *19*, 399–408; (d) McDowell, W. J.; Case, G. N.; McDonough, J. A.; Bartsch, R. A. *Anal. Chem.* **1992**, *64*, 3013–3017.
8. (a) Pipoosananakaton, B.; Sukwattanasinitt, M.; Jaiboon, N.; Chaichit, N.; Tuntulani, T. *Tetrahedron Lett.* **2000**, *41*, 9095–9100; (b) Sukwattanasinitt, M.; Rojanathanes, R.; Tuntulani, T.; Sritana-anant, Y.; Ruangpornvisuti, V. *Tetrahedron Lett.* **2001**, *42*, 5291–5293; (c) Rojanathanes, R.; Pipoosananakaton, B.; Tuntulani, T.; Bhanthumnavin, W.; Orton, J. B.; Cole, S. J.; Hursthouse, M. B.; Grossel, M. C.; Sukwattanasinitt, M. *Tetrahedron* **2005**, *61*, 1317–1324.
9. Rojanathanes, R.; Tutulani, T.; Bhabthumnavin, W.; Sukwattanasinitt, M. *Org. Lett.* **2005**, *7*, 3401–3404.
10. Spectroscopic data of stilbene calix[4]arene crown-5 or 6 (**3** and **4**); compound *o-cis*-**3**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.06, 3.42 (t, –OCH$_2$CH$_2$O-crown, 8H), 3.11, 3.45 (t, ArOCH$_2$CH$_2$O-crown, 8H), 3.56 (br, ArOCH$_2$CH$_2$OAr, 8H), 3.87 (m, ArCH$_2$Ar, 8H), 6.86, 6.90 (t, calix-ArH, 4H), 6.79, 7.18 (d, stilbene-ArH, 4H), 6.90, 7.16 (t, stilbene-ArH, 4H), 6.55 (s, CH=CH, 2H), 6.98, 7.10 (d, calix-ArH, 8H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 38.1 (ArCH$_2$Ar), 68.3 (OCH$_2$), 68.8 (OCH$_2$), 69.7 (OCH$_2$), 69.8 (OCH$_2$), 70.7 (OCH$_2$), 72.7 (OCH$_2$), 122.8 (calix-ArC), 123.7 (calix-ArC), 129.2 (calix-ArC), 129.7 (calix-ArC), 133.4 (calix-ArC), 133.9 (calix-ArC), 156.1 (calix-ArC), 156.3 (calix-ArC), 129.1 (stilbene-ArC), 127.9 (stilbene-ArC), 117.3 (stilbene-ArC), 117.7 (stilbene-ArC), 121.7 (stilbene-ArC), 122.8 (stilbene-ArC), 127.9 (stilbene-ArC), 129.1 (stilbene-ArC), 156.9 (stilbene-ArC), 126.7 (CH=CH); mp = 124–126 °C; FTMS calcd for C$_{54}$H$_{54}$O$_9$ [ESI, M$^+$ NH$_4$]: 846.4106, found: 864.4091; compound *o-trans*-**3**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.16, 3.53 (t, OCH$_2$CH$_2$O-crown, 8H), 3.25, 3.65 (t, ArOCH$_2$CH$_2$O-crown, 8H), 3.57, 3.64 (br, ArOCH$_2$CH$_2$OAr, 8H), 3.88 (m, ArCH$_2$Ar, 8H), 6.65, 7.15 (d, calix-ArH, 8H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 37.9 (ArCH$_2$Ar), 65.8 (OCH$_2$), 68.1 (OCH$_2$), 68.3 (OCH$_2$), 69.8 (OCH$_2$), 70.5 (OCH$_2$), 72.6 (OCH$_2$), 129.3 (calix-ArC), 129.3 (calix-ArC), 133.9 (calix-ArC), 134.1 (calix-ArC), 134.1 (calix-ArC), 139.3 (calix-ArC), 156.2 (calix-ArC), 158.5 (calix-ArC), 111.1 (stilbene-ArC), 115.3 (stilbene-ArC), 122.6 (stilbene-ArC), 122.7 (stilbene-ArC), 129.1 (stilbene-ArC), 156.1 (stilbene-ArC), 121.4 (CH=CH) FTMS calcd for C$_{54}$H$_{54}$O$_9$ [ESI, M$^+$ NH$_4$]: 846.4106, found: 864.4099; compound *m-cis*-**3**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.16, 3.46 (t, OCH$_2$CH$_2$O-crown, 8H), 3.27, 3.52 (t, ArOCH$_2$CH$_2$O-crown, 8H), 3.60 (br, ArOCH$_2$CH$_2$OAr, 8H), 3.87 (m, ArCH$_2$Ar, 8H), 6.65, 6.91 (t, calix-ArH, 4H), 6.83, 6.89 (d, stilbene-ArH, 4H), 7.27 (t, stilbene-ArH, 2H), 6.63 (s, stilbene-ArH, 2H), 6.78 (s, CH=CH, 2H), 7.05, 7.13 (d, calix-ArH, 8H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 38.1 (ArCH$_2$Ar), 67.0 (OCH$_2$), 68.3 (OCH$_2$), 68.4 (OCH$_2$), 69.7 (OCH$_2$), 70.7 (OCH$_2$), 72.8 (OCH$_2$), 129.5 (calix-ArC), 129.8 (calix-ArC), 130.0 (calix-ArC), 134.1 (calix-ArC), 134.2 (calix-ArC), 138.5 (calix-ArC), 156.1 (calix-ArC), 158.5 (calix-ArC), 109.9 (stilbene-ArC), 111.5 (stilbene-ArC), 116.5 (stilbene-ArC), 122.3 (stilbene-ArC), 111.5 (stilbene-ArC), 156.0 (stilbene-ArC), 122.4 (CH=CH); mp = 206–207 °C; Anal. Calcd for C$_{54}$H$_{54}$O$_9$: C, 76.62; H, 6.38. Found: C, 76.68; H, 6.45; compound *p-cis*-**3**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.32, 3.39 (t, OCH$_2$CH$_2$O-crown, 8H), 3.59 (br, ArOCH$_2$CH$_2$O-crown, 8H), 3.79 (br, ArOCH$_2$CH$_2$OAr, 8H), 3.92 (s, ArCH$_2$Ar, 8H), 6.52, 6.89 (t, calix-ArH, 4H), 6.75, 6.86 (d, stilbene-ArH, 8H), 6.78 (s, CH=CH, 2H), 7.08, 7.14 (d, calix-ArH, 8H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 37.8 (ArCH$_2$Ar), 68.9 (OCH$_2$), 68.9 (OCH$_2$), 69.4 (OCH$_2$), 70.5 (OCH$_2$), 70.6 (OCH$_2$), 71.9 (OCH$_2$), 130.1 (calix-ArC), 130.5 (calix-ArC), 130.6 (calix-ArC), 131.3 (calix-ArC), 133.8 (calix-ArC), 134.0 (calix-ArC), 155.8 (calix-ArC), 156.4 (calix-ArC), 117.4 (stilbene-ArC), 121.8 (stilbene-ArC), 115.5 (stilbene-ArC), 158.0 (stilbene-ArC), 122.7 (CH=CH); mp = 211 °C; Anal. Calcd for C$_{54}$H$_{56}$O: C, 76.62; H, 6.38. Found: C, 76.60; H, 6.38; compound *o-cis*-**4**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.12 (t, OCH$_2$, 4H) 3.19 (t, OCH$_2$, 4H) 3.42 (t, OCH$_2$, 4H), 3.46 (t, OCH$_2$, 4H), 3.55 (t, OCH$_2$, 4H), 3.61 (m, OCH$_2$, 8H), 3.75 (t, ArCH$_2$Ar, 8H), 6.41 (s, CH=CH, 2H), 6.89, 7.02 (d, calix-ArH, 8H), 6.82, 7.09 (t, calix-ArH, 4H), 6.75 (m, stilbene-ArH, 2H), 6.77 (m, stilbene-ArH, 2H), 6.82 (m, stilbene-ArH, 2H), 7.20 (d, stilbene-ArH, 2H); mp = 116–118 °C; Anal. Calcd for C$_{56}$H$_{58}$O$_{10}$: C, 75.53; H, 6.51. Found: C, 75.54; H, 6.56; compound *m-cis*-**4**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.35 (t, OCH$_2$, 8H), 3.46 (t, OCH$_2$, 4H), 3.53 (t, OCH$_2$, 4H), 3.61 (t, OCH$_2$, 4H), 3.64 (t, OCH$_2$, 4H), 3.67 (t, OCH$_2$, 4H), 3.71 (t, OCH$_2$, 4H), 3.85 (s, ArCH$_2$Ar, 8) 6.63, 7.27 (t, calix-ArH, 4H), 7.07, 7.12 (d, calix-ArH, 8H), 6.82, 6.91 (d, stilben-ArH, 4H), 6.90 (t, stilben-ArH, 2H), 6.64 (s, stilben-ArH, 2H) 6.78 (s, CH=CH, 2H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 38.0 (ArCH$_2$Ar), 61.7 (OCH$_2$), 66.9 (OCH$_2$), 68.3 (OCH$_2$), 68.9 (OCH$_2$), 69.4 (OCH$_2$), 72.7 (OCH$_2$), 1129.9 (calix-ArC), 130.1 (calix-ArC), 130.3 (calix-ArC), 134.0 (calix-ArC), 134.3 (calix-ArC), 138.5 (calix-ArC), 156.3 (calix-ArC), 158.4 (calix-ArC), 111.3 (stilbene-ArC), 116.4 (stilbene-ArC), 112.4 (stilbene-ArC), 122.6 (stilbene-ArC), 122.6 (stilbene-ArC), 156.0 (stilbene-ArC), 122.2 (CH=CH) FTMS calcd for C$_{56}$H$_{58}$O$_{10}$ [ESI, M$^+$ NH$_4$]: 908.4368, found: 908.4352; compound *p-cis*-**4**: ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.54 (t, OCH$_2$, 4H), 3.81 (t, OCH$_2$, 4H), 3.87 (t, OCH$_2$, 4H), 3.91 (t, OCH$_2$, 8H), 3.97 (t, OCH$_2$, 4H), 4.46 (t, OCH$_2$, 4H), 3.87 (s, ArCH$_2$Ar, 8H), 6.19, 6.78 (t, calix-ArH, 4H), 7.02, 7.19 (d, calix-ArH, 8H), 7.07, 7.14 (d, stilbene-ArH, 8H), 6.70 (s, CH=CH, 2H) mp = 256–257 °C; FTMS calcd for C$_{56}$H$_{58}$O$_{10}$ [ESI, M$^+$ NH$_4$]: 908.4368, found: 908.4375. The experimental details are available in Supplementary data.
11. (a) Lamare, V.; Dozol, J. F.; Ugozzoli, F.; Casnati, A.; Ungaro, R. *Eur. J. Org. Chem.* **1998**, *8*, 1559–1568; (b) Kim, J. S.; Ohki, A.; Ueki, R.; Ishizuka, T.; Shimotashiro, T.; Maeda, S. *Talanta* **1999**, *48*, 705–710.

Macromolecules **2008,** *41,* 675−681

Topological Polymerization of *tert*-Butylcalix[4]arenes Containing Diynes

Chantana Lim,[†] Daniel J. Sandman,[‡] and Mongkol Sukwattanasinitt*,[†]

Organic Synthesis Research Unit, Department of Chemistry, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand, and Center for Advanced Materials, Department of Chemistry, University of Massachusetts, Lowell, Massachusetts 01854

Received July 19, 2007; Revised Manuscript Received November 12, 2007

ABSTRACT: The new 25,26,27,28-tetra(8-hydroxylocta-2,4-diynyl)-*tert*-butylcalix[4]arene was synthesized in good yield from copper-catalyzed coupling reaction of 25,26,27,28-tetra(2-propynyl)-*tert*-butylcalix[4]arene with 5-iodo-4-pentynol in pyrrolidine. The hydroxyl end groups were converted to urethane groups through addition to alkyl or phenyl isocyanate. Di- and trisubstituted *tert*-butylcalix[4]arene analogs were also synthesized through the same approach. The solid-state photopolymerization study revealed that only the calix[4]arene derivatives containing four diyne units with alkyl urethane groups were substantially polymerized upon exposure to UV or gamma irradiation to give polydiacetylenes containing calix[4]arene. The visible absorption band at 350−600 nm and the Raman signals around 1500 and 2100 cm^{-1} characterized the ene−yne conjugation formed through the topological 1,4-addition polymerization of the diyne units.

Introduction

Topological polymerization of preorganized monomers can be used to control the structures of polymers at both the molecular and the supramolecular levels, which is vital for the preparation of unique materials with interesting properties that cannot be achieved by conventional polymerization.[1] Along this line, the favorable packing of diacetylene compounds has attracted much attention because their noncovalently organized structures can be topologically polymerized to form the corresponding polydiacetylenes. Closely-packed suprastructures of properly designed diacetylenes undergo 1,4-addition polymerization upon UV or gamma irradiation.[2] Tremendous interest in polydiacetylenes (PDAs) arises from the extensive ene−yne conjugation in the polymer backbone, leading to unique optical and electronic properties that are promising in a variety of applications such as chemical sensors,[3] biosensors,[4] nonlinear optical materials,[5] photoresists,[6] thermal,[7] and mechanical sensors.[8]

To make a polydiacetylene via topochemical polymerization, it is required that the monomer diyne units be arranged with a repeat distance (r) of ~5 Å and an orientation angle (θ) of ~45° relative to the translation axis, as shown in Figure 1.[9] These packing requirements limit the shape and size of the substituents (R) on diynes in that the sterically bulky substituents usually preclude the topopolymerization.[10] Due to this limitation, the design of molecules that can undergo intramolecular 1,4-addition reaction of diyne units is challenging and, to our knowledge, has not been reported.

Bisdiyne incorporated within an alkyl chain had been studied for topological polymerization in Langmuir−Blodgett films.[11] However, the mode of topological polymerization was purely intermolecular as the diyne units were not restricted to the parallel alignment. A molecule containing multiple diyne units aligned in an appropriate direction is required to demonstrate an intramolecular 1,4-addition reaction between the diyne groups.

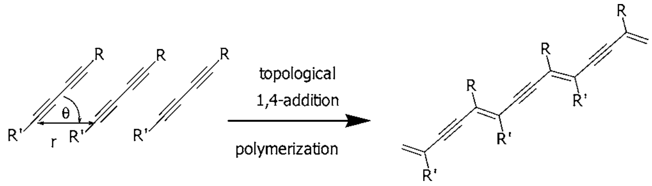


Figure 1. Packing parameters, $r = \sim 5$ Å and $\theta = \sim 45°$, required for the topological polymerization of a diacetylene monomer.

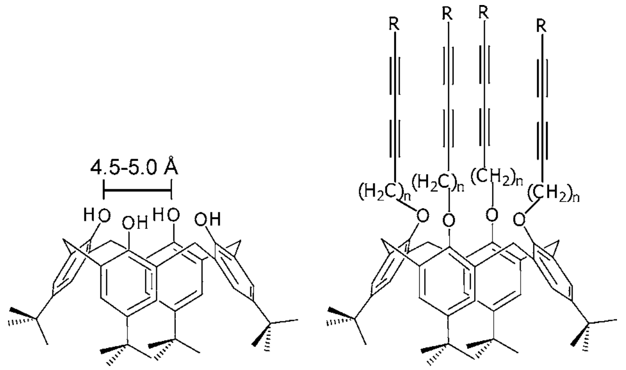


Figure 2. The structures of *tert*-butylcalix[4]arene and its tetradiyne derivative.

Calix[4]arene has a unique three-dimensional cavity-shaped architecture that its derivatives exhibit interesting supramolecular binding behaviors in solution[12] and in the solid state.[13] The self-assembled PDA/*tert*-butylcalix[4]arene bilayer on gold surface acts as a chemically sensitive interface for surface acoustic wave mass balances in vapor-phase sensing applications.[14] With the knowledge that *tert*-butylcalix[4]arene having four squarely arranged hydroxyl groups has a preorganized basket like structure and the distance between the neighboring hydroxyl groups is 4.5−5.0 Å (Figure 2),[15] we contemplated that its derivatives containing multiple diyne units may undergo topological polymerization to form PDA-containing *tert*-butylcalix[4]arene. Study of topological polymerization of *tert*-butylcalix[4]arene mounted with multiple diyne chains will not

---

* E-mail: smongkol@chula.ac.th.
[†] Chulalongkorn University.
[‡] University of Massachusetts.

10.1021/ma0716128 CCC: $40.75 © 2008 American Chemical Society
Published on Web 12/29/2007

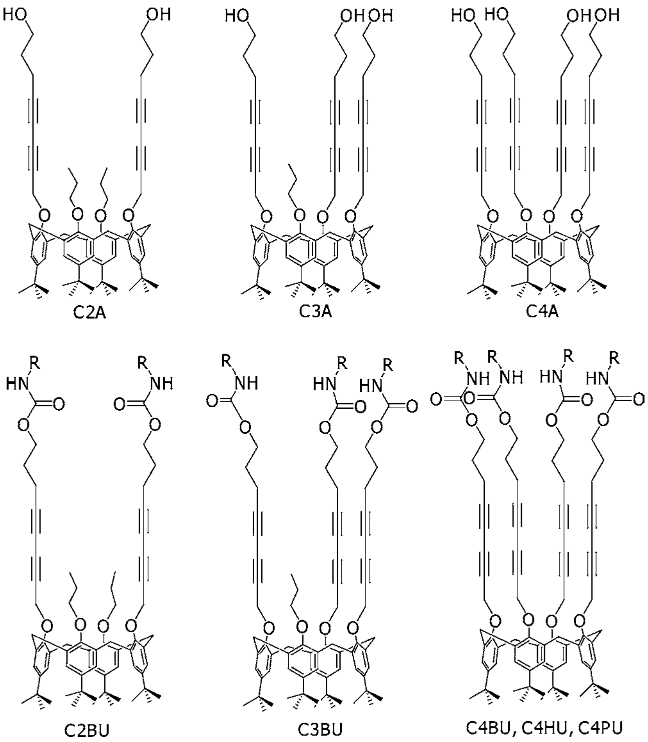


Figure 3. The structures of calix[4]arenes containing multiple diyne units synthesized in this work. The letters B, H, and P denote R = butyl, hexyl, and phenyl, respectively.

only be mechanistically interesting but may also give novel interesting sensing materials.

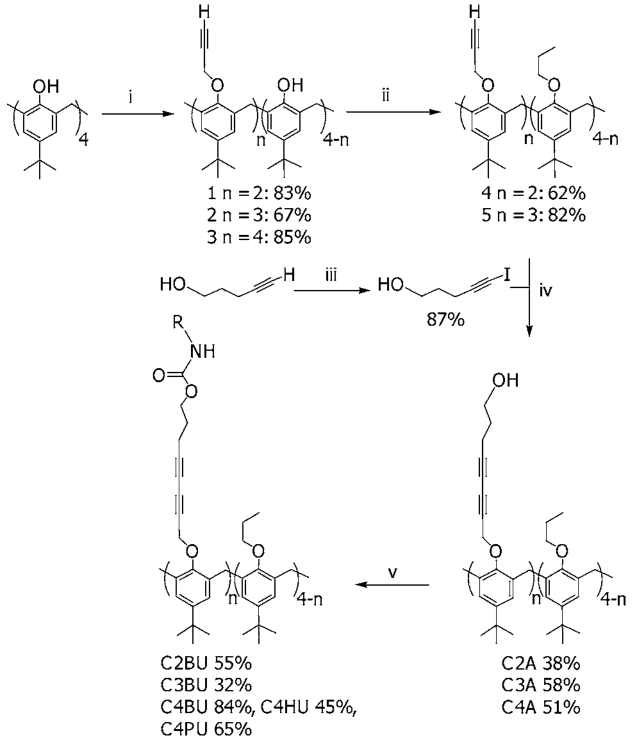
Results and Discussion

Synthesis of Calix[4]arenes Containing Multiple Diyne Units. Calix[4]arenes mounted with two, three, and four diyne units (Figure 3) were synthesized and studied for their possibility to undergo topological 1,4-addition polymerization. The synthesis was started from multiple *O*-alkylation of *tert*-butylcalix[4]arene with appropriate equivalents of propargyl bromide in the presence of a suitable inorganic base at reflux temperature.[16−18] Di-, tri-, and tetrapropargyl-*tert*-butylcalix[4]arenes were obtained in 65−85% yields (Scheme 1). The remaining phenolic hydroxyl groups of di- and tripropargyl-*tert*-butylcalix[4]arene were protected with propyl group prior to the subsequent coupling to form the diynes. The Cadiot−Chodkiewicz coupling[19] of the propargyl substituted *tert*-butylcalix[4]arenes with 5-iodo-4-pentynol afforded the desired calix[4]arenes containing multiple diyne units in good yields. The iodine-terminated alkyne used in the coupling step was generated from the iodination of 4-pentyn-1-ol with iodine in the presence of morpholine base.[20] Further modification of the hydroxyl end of the diyne chains to carbamate (urethane) was accomplished by the addition of hydroxyl group to an isocyanate. Unless commercially available, the isocyanates were generated in situ from the corresponding amine by reacting with triphosgene using triethylamine as a base in dry chloroform in the presence of dibutyltindilaurate as a catalyst.[21] All diacetylene products were purified by column chromatography until their ^{1}H NMR and ^{13}C NMR spectra were clean. The elemental analysis was used to confirm their purity prior to the study of their photopolymerization.

Solid-State Photopolymerization of *tert*-Butylcalix[4]arene Containing Four Diyne Units. UV irradiation (TUV 15W/G15 T18 lamp, Philips, Holland) at a distance of 30 cm of C4A, C4BU, C4HU, and C4PU powders showed that the white color of C4BU and C4HU rapidly turned into intense red color (within 5 min) while the white color of C4A and C4PU solids were virtually unchanged upon long exposure to UV irradiation (30 min) (Table 1). The intense color change of a diacetylene solid after UV irradiation typically signifies the formation of extensive ene−yne conjugation resulting from the topological 1,4-addition polymerization of the diyne units. Dissolution of the irradiated C4BU and C4HU in chloroform gave solutions of C4BU and C4HU (confirmed by TLC and NMR) and insoluble red powders. No significant insoluble solid was observed in the dissolution of irradiated C4A and C4PU in chloroform, and the soluble materials were identified as the starting C4A and C4PU. The red insoluble solids obtained from the irradiation of C4BU and C4HU are thus likely to be polydiacetylenes of the corresponding monomers which will be denoted as PC4BU and PC4HU, respectively, for later discussion.

Due to its low penetration power, UV irradiation is known to lead to only surface reaction on the solid. To obtain higher

Scheme 1. Reagents and Conditions[a]



[a] Key: (i) Propargyl bromide, K_2CO_3, CH_3CN, reflux for $n = 2$ and 4; $Ba(OH)_2{\cdot}8H_2O$, BaO, THF, reflux for $n = 3$; (ii) NaH, propyl bromide, THF, Reflux; (iii) I_2, morpholine, toluene; (iv) CuI, pyrrolidine; (v) R−N=C=O, dibutyltindilaurate, THF.

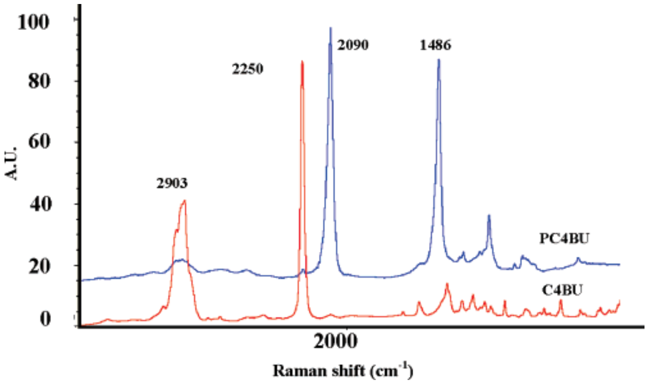


Figure 4. FT-Raman spectra of C4BU and PC4BU (in KBr).

Table 1. Color Change of *tert*-Butylcalix[4]arene Derivatives Containing Four Diyne Units upon Exposure to UV Irradiation for 30 min

Compound	Color			
	Before irradiation		After irradiation	
C4A	white		white	
C4BU	white		red	
C4HU	white		red	
C4PU	light yellow		yellow	

Table 2. Dispersion of PC4BU in Tetrahydrofuran and *N*,*N*-Dimethylformamide under Sonication and the Storage Stability of the Dispersion

Solvent	Appearance		
	Before sonication	After sonication	After 2 month in refrigerator
Tetrahydrofuran			
N,*N*-Dimethylformamide			

yields of PC4BU and PC4HU for a more definitive characterization, the polymerization was conducted by exposing C4BU and C4HU to 50 Mrad of γ radiation from ^{60}Co. The resulting deep red polymerized solid was dissolved in tetrahydrofuran with the assistance of ultrasonication. The red solution was filtered through a 0.45 μm cellulose acetate filter and concentrated under reduced pressure. The concentrated crude was dropped into methanol at room temperature to give a red insoluble precipitate. The precipitate was collected by filtration and dried under vacuum to afford pure red polydiacetylene (45% yield for PC4BU).

Raman scattering spectroscopy has been one of the most effective techniques to unambiguously characterize the ene−yne conjugation of polydiacetylenes especially for the insoluble polymers. The FT-Raman spectra of C4BU and PC4BU powders are shown in Figure 4. The spectrum of C4BU has a single C≡C stretching peak at 2250 cm^{-1} associated with the internal diyne groups. The C≡C stretching peak shifts to lower energy at 2090 cm^{-1} in the spectrum of PC4BU and a new C═C stretching peak appears at 1486 cm^{-1}, confirming the presence of ene−yne conjugation in the red PC4BU powder.

Initially, PC4BU appeared to be insoluble in all solvents tested. The polymer however formed clear red solution when sonicated in dimethylformamide or tetrahydrofuran for 5 min. The solution (5% w/w) was stable upon standing in refrigerator for months without noticeable precipitation as shown in Table 2. The electronic spectra of C4BU and PC4BU in tetrahydrofuran are shown in Figure 5 (For clarity sake, the similar spectra of C4HU and PC4HU are not included in the figure.) The spectrum of C4BU has no visible absorption, while that of PC4BU shows a broad absorption band in the range of 350−620 nm with maximum absorption peaks at 440 and 560 nm.

Due to the rigidity of the preorganized *tert*-butylcalix[4]arene platform, the topological 1,4-addition polymerization of the four diyne units of C4BU is most likely to proceed through a parallel intramolecular 1,4-addition (Scheme 2). The observation of polydiacetylene from C4BU thus provided us the first evidence of the intramolecular 1,4-addition of diynes. The resulting polydiacetylene also possesses intriguing molecular architecture containing a parallel conjugated ene−yne backbone with *tert*-butylcalix[4]arene as hollow side chains.

The good solubility of PC4BU and PC4HU in tetrahydrofuran indicated that the polymers were not crosslinked and allowed the molecular weight determination by gel permeation chromatography (GPC). The molecular weights of PC4BU and PC4HU were determined from the tetrahydrofuran eluted GPC chromatograms calculated against polystyrene standards using a universal calibration method. The GPC chromatograms of the purified PC4BU and the crude PC4HU have common bimodal features (Figure 6). The monomer peak appearing in the chromatogram of crude PC4HU but not in the chromatogram of purified PC4BU indicates that the purification of the polymers by precipitation is effective. The number average molecular weights of PC4BU are 3.62×10^5 Da ($M_w/M_n = 1.08$) and 5.31×10^4 Da ($M_w/M_n = 1.13$), and those of PC4HU are 7.39 $\times 10^5$ Da ($M_w/M_n = 1.03$), 1.58×10^5 Da ($M_w/M_n = 1.03$), and 1.01×10^5 Da ($M_w/M_n = 1.15$).

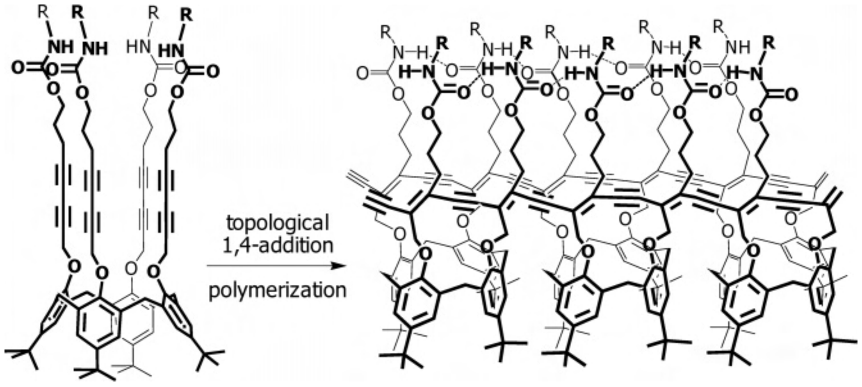
The inability to undergo topological polymerization of C4A indicated the importance of the carbamate group present at the movable end of the diyne chains. The strong hydrogen bonds among the carbamate groups in C4BU and C4HU are important for restraining the diyne units in an appropriate packing for topological polymerization. However, C4PU was also photoinactive despite having four carbamate groups probably due to the steric bulkiness of the phenyl end groups, preventing the intimate packing of the diyne chains.

Solid-State Polymerization of *tert*-Butylcalix[4]arene Containing Two and Three Diyne Units. The C2BU powder did not change its color while the color of C3BU powder changed to orange upon exposure to UV light. These results suggested that C2BU is photoinactive while C3BU can topologically polymerize somewhat but not as extensive as C4BU does. The difference in topological polymerizability of *tert*-butylcalix[4]arene containing different number of diyne units maybe explained by the molecular packing in the solid state of the monomers. For C4BU to be effectively polymerized topologically, the calix[4]arene cones must arrange themselves in the same direction that will allow the diyne units to align side by side. This arrangement can be continued for at least in each row of C4BU molecules and can be attributed to inter- and intramolecular hydrogen bonding among the carbarmate groups (Scheme 3). For C3BU, the same molecular arrangement is subjected to the possibility of some defects because of one missing diyne unit per each monomeric molecule. The topological polymerization of C3BU thus cannot proceed very far. With two diyne units missing, C2BU will not have any continuous alignment of the diyne units beyond two consecutive units, and thus its topological polymerization is totally forbidden. This packing analysis confirms that the topological polymerization of C4BU operates through parallel or antiparallel 1,4-addition involving both inter- and intramolecular reactions.

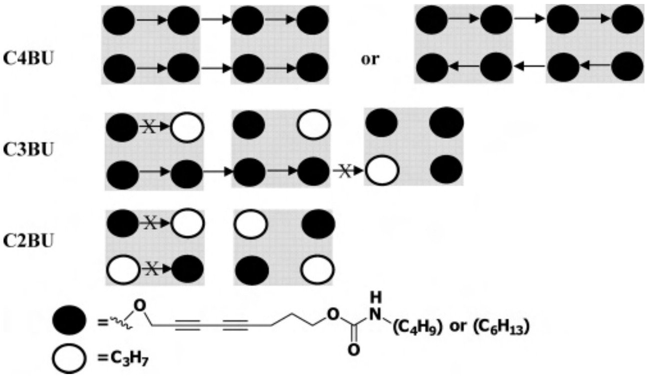
Conclusion

The derivatives of *tert*-butylcalix[4]arene containing two, three, and four diyne units were successfully synthesized. Only the derivatives that contain four diyne with *N*-alkyl carbamate moieties readily undergo solid-state topological photopolymerization to give ene−yne conjugated polydiacetylenes. The presence of carbamate groups is necessary for aligning the diynes through their continuous hydrogen bonding. The replacement one or two diyne units with a simple alkyl chain results

Scheme 2. Proposed Topological 1,4-Addition Polymerization of *tert*-Butylcalix[4]arene Containing Four Diyne Units



Scheme 3. Top View of the Proposed Molecular Packing Patterns in the Solid State of C4BU, C3BU, and C2BU[a]



[a] The arrow indicates the direction of the topological polymerization and X indicates the mismatched pair of the substituents to undergo the topological polymerization.

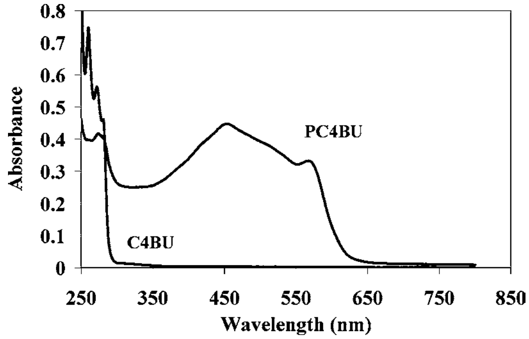


Figure 5. UV−vis spectra of 2.5 mM C4BU and 0.05 mM PC4BU in tetrahydrofuran.

in the reduction of the molecular symmetry and hence the topological polymerizability of the compound. The polymerizability of the tetradiyne derivatives provides not only the first evidence of the intramolecular 1,4-addition of diynes but also a route to synthesize some novel polydiacetylenes with interesting molecular architecture.

Experimental Section

Materials. Propargyl bromide, iodine, morpholine, copper(I) iodide, pyrrolidine, propyl bromide, sodium hydride, potassium carbonate, barium oxide, barium hydroxide octahydrate, triethylamine, and butylamine were purchased from Fluka (Switzerland). Dibutyltindilaurate, 4-pentyn-1-ol, butylamine, hexyl isocyanate, phenyl isocyanate, and triphosgene were purchased from Aldrich (USA). Butyl isocyanate was purchased from Merck (Germany) and used without further purification. *tert*-butylcalix[4]arene was prepared according to the literature.[22] Tetrahydrofuran was distilled over sodium and benzophenone, and acetonitrile was distilled over calcium hydride and stored over molecular sieves. Other analytical grade solvents were used as received without further distillation. Unless otherwise noted, all reactions were carried out under nitrogen atmosphere. Column chromatography was performed using Merck silica gel 60 (70−230 mesh).

Analytical Instruments. ^{1}H spectra were recorded on Varian Mercury 400 MHz NMR spectrometer (Varian, USA) and AC Bruker 200, 250, and 500 MHz NMR spectrometer (Bruker, USA) using the residual solvent proton resonance of $CDCl_3$ at 7.26 ppm as the reference. ^{13}C NMR spectra were recorded on the same instruments as ^{1}H NMR and the data are provided in Supporting Information. Elemental analysis was performed on PE 2400 Series II (Perkin-Elmer, USA). Infrared spectra (data provided in Supporting Information) were measured from KBr pellets on a Nicolet Impact 410 FT-IR spectrophotometer (Thermo Nicolet, USA). UV−vis spectra were recorded on Varian Cary 100 Bio UV−vis spectrophotometer (Varian, USA). The melting points were recorded on a Mettler Toledo DSC 823e (Mettler Toledo, USA) instrument with an aluminum standard cell (40 μL) as a holder at a heating rate of 10 °C/min. The FT-Raman experiments were performed by exciting neat solid samples with a cw Nd:YAG laser at 1.064 μm, and the Raman spectra were recorded on the same IR spectrometer with Raman accessories using 180° optical collection geometry. GPC analysis was measured on a Water system (Waters, USA) with a Water 600 pump, a Water 2414 refractive index detector, and a set of Styragel columns (HR1, HR3, and HR4) at 35 °C using tetrahydrofuran as an eluent at a flow rate of 1.00 mL/min.

Synthesis Procedures. *25,27-Dipropagyloxy-26,28-dihydroxy-tert-butylcalix[4]arene (**1**).* A mixture of potassium carbonate (1.71 g, 12.34 mmol) and *tert*-butylcalix[4]arene (4.01 g, 6.18 mmol) in acetonitrile (200 mL) was stirred at room temperature for 1 h. A solution of propargyl bromide (1.24 g, 12.98 mmol) in acetonitrile (50 mL) was added dropwise into the stirred mixture over 30 min. The reaction mixture was refluxed for 48 h and was then allowed to cool to room temperature. The reaction mixture was filtered to remove insoluble particles, and the filtrate was concentrated in a rotating evaporator. To the concentrated reaction mixture was added 2 M HCl (100 mL) and then extracted with dichloromethane (3 × 100 mL). The combined organic extracts were washed with brine (100 mL), dried over anhydrous Na_2SO_4, filtered, and evaporated to dryness in vacuo. The crude mixture was crystallized from CH_2Cl_2/CH_3OH to afford **1** as a white solid (3.72 g, 83% yield). Mp: 232 °C (decomposed). ^{1}H NMR (200 MHz, $CDCl_3$): δ 7.13 (s, 4H, Ar-*H*), 6.78 (s, 4H, Ar-*H*), 6.55 (s, 2H, OH), 4.80 (d, $J = 4.0$ Hz, 4H, OCH_2), 4.42 (d, $J = 14.0$ Hz, 4H, $ArCH_2Ar$), 3.38 (d, $J = 14.0$ Hz, 4H, $ArCH_2Ar$), 2.58 (t, $J = 4.0$ Hz, 2H, $C\equiv CH$), 1.35 (s, 18H, $(CH_3)_3$), 0.94 (s, 18H, $(CH_3)_3$).

*25,26,27-Tripropargyloxy-28-hydroxy-tert-butylcalix[4]arene (**2**).* A mixture of $Ba(OH)_2{\cdot}8H_2O$ (3.66 g, 11.60 mmol), BaO (1.02 g, 6.63 mmol), and *tert*-butylcalix[4]arene (2.15 g, 3.31 mmol) were dissolved in tetrahydrofuran (50.0 mL), and the solution was stirred at room temperature for 1 h. A solution of propargyl bromide (4.93 g, 33.0 mmol) in tetrahydrofuran (30 mL) was added dropwise into

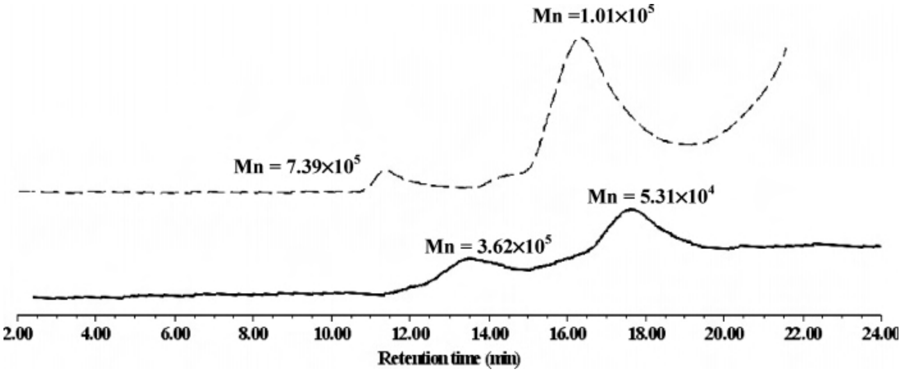


Figure 6. GPC traces of purified PC4BU (solid line) and crude PC4HU (dash line) using tetrahydrofuran as an eluent.

the stirred mixture over 30 min. The reaction mixture was refluxed for 48 h and was then allowed to cool to room temperature. The reaction mixture was filtered to remove insoluble particles, and the filtrate was concentrated in a rotating evaporator. To the concentrated reaction mixture was added 2 M HCl (50 mL) and then extracted with dichloromethane (3 × 60 mL). The combined organic extracts were dried over anhydrous Na_2SO_4 and filtered, and the solvent was removed to give a brown oily residue. The residue was purified by column chromatography with dichloromethane/hexane (15/85) to give **2** as a white solid (67% yield, 1.69 g). Mp: 157 °C. ^1H NMR (200 MHz, $CDCl_3$): δ 7.18 (s, 2H, Ar-*H*), 7.13 (s, 2H, Ar-*H*), 6.63 (s, 2H, Ar-*H*), 6.59 (s, 2H, Ar-*H*), 5.83 (s, 1H, OH), 5.08 (d, *J* = 2.5 Hz, 2H, OCH_2), 4.70 (d, *J* = 3.0 Hz, 4H, OCH_2), 4.66 (d, *J* = 14.0 Hz, 2H, $ArCH_2Ar$), 4.43 (d, *J* = 14.0 Hz, 2H, $ArCH_2Ar$), 3.36 (d, *J* = 14.0 Hz, 2H, $ArCH_2Ar$), 3.27 (d, *J* = 14.0 Hz, 2H, $ArCH_2Ar$), 2.56 (t, *J* = 3.0 Hz, 2H, $C\equiv CH$), 2.50 (t, *J* = 2.5 Hz, 1H, $C\equiv CH$), 1.37 (s, 18H, $(CH_3)_3$), 0.90 (s, 9H, $(CH_3)_3$), 0.89 (s, 9H, $(CH_3)_3$).

*25,26,27,28-Tetra(propargyloxy)-tert-butylcalix[4]arene (**3**).* A mixture of potassium carbonate (43.37 g, 313.76 mmol) and *tert*-butylcalix[4]arene(10.18 g, 15.68 mmol) in acetonitrile (200 mL) was stirred at room temperature for 1 h. A solution of propargyl bromide (23.33 g, 156.88 mmol) in acetonitrile (50 mL) was added dropwise into the stirred mixture over 30 min. The reaction mixture was allowed to reflux for 48 h and then allowed to cool to room temperature. The reaction mixture was filtered to remove insoluble particles, and the filtrate was concentrated in a rotating evaporator. To the concentrated reaction mixture was added 2 M HCl (100 mL) and then extracted with dichloromethane (3 × 100 mL). The combined organic extracts were washed with brine (100 mL), dried over anhydrous Na_2SO_4, filtered, and evaporated to dryness in vacuo. The crude mixture was crystallized from CH_2Cl_2/CH_3OH to afford **3** as a white solid (10.68 g, 85% yield). Mp: 107 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 6.78 (s, 8H, Ar-*H*), 4.80 (d, *J* = 2.4 Hz, 8H, OCH_2), 4.60 (d, *J* = 13.2 Hz, 4H, $ArCH_2Ar$), 3.16 (d, *J* = 13.2 Hz, 4H, $ArCH_2Ar$), 2.48 (t, *J* = 2.4 Hz, 3H, $C\equiv CH$), 1.07 (s, 36H, $(CH_3)_3$).

*25,27-Dipropargyloxy-26,28-dipropyl-tert-butylcalix[4]arene (**4**).* **1** (1.03 g, 1.42 mmol) and NaH (0.40 g, 14.16 mmol), which was washed with hexane (3 × 10 mL), were dissolved in tetrahydrofuran (20 mL), and the solution was stirred at room temperature for 1 h. Then a solution of propyl bromide (1.74 g, 14.16 mmol) in tetrahydrofuran (20 mL) was added dropwise to the above mixture. After the addition was complete, the reaction mixture was allowed to reflux for 24 h. The reaction mixture was then allowed to cool to room temperature and quenched with ethanol (20 mL). The solvent was removed in vacuo to obtain a yellow residue, and then the residue was extracted with dichloromethane (3 × 30 mL). The combined organic layers were washed with brine (50 mL), dried over anhydrous Na_2SO_4, and filtered, and the solvent was removed in vacuo to give a brown oily residue. The residue was isolated by column chromatography with dichloromethane as an eluent to afford **4** as a white solid (0.35 g, 31% yield). Mp: 190 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.09 (s, 4H, Ar-*H*), 6.45 (s, 4H, Ar-*H*), 5.02 (s, *J* = 2.4 Hz, 4H, OCH_2Ar), 4.52 (d, *J* = 12.0 Hz, 4H, $ArCH_2Ar$), 3.71 (t, *J* = 6.0 Hz, 4H, $CH_2CH_2CH_3$), 3.14 (d, *J* = 12.0 Hz, 4H, $ArCH_2Ar$), 2.39 (t, *J* = 2.4 Hz, 3H, $C\equiv CH$), 2.00 (m, 4H, $CH_2CH_2CH_3$), 1.33 (s, 18H, $(CH_3)_3$), 1.05 (t, *J* = 6.0 Hz, 6H, $CH_2CH_2CH_3$), 0.83 (s, 18H, $(CH_3)_3$).

*25,26,27-Tripropargyloxy-28-propyl-tert-butylcalix[4]arene (**5**).* **2** (0.93 g, 1.22 mmol) and NaH (0.15 g, 6.08 mmol), which was washed with hexane (3 × 10 mL), were dissolved in tetrahydrofuran (20 mL), and the solution was stirred at room temperature for 1 h. Then a solution of propyl bromide (0.75 g, 6.08 mmol) in tetrahydrofuran (20 mL) was added by dropwise to the above mixture. After the addition was complete, the reaction mixture was allowed to reflux for 24 h. The reaction mixture was then allowed to cool to room temperature and quenched with ethanol (20 mL). The solvent was removed in vacuo to obtain a yellow residue, and then the residue was extracted with dichloromethane (3 × 30 mL). The combined organic layers were washed with brine (50 mL), dried over anhydrous Na_2SO_4, and filtered, and the solvent was removed in vacuo to give a brown oily residue. The residue was isolated by column chromatography with dichloromethane as an eluent to afford **5** as a white solid (0.80 g, 82% yield). Mp: 140 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.00 (s, 2H, Ar-*H*), 6.98 (s, 2H, Ar-*H*), 6.60 (s, 2H, Ar-*H*), 6.54 (s, 2H, Ar-*H*), 4.98 (d, *J* = 2.4 Hz, 2H, $CH_2C\equiv C$), 4.89 (d, *J* = 2.4 Hz, 2H, $CH_2C\equiv C$), 4.63 (d, *J* = 2.0 Hz, 2H, $CH_2C\equiv C$), 4.59 (d, *J* = 12.5 Hz, 2H, $ArCH_2Ar$), 4.51 (d, *J* = 12.5 Hz, 2H, $ArCH_2Ar$), 3.76 (t, *J* = 7.4 Hz, 2H, $CH_2CH_2CH_3$), 3.17 (d, *J* = 5.6 Hz, 2H, $ArCH_2Ar$), 3.13 (d, *J* = 5.6 Hz, 2H, $ArCH_2Ar$), 2.4 (t, *J* = 2.0 Hz, 1H, $C\equiv CH$), 2.44 (t, *J* = 2.4 Hz, 2H, $C\equiv CH$), 2.00 (m, 2H, $CH_2CH_2CH_3$), 1.28 (s, 18H, $(CH_3)_3$), 1.07 (t, *J* = 7.4 Hz, 3H, $CH_2CH_2CH_3$), 0.96 (s, 9H, $(CH_3)_3$), 0.94 (s, 9H, $(CH_3)_3$).

5-Iodo-4-pentynol. A solution of morpholine (33.25 mL, 381.60 mmol) in toluene (350 mL) at 45 °C was treated with iodine (13.56 g, 53.42 mmol) shielded from light and stirred for 1 h. A solution of 4-pentyn-1-ol (3.21 g, 38.16 mmol) in toluene (30 mL) was added and the reaction mixture was stirred at 45 °C for 1 h. The reaction mixture was cooled to room temperature and filtered to remove the salt. The filtrate was poured over a mixture of diethylether (200 mL) and a saturated aqueous solution of $Na_2S_2O_3$ (100 mL) and shaken vigorously until the organic layer was colorless. The organic layer was separated, washed with $Na_2S_2O_3$ (100 mL), dried over anhydrous Na_2SO_4, filtered, concentrated, and purified by column chromatography (ethyl acetate/hexane = 7/93) to afford 5-iodo-4-pentynol as a light yellow oil (6.97 g, 87% yield). ^1H NMR (400 MHz, $CDCl_3$): δ 3.78 (t, *J* = 6.0 Hz, 2H, CH_2OH), 2.53 (t, *J* = 6.0 Hz, 2H, $C\equiv CCH_2$), 1.80 (quintet, *J* = 6.0 Hz, 2H, $CH_2CH_2CH_2OH$), 1.61 (br s, 1H, OH).

25,27-Di(octa-4,6-diyn-1-ol)oxy-26,28-dipropyl-tert-butylcalix[4]arene (C2A). To a stirred solution of **4** (0.22 g, 0.27 mmol) and 5-iodo-4-pentynol (0.28 g, 1.34 mmol) in pyrrolidine (1.0 mL) was added copper(I) iodide (0.01 g, 0.05 mmol). After the reaction mixture was stirred at room temperature for 2 h, it was hydrolyzed with a saturated aqueous solution of ammonium chloride (30 mL) and extracted with diethyl ether (3 × 50 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and filtered, and the solvent was removed in vacuo. The crude product was purified by column chromatography (dichloromethane/ethyl acetate = 10/90) to obtain C2A as a light yellow solid (0.10 g, 38% yield). Mp: 168 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 7.09 (s, 4H, Ar-*H*), 6.43 (s, 4H, Ar-*H*), 5.01 (s, 4H, OC*H*$_2$C≡C), 4.48 (d, *J* = 13.6 Hz, 4H, ArC*H*$_2$Ar), 3.76 (t, *J* = 6.0 Hz, 4H, C*H*$_2$CH$_2$CH$_3$), 3.71 (t, *J* = 7.5 Hz, 4H, C*H*$_2$OH), 3.14 (d, *J* = 13.6 Hz, 4H, ArC*H*$_2$Ar), 2.43 (t, *J* = 7.5 Hz, 4H, C*H*$_2$CH$_2$CH$_2$OH), 2.00 (m, 4H, CH$_2$C*H*$_2$CH$_3$), 1.81 (quintet, *J* = 7.5 Hz, 4H, C*H*$_2$CH$_2$OH), 1.33 (s, 18H, (C*H*$_3$)$_3$), 1.05 (t, *J* = 6.0 Hz, 6H, CH$_2$CH$_2$C*H*$_3$), 0.82 (s, 18H, (C*H*$_3$)$_3$).

25,26,27-Tri(octa-4,6-diyn-1-ol)oxy-28-propyl-tert-butylcalix[4]-arene (C3A). To a stirred solution of **5** (0.24 g, 0.30 mmol) and 5-iodo-4-pentynol (0.36 g, 1.79 mmol) in pyrrolidine (2.00 mL) was added copper(I) iodide (0.02 g, 0.08 mmol). After the reaction mixture was stirred at room temperature for 2 h, it was hydrolyzed with a saturated aqueous solution of ammonium chloride (30 mL) and extracted with diethyl ether (3 × 50 mL). The combined organic layers were dried over anhydrous Na$_2$SO$_4$ and filtered, and the solvent was removed in vacuo. The crude product was purified by column chromatography (dichloromethane/ethyl acetate = 50/50) to give C3A as a light yellow solid (0.18 g, 58% yield). Mp: 145 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 7.00 (s, 4H, Ar-*H*), 6.58 (s, 2H, Ar-*H*), 6.51 (s, 2H, Ar-*H*), 5.01 (s, 2H, C*H*$_2$C≡C), 4.87 (s, 2H, C*H*$_2$C≡C), 4.71 (s, 2H, C*H*$_2$C≡C), 4.55 (d, *J* = 12.5 Hz, 2H, ArC*H*$_2$Ar), 4.46 (d, *J* = 12.5 Hz, 2H, ArC*H*$_2$Ar), 3.76 (m, 8H, C*H*$_2$CH$_2$CH$_3$ and C*H*$_2$OH), 3.17 (d, *J* = 6.4 Hz, 2H, ArC*H*$_2$Ar), 3.14 (d, *J* = 6.4 Hz, 2H, ArC*H*$_2$Ar), 2.44 (t, *J* = 6.6 Hz, 6H, C*H*$_2$-CH$_2$CH$_2$OH), 2.00 (m, 4H, CH$_2$C*H*$_2$CH$_3$), 1.81 (m, 6H, C*H*$_2$CH$_2$-OH), 1.25 (s, 18H, (C*H*$_3$)$_3$), 1.08 (t, *J* = 7.4 Hz, 3H, CH$_2$CH$_2$C*H*$_3$), 0.92 (s, 9H, (C*H*$_3$)$_3$), 0.87 (s, 9H, (C*H*$_3$)$_3$).

25,26,27,28-Tetra(octa-4,6-diyn-1-ol)oxy-tert-butylcalix[4]-arene (C4A). To a stirred solution of **3** (4.18 g, 5.22 mmol), and 5-iodo-4-pentynol (10.96 g, 52.18 mmol) in pyrrolidine (40.00 mL) was added copper(I) iodide (0.40 g, 2.09 mmol). After the reaction mixture was stirred at room temperature for 2 h, it was hydrolyzed with a saturated aqueous solution of ammonium chloride (200 mL) and extracted with diethyl ether (3 × 150 mL). The combined organic layers were dried over anhydrous Na$_2$SO$_4$ and filtered, and the solvent was removed in vacuo. The crude product was purified by column chromatography (ethyl acetate) to afford C4A as a light yellow solid (2.73 g, 51% yield). Mp: 212 °C (decomposed). ^{1}H NMR (400 MHz, CDCl$_3$): δ 6.77 (s, 8H, Ar-*H*), 4.82 (s, 8H, OC*H*$_2$), 4.53 (d, *J* = 13.2 Hz, 4H, ArC*H*$_2$Ar), 3.77 (t, *J* = 7.0 Hz, 8H, C*H*$_2$OH), 3.17 (d, *J* = 13.2 Hz, 4H, ArC*H*$_2$Ar), 2.45 (t, *J* = 7.0 Hz, 8H, C≡CC*H*$_2$), 1.90 (bs, 1H, OH), 1.81 (quintet, *J* = 7.0 Hz, 8H, CH$_2$C*H*$_2$CH$_2$), 1.07 (s, 36H, (C*H*$_3$)$_3$).

Urethane Formation of C2BU and C3BU. *General Procedure for Synthesis.*

Butylamine was dissolved in chloroform. Triphosgene was gradually added to this solution with stirring. Triethylamine was added dropwise to this stirred mixture (a water bath may be needed to keep the temperature below 30 °C). The reaction mixture was refluxed for 2 h before diacetylenic alcohol-*tert*-butylcalix[4]arene derivatives [C2A or C3A] and dibutyltindilaurate were added. The stirring was continued for 10 h at room temperature. The solvent was evaporated, and the residue was redissolved in hexane. The resulting solution was filtered, and the solid was washed several times with hexane. The filtrate was collected, and the solvent was evaporated. The residue was eluted through a silica gel column.

25,27-Di[octa-4,6-diyn-1-ol-(carboxy-butyl-urethane)]oxy-26,28-dipropyl-tert-butylcalix-[4]arene (C2BU). C2BU was synthesized according to the above urethane formation procedure from C2A (0.07 g, 0.07 mmol), butylamine (0.32 g, 4.32 mmol), triphosgene (0.43 g, 1.44 mmol), triethylamine (1.20 mL, 8.63 mmol), and dibutyltindilaurate (0.18 g, 0.29 mmol) in chloroform (10 mL) and purified by column chromatography (ethyl acetate/dichloromethane = 1/99). A light yellow solid (0.05 g, 55% yield) was obtained. Mp: 100 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 7.09 (s, 4H, Ar-*H*), 6.42 (s, 4H, Ar-*H*), 5.01 (s, 4H, OC*H*$_2$C≡C), 4.69 (br s, 2H, NH), 4.48 (d, *J* = 13.6 Hz, 4H, ArC*H*$_2$Ar), 4.12 (t, *J* = 5.8 Hz, 4H, OCOC*H*$_2$), 3.70 (t, *J* = 6.0 Hz, 4H, C*H*$_2$CH$_2$CH$_3$), 3.14 (m, *J* = 13.6 Hz, 8H, ArC*H*$_2$Ar and NC*H*$_2$), 2.38 (t, *J* = 6.6 Hz, 4H, C≡CC*H*$_2$), 2.00 (m, 4H, CH$_2$C*H*$_2$CH$_3$), 1.84 (quintet, *J* = 5.8 Hz, 4H, C≡CCH$_2$C*H*$_2$), 1.47 (m, 4H, CH$_2$C*H*$_2$CH$_2$CH$_3$), 1.32 (s, 18H, (C*H*$_3$)$_3$), 1.05 (t, *J* = 6.0 Hz, 6H, CH$_2$CH$_2$C*H*$_3$), 0.92 (m, 6H, CH$_2$-CH$_2$CH$_2$C*H*$_3$), 0.81 (s, 18H, (C*H*$_3$)$_3$). Anal. Calcd for $C_{76}H_{102}N_2O_8$: C, 77.91; H, 8.77; N, 2.89. Found: C, 76.28; H, 8.43; N, 3.19.

25,26,27-Tri[octa-4,6-diyn-1-ol-(carboxy-butyl-urethane)]oxy-28-propyl-tert-butylcalix[4]arene (C3BU). C3BU was synthesized according to the above urethane formation procedure from C3A (0.07 g, 0.07 mmol), butylamine (0.07 g, 1.00 mmol), triphosgene (0.10 g, 0.30 mmol), triethylamine (0.28 mL, 2.00 mmol), and dibutyltindilaurate (0.13 g, 0.21 mmol) in chloroform (10 mL) and purified by column chromatography (ethyl acetate/hexane = 15/85). A light yellow solid (0.03 g, 32% yield) was obtained. Mp: 117 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 7.00 (s, 4H, Ar-*H*), 6.56 (s, 2H, Ar-*H*), 6.50 (s, 2H, Ar-*H*), 4.99 (s, 2H, OC*H*$_2$C≡C), 4.88 (s, 2H, OC*H*$_2$C≡C), 4.80 (br s, 3H, NH), 4.70 (s, 2H, OC*H*$_2$C≡C), 4.54 (d, *J* = 13.0 Hz, 2H, ArC*H*$_2$Ar), 4.47 (d, *J* = 13.0 Hz, 2H, ArC*H*$_2$Ar), 4.12 (t, *J* = 5.6 Hz, 6H, C*H*$_2$OCO), 3.74 (t, 2H, C*H*$_2$CH$_2$CH$_3$), 3.15 (m, 10H, ArC*H*$_2$Ar and NHC*H*$_2$), 2.39 (t, *J* = 6.4 Hz, 6H, C*H*$_2$CH$_2$CH$_2$OCO), 2.03 (m, 4H, CH$_2$C*H*$_2$CH$_3$), 1.86 (m, 6H, C*H*$_2$CH$_2$OCO), 1.47 (m, 6H, CH$_2$C*H*$_2$CH$_2$CH$_3$), 1.34 (m, 6H, CH$_2$CH$_2$C*H*$_2$CH$_3$), 1.25 (s, 18H, (C*H*$_3$)$_3$), 1.07 (m, 9H, CH$_2$-CH$_2$CH$_2$C*H*$_3$), 0.91 (s, 9H, (C*H*$_3$)$_3$), 0.86 (s, 9H, (C*H*$_3$)$_3$). Anal. Calcd for $C_{86}H_{113}N_3O_{10}$: C, 76.58; H, 8.44; N, 3.12. Found: C, 74.40; H, 7.71; N 3.21.

Urethane Formation of C4BU, C4HU, and C4PU. *General Procedure for Synthesis.* Diacetylenic alcohol-*tert*-butylcalix[4]arene derivatives and dibutyltindilaurate were dissolved in tetrahydrofuran, and R— N═C═O (commercially available) was added dropwise to this solution with stirring at 0 °C. The mixture was allowed to warm up to room temperature and the stirring was continued for another 2 h before ice/water was added. Tetrahydrofuran was evaporated, and the aqueous residue was extracted several times with CH$_2$Cl$_2$ and brine. The combined organic layers were dried over anhydrous Na$_2$SO$_4$ and filtered, and the solvent was removed in vacuo. The crude product was eluted through a silica gel column.

25,26,27,28-Tetra[octa-4,6-diyn-1-ol-(carboxy-butyl-urethane)]-oxy-tert-butylcalix[4]arene (C4BU). C4BU was synthesized according to the above urethane formation procedure from C4A (0.85 g, 0.75 mmol), butyl isocyanate (0.75 g, 7.53 mmol), and dibutyltindilaurate (1.90 g, 3.01 mmol) in tetrahydrofuran (20 mL) and purified by column chromatography (ethyl acetate/hexane = 45/55). A white solid (0.96 g, 84% yield) was obtained. Mp: 119 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 6.77 (s, 8H, Ar-*H*), 4.82 (s, 8H, OC*H*$_2$ and NH), 4.53 (d, *J* = 13.2 Hz, 4H, ArC*H*$_2$Ar), 4.13 (t, *J* = 5.8 Hz, 8H, OCOC*H*$_2$), 3.17 (m, 12H, ArC*H*$_2$Ar and NC*H*$_2$), 2.39 (t, *J* = 6.8 Hz, 8H, C≡CC*H*$_2$CH$_2$), 1.87 (quintet, *J* = 6.0 Hz, 8H, C≡CCH$_2$C*H*$_2$), 1.47 (quintet, *J* = 6.6 Hz, 8H, CH$_2$C*H*$_2$CH$_2$CH$_3$), 1.33 (m, 8H, C*H*$_2$CH$_3$), 1.06 (s, 36H (C*H*$_3$)$_3$), 0.95 (t, *J* = 7.4 Hz, 12H, C*H*$_3$). Anal. Calcd for $C_{96}H_{124}N_4O_{12}$: C, 75.56; H, 8.19; N, 3.67. Found: C, 75.58; H, 8.39; N 3.65. Raman: 2250 cm^{-1} (—C≡C—C≡C—).

25,26,27,28-Tetra[octa-4,6-diyn-1-ol-(carboxy-hexyl-urethane)]-oxy-tert-butylcalix[4]arene (C4HU). C4HU was prepared as described above from C4A (0.54 g, 0.48 mmol), butyl isocyanate (0.61 g, 4.78 mmol), and dibutyltindilaurate (1.21 g, 1.91 mmol) in tetrahydrofuran (15 mL) and purified by column chromatography (ethyl acetate/hexane = 27/73). A white solid (0.35 g, 45% yield) was obtained. Mp: 103 °C. ^{1}H NMR (400 MHz, CDCl$_3$): δ 6.76 (s, 8H, Ar-*H*), 4.91 (br s, NH), 4.80 (s, 8H, OC*H*$_2$), 4.53 (d, *J* = 12.8 Hz, 4H, ArC*H*$_2$Ar), 4.12 (t, *J* = 6.0 Hz, 8H, C*H*$_2$OCO), 3.16 (d, *J* = 12.8 Hz, 4H, ArC*H*$_2$Ar), 3.12 (t, *J* = 6.0 Hz, 8H, NHC*H*$_2$), 2.38 (t, *J* = 6.4 Hz, 8H, C≡CC*H*$_2$), 1.85 (quintet, *J* = 6.4 Hz, 8H, C≡CCH$_2$C*H*$_2$), 1.47 (m, 8H, NHCH$_2$C*H*$_2$), 1.27 (m, 24H, C*H*$_2$C*H*$_2$C*H*$_2$-CH$_3$), 1.05 (s, 36H, (C*H*$_3$)$_3$), 0.87 (t, *J* = 6.2 Hz, 12H, C*H*$_3$). Anal. Calcd for $C_{104}H_{140}N_4O_{12}$: C, 76.25; H, 8.61; N, 3.42. Found: C, 76.24; H, 8.64; N 3.76.

25,26,27,28-Tetra[octa-4,6-diyn-1-ol-(carboxy-phenyl-urethane)]-oxy-tert-butylcalix[4]arene (C4PU). C4PU was prepared as described above from C4A (0.36 g, 0.32 mmol), phenyl isocyanate

(0.38 g, 3.19 mmol), and dibutyltindilaurate (0.81 g, 1.27 mmol) in tetrahydrofuran (15 mL) and purified by column chromatography (ethyl acetate/hexane = 22/78). A light yellow solid (0.33 g, 65% yield) was obtained. Mp: 107 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, $J = 8.0$ Hz, 8H, H_{ortho}-Ar), 7.28 (t, $J = 8.0$ Hz, 8H, H_{meta}-Ar), 7.04 (t, $J = 8.0$ Hz, 4H, H_{para}-Ar), 6.90 (br s, NH), 6.78 (s, 8H, H-Ar_{calix}), 4.82 (s, 8H, OCH_2), 4.54 (d, $J = 12.8$ Hz, 4H, $ArCH_2Ar$), 4.27 (t, $J = 6.0$ Hz, 8H, $OCOCH_2$), 3.18 (d, $J = 12.8$ Hz, 4H, $ArCH_2Ar$), 2.44 (t, $J = 7.0$ Hz, 8H, $C{\equiv}CCH_2$), 1.96 (m, 8H, $CH_2CH_2CH_2$), 1.06 (s, 36H, $(CH_3)_3$). Anal. Calcd for $C_{104}H_{108}N_4O_{12}$: C, 77.78; H, 6.78; N, 3.49. Found: C, 77.39; H, 6.78; N 3.24.

Poly(25,26,27,28-Tetra[octa-4,6-diyn-1-ol-(carboxy-butyl-urethane)]oxy-*tert*-butylcalix[4]arene) (PC4BU). The monomer C4BU (50 mg) was exposed to 50 Mrad of γ radiation from ^{60}Co. The resulting deep red polymerized solid was dissolved in 20 mL tetrahydrofuran with the assistance of ultrasonication. The red solution was filtered through a 0.45 μm cellulose acetate filter and concentrated to 2 mL under reduced pressure. The concentrated crude was dropped into methanol (100 mL) and stirred for 2 h at room temperature to give a red precipitate. The precipitate was collected by filtration and dried under vacuum to afford pure red polydiacetylene (23 mg, 45% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.05 (br, 8H), 6.77 (br, 8H), 4.97 (br, 8H), 4.82 (br, 8H), 4.54 (br, 8H), 4.15 (br), 4.00 (br), 3.12 (br), 2.39 (br, 8H), 1.66−0.90 (br). Raman: 2090 cm^{-1} ($-C{\equiv}C-$), 1486 cm^{-1} ($-C{=}C-$).

Acknowledgment. We are thankful for the financial support from the Thailand Research Fund, Commission on Higher Education (Grant Nos. PHD/0040/2546 and RMU4980024) and the Petroleum Research Fund (Grant No.40263-AC7). We also would like to thank the Office of Atoms for Peaces, Thailand and the University of Massachusetts Lowell, U.S.A. for their permission to use the ^{60}Co irradiator.

Supporting Information Available: Preparation procedures and full spectroscopic data of all compounds synthesized. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Tajima, K.; Aida, T. *Chem. Commun.* **2000**, 2399.

(2) (a) Tachibana, H.; Kumai, R.; Hosaka, N.; Tokura, Y. *Chem. Mater.* **2001**, *13*, 155. (b) Goroff, N. S.; Curtis, S. M.; Webb, J. A.; Fowler, F. W.; Lauher, J. W. *Org. Lett.* **2005**, *7*, 1891. (c) Enkelmann, V. *Chem. Mater*. **1994**, *6*, 1337. (d) Ouyang, X.; Fowler, R. W.; Lauher, J. W. *J. Am. Chem. Soc.* **2003**, *125*, 12400. (e) Carre, F.; Devylder, N.; Dutremez, S. G.; Guerin, C.; Henner, B. J. L.; Jolivet, A.; Tomberli, V. *Organometallics* **2003**, *22*, 2014.

(3) (a) Yoon, J.; Kyun, S. K.; Kim, J. M. *J. Am. Chem. Soc.* **2007**, *129*, 3038. (b) Dermody, D. L.; Lee, Y.; Kim, T.; Crooks, R. M. *Langmuir* **1999**, *15*, 8435.

(4) (a) Charych, D. H.; Nagy, J. O.; Spevak, W.; Bednarski, M. D. *Science* **1993**, *261*, 585. (b) Pan, J. J.; Charych, D. Langmuir **1997**, *13*, 1365. (c) Huo, Q.; Russell, K. C.; Leblanc, R. M. *Langmuir* **1999**, *15*, 3972. (d) Ma, G.; Cheng, Q. *Langmuir*, **2005**, *21*, 6123.

(5) (a) Fomine, S.; Adem, E.; Ogawa, E.; Rao, D. V. G. L. N. *Polym. Bull.* **1995**, *34*, 169. (b) He, J. N.; Yang, K.; Kumar, J.; Tripathy, S. K.; *J. Phys. Chem. B* **1999**, *103*, 11050.

(6) Chan, K. C.; Kim, T.; Schoer, J. K.; Crooks, R. M. *J. Am. Chem. Soc.* **1995**, *117*, 5875.

(7) (a) Song, J.; Cheng, Q.; Kopta, S.; Stevens, R. C. *J. Am. Chem. Soc.* **2001**, *123*, 3205. (b) Cheng, Q.; Stevens, R. C. *Langmuir* **1998**, *14*, 1974. (c) Huo, Q.; Russell, K. C.; Leblanc, R. M. *Langmuir* **1999**, *15*, 3972. (d) Lio, A.; Reichert, A.; Ahn, D. J.; Nagy, J. O.; Salmeron, M.; Charych, D. H. *Langmuir* **1997**, *13*, 6524.

(8) Yang, Y.; Lu, Y.; Lu, M.; Huang, J.; Haddad, R.; Xomeritakis, G.; Liu, N.; Malanoski, A. P.; Sturmayr, D.; Fan, H.; Sasaki, D. Y.; Assink, R. A.; Shelnutt, J. A.; van Swol, F.; Lopez, G. P.; Burns, A. R.; Brinker, C. J. *J. Am. Chem. Soc.* **2003**, *125*, 1269.

(9) (a) Baughman, R. H. *J. Polym. Sci., Part B: Polym. Phys.* **1974**, *12*, 1511. (b) Baughman, R. H.; Yee, K. C. *J. Polym. Sci., Part D: Macromol. Rev.* **1978**, *13*, 248.

(10) Lim, C.; Sandman, D. J.; Sukwattanasinitt, M.; Foxman, B. M. *J. Macromol. Sci., Pure Appl. Chem.* **2006**, *43*, 1929.

(11) Nadizadeh, H.; Mattern, D. L. *Chem. Mater.* **1994**, *6*, 268.

(12) (a) Pipoosananakaton, B.; Sukwattanasinitt, M.; Jaiboon, N.; Chaichit, N.; Tuntulani, T. *Tet. Lett.* **2000**, *41*, 9095. (b) Rojanathanes, R.; Tuntulani, T.; Bhanthumnavin, W.; Sukwattanasinitt, M. *Org. Lett.* **2005**, *16*, 3401. (c) Jaiyu, A.; Rojanathanes, R.; Sukwattanasinitt, M. *Tet. Lett.* **2007**, *48*, 1817.

(13) (a) Thallapally, P. K.; Dalgarno, S. J.; Atwood, J. L. *J. Am. Chem. Soc.* **2006**, *128*, 15060. (b) Casnati, A.; Sansone, F.; Ungaro, R. *Acc. Chem. Res.* **2003**, *36*, 246. (c) Kim, S. J.; Jo, M. G.; Lee, J. Y.; Kim, B. H. *Org. Lett.* **2004**, *6*, 1963.

(14) Dermody, D. L.; Crooks, R. M.; Kim, T. *J. Am. Chem. Soc.* **1996**, *118*, 11912.

(15) Gutsche, C. D. *Calix[4]arene*; Stoddart, J. F., Ed.; The Royal Society of Chemistry: Cambridge, U.K., 1989; Vol. 1.

(16) For selection of bases used in the double *O*-alkylation see (a) Iwamoto, K.; Shimizu, H.; Araki, K.; Shinkai, S. *J. Am. Chem. Soc.* **1993**, *115*, 3997. (b) Reddy, P. A.; Gutsche, C. D. *J. Org. Chem.* **1991**, *56*, 4783.

(17) For selection of bases used in the triple *O*-alkylation see (a) Tuntulani, T.; Thavornyutikarn, P.; Poompradub, S.; Jaiboon, N.; Ruangpornvisuti, V.; Chaichit, N.; Asfari, Z.; Vicens, J. *Tetrahedron*, ***2002***, *58*, 10277. (b) Iwamoto, K.; Shimizu, H.; Araki, K.; Shinkai, S. *J. Am. Chem. Soc.* **1993**, *115*, 3997.

(18) For selection of bases used in the quadruple *O*-alkylation see Xu, W.; Vittal, J. J.; Puddephatt, R. J. *Can. J. Chem.* **1996**, *74*, 766.

(19) (a) Alami, M.; Ferri, F. *Tet. Lett.* **1996**, *37*, 2763. (b) Lopez, S.; Trillo, F. F.; Midon, P.; Castedo, L.; Saa, C. *J. Org. Chem.* **2005**, *70*, 6346.

(20) (a) Banfi, L.; Guanti, G. *Eur. J. Org. Chem.* **1998**, *1998*, 1543. (b) Bruce, M. I.; Skelton, B. W.; Smith, M. E.; White, A. H. *Aust. J. Chem.* **1999**, *52*, 431. (c) Yenjai, C.; Isobe, M. *Tetrahedron*, **1998**, *54*, 2509.

(21) Sukwattanasinitt, M.; Lee, D. C.; Kim, M.; Wang, X.; Li, L.; Yang, K.; Kumar, J.; Tripathy, S. K.; Sandman, J. *Macromolecules* **1999**, *32*, 7361.

(22) (a) Gutche, C. D.; Iqbal, M. *Org. Synth.* **1989**, *68*, 234. (b) Coplan, M. A.; Fuoss, R. M. *J. Phys. Chem.* **1964**, *68*, 1177.

MA0716128

X-ray guided ^{1}H NMR analysis of pinched cone calix[4]arenes

Paitoon Rashatasakhon,[a] Arisa Jaiyu,[a] Rojrit Rojanathanes,[a] Nongnuj Muangsin,[a] Narongsak Chaichit[b] and Mongkol Sukwattanasinitt[ac*]

[a]*Organic Synthesis Research Unit, Department of Chemistry, Faculty of Science, Chulalongkorn University, Phyathai Rd., Pathumwan, Bangkok 10330, Thailand,* [b]*Department of Chemistry, Faculty of Science, Thammasat University at Rangsit, Pathumthani 12121, Thailand, and* [c]*Center for Petroleum, Petrochemicals and Advanced Materials, Chulalongkorn University, Bangkok 10330, Thailand. E-mail: smongkol@chula.ac.th*

Synopsis Structural analyses of bridged calix[4]arenes by X-ray and AM1 calculation revealed that bridges longer than 7.0 Å considerably distort the conformation of calix[4]arene from the perfect cone to pinched cone with the average O-O distance greater than 3.0 Å. The distortion is well correlated with the significant upfield shift of ^{1}H NMR signals of the phenoxyl protons which can be used for quick identification of pinched cone conformation of new calix[4]arene compounds.

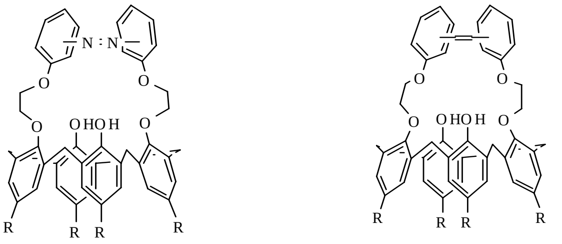
Abstract The analysis of structural parameters of azobenzene- and stilbene-bridged calix[4]arene obtained from AM1 calculation are in good agreement with those obtained from X-ray crystallography. The bridge longer than 9.0 Å such as *p,p-trans*-azobenzene and *p,p-trans*-stilbene cannot be constructed over the narrow rim of calix[4]arene through two ethylenoxide linkers. The *m,m*-stilbene bridge is the most promising photoswitch because its shorter *cis* stereoisomer (5.85 Å) allows calix[4]arene to assume the perfect cone conformation, whilst its longer *trans* stereoisomer (8.00 Å) forces calix[4]arene to adapt a pinched cone conformation. The pinched cone conformation has longer distances between the neighbouring phenoxyl groups causing the weaker intramolecular hydrogen bonding and the upfield shifts of the phenolic proton signals to below 7.00 ppm. This upfield shift is useful for quick identification of pinched cone conformation of new calix[4]arene compounds.

Keywords: Azobenzene, Calix[4]arene, Conformation, Host-guest Complex, Isomer

Supramolecular interaction is the vital initial process triggering biological and chemical events. Studies on binding between converging sites of synthetic hosts with diverging sites of guest molecules or ions have progressively provided valuable information towards understanding of the supramolecular interaction of complicated natural molecules.[1] Much attention has recently been paid to achieve the binding selectivity between the host and the guest molecules by controlling the size and shape of the binding cleft of the host molecule.[2] A host molecule that can controllably switch its binding selectivity as desired is rare[3] but extremely desirable for various applications including imitating biological events.

Owing to its pre-organized structure, calix[4]arene is one of the most established molecular platforms for constructing three-dimensional hosts for molecules or ions.[4] The structure of calix[4]arene consists of four phenol rings linked together with four methylene units in a circular fashion producing a basket like architecture.[5] Flipping one or more phenyl rings around the flexible methylene linkages allows calix[4]arene to exist in one or more of the four main conformers *viz.* cone, partial cone, 1,2–alternate and 1,3–alternate.[6] The cone conformer, which is the most stable conformation for unmodified calix[4]arene, has all four hydroxyl groups oriented along the same rim of the basket to maximize the intramolecular hydrogen bonding among them. If two of the four phenol rings are tilted over from the perfect circular alignment to adopt an oval–shaped basket, the resulting conformer is called a pinched cone.[7] The difference in the cavity shapes between cone and pinched cone provides an opportunity to regulate the selectivity of calix[4]arene hosts towards ionic or molecular guests. The guidelines for synthesis and analysis by ^{1}H-NMR of calix[4]arene derivatives for cone and 1,3-alternate conformers using alkali metal templates have been well established.[8] The use of aromatic proton signals in ^{1}H NMR have been proposed for discrimination between cone and pinched cone conformation of calix[4]arene.[9] Unfortunately, the unambiguous assignment of aromotic proton signals of calix[4]arenes are not viable for many derivatives, especially when the calix[4]arenes possess aromatic substituents.

We have previously reported the synthesis of calix[4]arene derivatives (**1-3**) containing a geometrically photoisomerizable bridge, azobenzene or stilbene, over its narrow rim.[10] The *meta* stilbene bridge is particularly of interest as the photo-switching between a binding and non-binding states of ***cis-m*-2** and ***trans-m*-2**.[11] The switching of the binding properties have been hypothesized as a result of the switching between a cone and pinched cone conformation of the calix[4]arene upon *cis/trans* photoizomerization of the stilbene bridge. The inability of ***m-trans-3*** to form 1,3-altermate conformation in the Cs^+ templated synthesis also implied its pinched conformation.[12] To reallize if a calix[4]arene derivative is in a pinched cone conformer, a single crystal of the compound was required for X-ray crystallography. We have re-examined the X-ray and AM1 geometry optimized structurres of these compounds that leads to guidelines for quick identification of pinched cone conformation by using NMR signals of phenolic protons of calix[4]arene as reported herein. Unlike the aromatic proton signals, the hydroxyl proton signals of calix[4]arenes can be readily assigned and confirmed by deuterium exchange with D_2O that is attractive to be used for quick discrimination of cone and pinched cone conformation of new calix[4]arene derivatives.



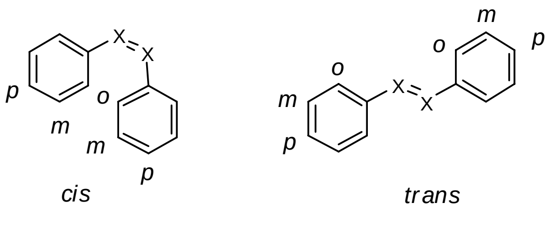
1: R= t-butyl

2: R= t-butyl
3: R= H

Figure 1 Structures of azobenzene bridged calix[4]arene and stilbene bridged calix[4]arenes.

Results and Discussion

The length of relatively rigid azobenzene and stilbene units can be calculated using simple computational routines for geometry optimization, such as AM1.[13] The calculated bridge length is dependent not only on the *cis/trans* geometrical isomers but also on the regio-positions where the bridge is connected (Table 1). The calculated unit length strongly supports the previous synthesis results. For azobenzene-bridged calix[4]arenes, only *trans* stereoisomer of the ortho and meta isomers (***o*-1** and ***m*-1**) were obtained.[10a] The stereospecificity was attributed to the instability of *cis*-azobenzenes, whilst the unsuccessful isolation of the coupling product from the *p*-isomer is well supported by the meticulously long length of the *trans* isomer (9.21 Å). For the the stilbene bridged calix[4]arene**,** five isomers of **2** (***o*-*cis*-2**, ***o*-*trans*-2**, ***m*-*cis*-2**, ***m*-*trans*-2** and ***p*-*cis*-2**) and five isomers of **3** (***o*-*cis*-3**, ***o*-*trans*-3**, ***m*-*cis*-3**, ***m*-*trans*-3** and ***p*-*cis*-3**) were all successfully isolated.[10b,c] The isolated products showed the preference of *cis* stereoisomers for all regioisomers that are well substantiated by the short distance between the opposite hydroxyl groups of calix[4]arene (at only 4.0 Å)[14] in comparison to the bridge length. The results clearly demonstrate that the calculated lengths of the bridging units can be used as a quantitative specification of the bridge length (< 9.0 Å) which may be constructed over the narrow rim of calix[4]arene.

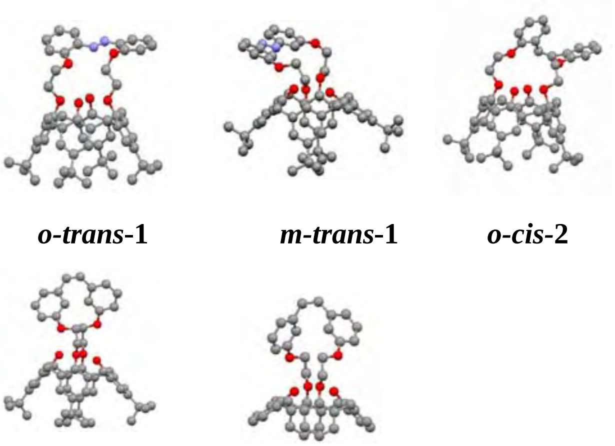


azobenzene: X = N
stilbene: X = CH

Table 1 The AM1 calculated distance between various symmetrical positions on phenyl rings of stilbene.

Isomer	Molecular lengths of			
	Azobenzene (Å)		Stilbene (Å)	
	cis	*trans*	*cis*	*trans*
o-o	3.48	5.05	3.51	5.24
m-m	5.90	7.81	5.85	8.00
p-p	8.32	9.21	8.35	9.39

Two new X-ray structures (***m-cis*-2** and ***m-cis*-3**) in combination with three previously reported structures (***o-trans*-1**, ***m-trans*-1**, ***o-cis*-2**) are shown Figure 2. The X-ray structures reveal that these bridged calix[4]arenes assume a cone conformation. To obtain adequate structural parameters for conformation analysis, the structures of all synthesized compounds were computationally calculated with AM1 geometry optimization. The distances between neighbouring phenolic oxygen atoms on the calix[4]arene rim obtained from the AM1 geometrically optimized structures agree very well (< 5% difference) with those obtained from the X-ray structures (Table 2) justifying that the structural parameters obtained from AM1 structures are suitable for further conformation analysis.



***o-trans*-1** ***m-trans*-1** ***o-cis*-2**

***m-cis*-2** ***m-cis*-3**

Figure 2 The X-ray Structure of azobenene and stilbene bridges calix[4]arenes.

Table 2 The distances between two neighboring phenoxyl oxygen (O-O distance) on the narrow rim of azobenzene and stilbene bridged calix[4]arenes obtained from AM1 optimized (and X-ray) structures.

Compounds	O-O distance in Å*			
	2.86	2.95	2.95	3.03
***o-trans*-1**	(2.76)	(2.80)	(3.03)	(3.04)
***m-trans*-1**	2.85	3.05	3.31	3.41

	(2.75)	(2.92)	(3.32)	(3.47)
	2.73	2.76	2.92	2.95
***o-cis*-2**	(2.70)	(2.70)	(2.90)	(2.96)
***o-trans*-2**	2.71	2.84	2.91	2.96
	2.78	2.83	2.88	2.90
***m-cis*-2**	(2.76)	(2.80)	(2.82)	(3.02)
***m-trans*-2**	2.86	3.05	3.29	3.47
***p-cis*-2**	3.04	3.23	3.37	3.61
***o-cis*-3**	2.74	2.76	2.92	2.95
***o-trans*-3**	2.77	2.84	2.89	2.99
	2.78	2.83	2.88	2.90
***m-cis*-3**	(2.74)	(2.82)	(2.83)	(2.84)
***m-trans*-3**	2.86	3.05	3.28	3.54
***p-cis*-3**	2.80	3.15	3.26	3.52

*There are four pairs of neighboring oxygen atoms around the calix[4]arene rim. The distances obtained from x-ray structures are shown in parenthesis.

Re-examining the ^{1}H NMR spectra of all synthesized compounds, we found that the phenolic protons display conspicuous chemical shifts. The signals of phenolic protons in *m-trans* and *p-cis* isomers appeared significantly upfield comparing to those of the rests (representatively shown in Figure 3). The upfield shifts in the chemical shifts suggest that the intramolecular hydrogen bonding between the phenoxyl groups in the *m-trans* and *p-cis* isomers is relatively weaker than those of the other isomers.

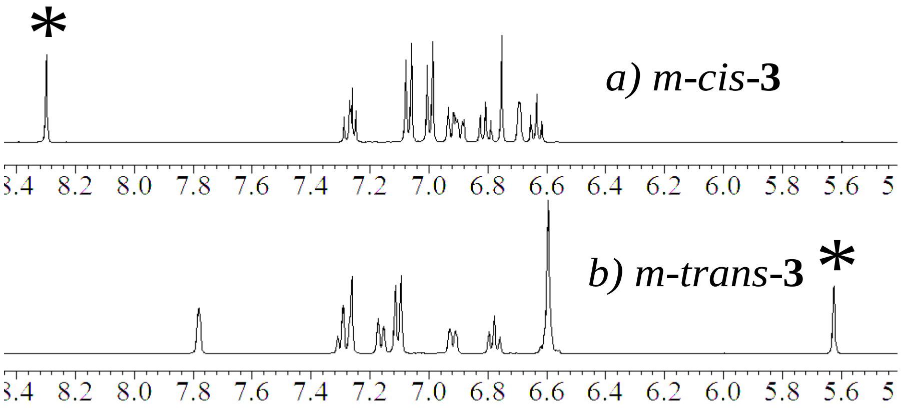


Figure 3 ^{1}H NMR spectra of a) ***m-cis*-3** b) ***m-trans*-3**. The asterisk (*) designated for phenolic proton signal verified by D exchange with D_2O.

To relate the chemical shifts of the phenolic protons to the molecular structures, the distances of the four pairs of neighbouring phenoxyl oxygen atoms around the calix[4]arene were averaged and presented along with the chemical shifts of the corresponding calix[4]arene derivatives (Table 3). The compounds with an average O-O distance longer than

3.0 Å show the signals of phenolic protons below 7.0 ppm whilst the compounds with an average O-O distance shorter than 3.0 Å show the signals above 7.0 ppm (Table 3). This correlation of the average O-O distances with the chemical shifts is a strong evidence to support that the upfield chemical shifts are the result of weaker hydrogen bonding between the neighboring phenoxyl groups due to the distortion of the calix[4]arene rim caused by the longer azobenzene and stilbene bridges *i.e. m-trans* and *p-cis* isomers (bridge length > 7.0 Å, Table 1)

Table 3 The ^{1}H NMR chemical shifts of the phenolic protons and the average O-O distances of azobenzene and stilbene bridged calix[4]arenes from AM1optimized structures (and X-ray structures).

Compounds	^{1}H NMR δ (ppm)	Average O-O distance (Å)
***o-trans*-1**	7.61	2.95 (2.91)
***m-trans*-1**	6.07	3.15 (3.12)
***o-cis*-2**	7.70	2.84 (2.82)
***o-trans*-2**	8.43	2.85
***m-cis*-2**	8.08	2.85 (2.85)
***m-trans*-2**	6.60	3.17
***p-cis*-2**	6.29	3.31
***o-cis*-3**	8.10	2.84
***o-trans*-3**	8.44	2.87
***m-cis*-3**	8.30	2.85 (2.81)
***m-trans*-3**	5.62	3.18
***p-cis*-3**	6.65	3.18

The plot between the average O-O distances and the chemical shifts shows a striking division of the compounds into two groups (Figure 4) suggesting the possibility to use the phenolic ^{1}H NMR signals for identifying the highly distorted or pinched cone conformer of calix[4]arene derivatives. It is important to point out here that the distances between the neighbouring phenoxyl protons observed by X-ray crystallography and AM1 calculation are so varied that the classification between cone and pinched cone conformation cannot be well justified by using just individual or a pair of distances. This variation in the distances is attributed to the fact that the structures derived from both X-ray crystallography and AM1 calculation are static. On the other hand, the chemical shifts observed by ^{1}H NMR in solution are the average values resulting from the dynamic exchange process of the intramolecular hydrogen bonding. It is thus reasonable that the chemical shifts are more correlated with the average distances and they can be very useful for conformation analysis of new calix[4]arene derivatives in solution. The conformational information in solution is important for explaining and predicting the conformational related binding properties of calix[4]arene in host-guest chemistry.

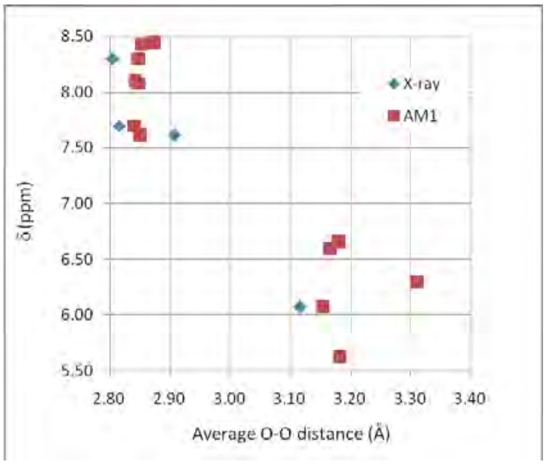


Figure 4 The correlation between the average O-O distance and the chemical shifts of phenolic protons.

To apply our method for classification of cone and pinched cone conformation by ^{1}H NMR spectrum can be applied to previously reported calix[4]arene derivatives, we retrieved the crystal structures of all calix[4]arene derivatives from the Cambridge Structural Database (CSD). The data set of over a thousand structures was refined to 176 structures containing two narrow rim substituents that adopt the cone conformation. Those structures having 1,2- or 1,3-alternate conformation were disregarded. The average O-O distances were calculated from the structural parameters retrieved from the database and plot them in an ascending order (Figure 5). It is clear that the majority of structures have the average O-O distances between 2.6 to 3.0 Å. There are only seven out of 176 structures[10C, 15] with the average O-O distance greater than 3.0 Å, which maybe considered as a highly pinched cone conformation. Indeed, the phenolic OH signal of all these pinched cone compounds, with one exception,[15b] were observed at the chemical shift below 7.0 ppm.

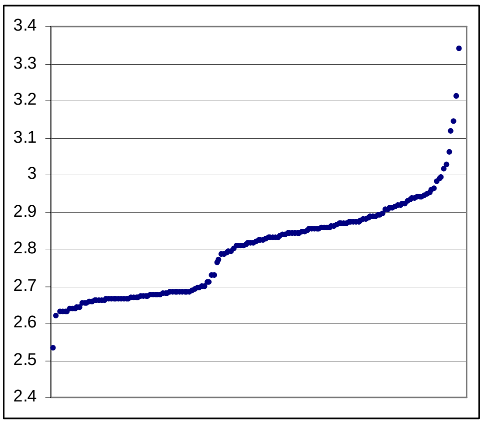


Figure 5 Average O-O distance of related calix[4]arene derivatives calculated based on the structural parameters retrieved from CSD.

Conclusion

Detailed structural analyses of azobenzene- and stilbene-bridged calix[4]arenes by X-ray and AM1 calculation revealed that bridges with a unit length longer than 7.0 Å could considerably distort the conformation of calix[4]arene from the perfect cone shape. The highly distorted (or pinched) cone calix[4]arene has the average O-O distance around the narrow rim greater than 3.0 Å. This distortion is well correlated with the significant upfield shift of ^{1}H NMR signals of the phenoxyl protons which can be used for quick identification of pinched cone conformation of new calix[4]arene compounds. The ability to identify the cone or pinched cone conformation of calix[4]arene in solution is useful for predicting controlling and explaining previously unforeseeable supramolecular binding activity of new calix[4]arene derivatives.

Acknowledgements This work was financially supported by the Thailand Research Fund (TRF) and the Commission of Higher Education.

References

1. (a) Allen, W. E.; Gale, P. A.; Brown, C. T.; Lynch, V. M.; Sessler, J. L. *J. Am. Chem. Soc.* 1996, **118**, 12471-12472. (b) Kovbasyuk, L.; Kramer, R. *Chem. Rev.* 2004, **104**, 3161-3188. (c) Gokel, G. W.; Leevy, W. M.; Weber, M. E. *Chem. Rev.* 2004, **104**, 2723-2750. (d) Haino, T.; Matsumoto, Y.; Fukazawa, Y. *J. Am. Chem. Soc.* 2005, **127**, 8936-8937.

2. (a) Arduini, A.; Secchi, A.; Pochini, A. *J. Org. Chem*. 2000, **65**, 9085-9091. (b) Douhal, A. *Chem. Rev*. 2004, **104**, 1955-1976. (c) Borovkov, V. V.; Inoue, Y. *Org. Lett.*, 2006, **8**, 2337-2340. (d) Alekseeva, E. A.; Basok, S. S.; Mazepa, A. V.; Gren, A. I. *Russ. J. of Org. Chem.* 2008, **44**, 348-352.

3. (a) Shimasaki, T.; Kato, S.-I.; Ideta, K.; Goto, K., Shinmyozu, T. *Journal of Organic Chemistry* 2007, **72**, 1073-1087. (b) Koerner, H.; White, T. J.; Tabiryan, N. V.; Bunning, T. J.; Vaia, R. A. *Materials Today* 2008, **11**, 34-42.

4. (a) Gutsche, C. D. *Calixarenes* Revisited, Monograph in Supramolecular Chemistry, Stoddart, J. F., Ed.; The Royal Society of Chemistry: London, 1998. (b) Ikeda, A.; Shinkai, S. *Chem. Rev.* 1997, **97**, 1713-1734.

5. Gutsche, C. D.; Iqbal, M. *Organic Syntheses Coll.* 1990, **68**, 234-236.

6. (a) Gutsche, C. D.; Bauer, L. J. *J. Am..Chem. Soc.* 1985, **107**, 6052-6059. (b) Gutsche, C. D.; Reddy, P. A. *J. Org. Chem.* 1991, **56**, 4783-4791. (c) Iwamoto, K.; Shinkai, S. *J. Org. Chem.* 1992, **57**, 7066-7073. (d) Brzezinski, B.; Urjasz, H.; Zundel, G. *J. Phys. Chem.* 1996, **100**, 9021-9023.

7. (a) Conner, M.; Janout, V.; Regen, S. L. *J. Am. Chem. Soc.* 1991, **113**, 9670-9671. (b) Evans, D. R.; Huang, M.; Fettinger, J. C.; Williams, T. L. *Inorg. Chem.*2002, **41**, 5986-6000. (c) Scheerder, J.; Vreekamp, R. H.; Engbersen, J. F. J.; Verboom, W.; Duynhoven, J. P. M.; Reinhoudt, D. N. *J. Org. Chem.* 1996, **61**, 3476-3481.

8. (a) Ikeda, A.; Shinkai, S. *Chem. Rev*. 1997, 97, 1713-1734. (b) Ferguson, G.; Gallagher, J. F.; Lough, A. J.; Notti, A.; Pappalardo, S.; Parisi, M. F. *J. Org. Chem.* 1999, **64**, 5876-5885. (c) Guillon, J.; Leger, J.-M.; Sonnet, P.; Jarry, C.; Robba, M. *J. Org. Chem*. 2000, **65**, 8283-8289.

9. (a) Goldmann, H.; Vogt, W.; Paulus, E.; Bohmer, V. *J. Am. Chem. Soc.* 1988**, 110,** 6811-6817. (b) Arduini, A.; Fabbi, M.; Mantovani, M.; Mirone, L. ; Pochini, A.; Secchi, A.; Ungaro, R. *J. Org. Chem.*, 1995, **60**, 1454-1457.

10. (a) Pipoosananakaton, B.; Sukwattanasinitt, M.; Jaiboon, N.; Chaichit, N.; Tuntulani, T. *Tetrahedron Lett.* 2000, **41**, 9095. (b) Sukwattanasinitt, M.; Rojanathanes, R.; Tuntulani, T.; Sritana-Anant, Y.; Ruangpornvisuti, *Tetrahedron Lett.* 2001, **42**, 5291–5293. (c) Rojanathanes, R.; Pipoosananakaton, B.; Tuntulani, T.; Bhanthumnavin, W.; Orton, J. B.; Cole, S. J.; Hursthouse, M. B.; Grossel, M. C.; Sukwattanasinitt, M. *Tetrahedron* 2005, **61**, 1317-1324.

11. Rojanathanes, R.; Tuntulani, T.; Bhanthumnavin, W.; Sukwattanasinitt, M. *Org. Lett.* 2005, **7**, 3401-3404.

12. Jaiyu, A.; Rojanathanes, R.; Sukwattanasinitt, M. *Tetrahedron Lett.* 2007, **48**, 1817-1821.

13. (a) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P., *J. Am. Chem. Soc.* 1985, **107**, 3902-3909. (b) Dewar, M. J. S.; Jie, C.; Yu. J., *Tetrahedron* 1993, **49**, 5003-5038. (c) Rocha, G. B.; Freire, R. O.; Simas, A. M.; Stewart, J. J. P. *J. Comput. Chem.* 2006, **27**, 1101-1111.

14. Shahgaldian, P.; Coleman, A. W.; Rather, B.; Zaworotko, M. J. *J. Incl. Phenom. Macro.* 2005, **52**, 241-245.

15. (a) See, K.A.; Fronczek, F.R.; Watson, W.H.; Kashyap, R.P.; Gutsche, C.D. *J.Org.Chem*. 1991 ,**56,** 7256-7268. (b) Bohmer, V.; Ferguson, G.; Gallagher, J.F.; Lough, A.J.; McKervey, M.A.; Madigan, E.; Moran, M.B.; Phillips, J.; Williams G. *J.Chem.Soc.,Perkin Trans.1* 1993, 1521-1527. (c)Marchand, A.P.; Chong, H-S.; Kumar, T.P.; Huang, Z.; Alihodzic, S.; Watson, W.H.; Ejsmont, K. *Tetrahedron* 2002, **58,** 10205-10212. (d) Ladipo, F.T.; Sarveswaran, V.; Kingston, J.V.;.Huyck, R.A; Bylikin, S.Y.; Carr, S.D.; Watts, R.; Parkin S. *J.Organomet.Chem*. 2004, **689,** 502-514. (e) Shiao, Y-J.; Chiang, P-C.; Senthilvelan, A.; Tsai, M-T.; Lee, G-H.; Chung W-S. *Tetrahedron Lett.* 2006 ,**47,** 8383-8386. (f) Light, M.E.;.Evans, L.S ; Gale, P.A. (2007) *Private Communication*

ORGANIC LETTERS

2009
Vol. 11, No. 13
2768−2771

A Polyanionic Dendritic Fluorophore for Selective Detection of Hg^{2+} in Triton X-100 Aqueous Media

Nakorn Niamnont,[†] Warathip Siripornnoppakhun,[†] Paitoon Rashatasakhon,[†] and Mongkol Sukwattanasinitt*,[†,‡]

Organic Synthesis Research Unit, Department of Chemistry, Faculty of Science, and Center for Petroleum, Petrochemicals and Advanced Materials, Chulalongkorn University, Bangkok 10330, Thailand

smongkol@chula.ac.th

Received April 29, 2009

ABSTRACT

A series of water-soluble fluorescent dendritic compounds composed of phenylene-ethynylene repeating units and anionic carboxylate or cationic ammonium peripheral groups were synthesized. The first generation fluorescent dendrimer containing nine phenylene-ethynylene units and six carboxylate peripheral groups exhibited a highly selective fluorescence quenching by Hg^{2+} ions. The Stern−Volmer constant (K_{sv}) was 33,700 M^{-1} in aqueous media in the presence of Triton X-100 surfactant.

Mercury is one of the most toxic environmental pollutants generated from industrial sources. The most abundant ionic form of this element is the mercuric ion (Hg^{2+}), which can be accumulated in the organs of human or animal bodies through the food chain.[1] Inorganic mercury has been reported to produce harmful effects at a concentration of 5 ppb.[2] Development of highly sensitive and selective Hg^{2+} sensors that can provide direct determinations of the amount of Hg^{2+} in aqueous media is therefore of great interest.[3] Chemosensors for Hg^{2+} have been progressively improved using redox,[4] chromogenic,[5] or fluorogenic[6] changes as the means of detection.

Fluorescence-based methodologies have attracted much interest due to their intrinsic sensitivity and selectivity.[7] Considerable efforts have been devoted to the design of fluorescent compounds to be used as sensors for mercury. However, their poor solubility in water and low fluorescence quantum yield due to aggregation have limited the satisfactory application of these compounds in aqueous media.[8]

[†] Department of Chemistry, Faculty of Science.

[‡] Center for Petroleum, Petrochemicals and Advanced Materials.

(1) (a) Stern, A. H.; Hudson, R. J. M.; Shade, C. W.; Ekino, S.; Ninomiya, T.; Susa, M.; Harris, H. H.; Pickering, I. J.; George, G. N. *Science* **2004**, *303*, 763–766. (b) Nendza, M.; Herbst, T.; Kussatz, C.; Gies, A. *Chemosphere* **1997**, *35*, 1875–1885.

(2) Boening, D. W. *Chemosphere* **2000**, *40*, 1335–1351.

(3) Darbha, G. K.; Singh, A. K.; Rai, U. S.; Yu, E.; Yu, H; Ra, P. C. *J. Am. Chem. Soc.* **2008**, *130*, 8038–8043.

(4) Caballero, A.; Martínez, R.; Lloveras, V.; Ratera, I.; Vidal-Gancedo, J.; Wurst, K.; Tárraga, A.; Molina, P.; Veciana, J. *J. Am. Chem. Soc.* **2005**, *127*, 15666–15667.

(5) (a) Zhang, X.; Shiraishi, Y.; Hirai, T. *Org. Lett.* **2007**, *9*, 5039–5042. (b) Caballero, A.; Espinosa, A.; Tárraga, A; Molina, P. *J. Org. Chem.* **2008**, *73*, 5489–5497.

(6) (a) Wang, J. B.; Qian, X. H. *Org. Lett.* **2006**, *8*, 3721–3724. (b) Zhao, Y.; Zhong, Z. Q. *Org. Lett.* **2006**, *8*, 4715–4717. (c) Zhao, Y.; Zhong, Z. *J. Am. Chem. Soc.* **2006**, *128*, 9988–9989. (d) Huang, C.-C.; Chang, H.-T. *Anal. Chem.* **2006**, *78*, 8332–8338. (e) Huang, C.-C.; Yang, Z.; Lee, K.-H.; Chang, H.-T. *Angew. Chem., Int. Ed.* **2007**, *46*, 6824–6828. (f) Nolan, E. M.; Lippard, S. J. *Chem. Rev.* **2008**, *108*, 3443–3480. (g) Liu, C. W.; Huang, C. C; Chang, H. T. *Langmuir* **2008**, *24*, 8346–8350.

(7) (a) De Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515–1566. (b) Avirah, R. R.; Jyothish, K.; Ramaiah, D. *Org. Lett.* **2007**, *9*, 1133–1136.

10.1021/ol900929g CCC: $40.75 © 2009 American Chemical Society
Published on Web 06/04/2009

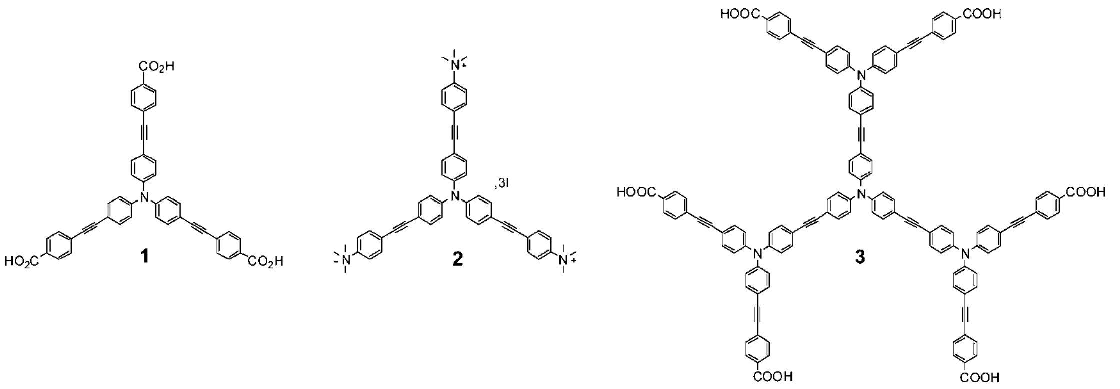


Figure 1. Structures of dendritic molecules **1**, **2**, and **3**.

Several methods have been used to prevent aggregation and increase quantum efficiencies, for example, the use of polyelectrolytes or surfactants.

Conjugated polyelectrolytes have been applied to the detection of metals due to their efficient static quenching properties with quenchers.[9] In some recent studies, surfactants were also used to enhance the fluorescence quantum yields of hydrophobic conjugated polymers containing hydrophilic side chains.[10] The dominant hydrophobic interactions between surfactants and fluorophores can significantly reduce the aggregation. An application of surfactants for amplification of the quenching effect between the fluorescent polymers and quenchers has also been reported.[11]

The fluorescent linear polymers poly(phenylene-ethynylenes) substituted by carboxylate groups have been reported to exhibit a quenching effect by Hg^{2+} in aqueous media in the absence and presence of avidin, with Stern−Volmer constant (K_{sv}) values of 10^4 and 10^5 M^{-1}, respectively.[12] Despite offering high sensivity, the unpredictable secondary and tertiary structures in solution, due to a wide number of repeating fluorophores and random molecular conformations in linear conjugated polymers, can lead to inconsistent quenching effects and inexplicable behaviors.

In comparison with linear polymers, the numbers of fluorophore units in dendrimers can be controlled by a stepwise synthesis. This should reflect in the more predictable fluorescence property and other structure-related behaviors of dendritic molecules. We thus decided to synthesize dendritic compounds **1**−**3** (Figure 1) and study their fluorescent sensing applications.

Diphenylacetylene is selected as the repeating fluorescent unit for its known high fluoresence quantum yield and structural rigidity. To make the dendritic compounds water-soluble, carboxyl or quaternary ammonium groups have been installed as the peripheral groups. The compounds were synthesized by a convergent approach as outlined in Scheme 1. The reactive core, 4,4′,4′′-triiodotriphenylamine **4**, was prepared from the iodination of triphenylamine using benzyltrimethylammonium iododichloride ($BnMe_3$-ICl_2).[13] The peripheral building blocks, methyl 4-ethynyl benzoate **5** and *N*,*N*-dimethyl-4-ethynylaniline **6**, were obtained through the Sonogashira coupling[14] of trimethylsilylacetylene with the corresponding aryl iodide and a subsequent base-catalyzed desilylation. With the required building blocks in hands, we proceeded with the Sonogashira coupling between **4** and **5** followed by the hydrolysis of triester **7** to afford ionizable fluorophore **1**. Similarly, the reaction between **4** and **6** gave rise to the triamine **8**, which was treated with an excess of MeI to provide the polycationic fluorescent compound **2**. In order to obtain the first generation fluorescent dendrimer **3**, we carried out a reaction of the core **4** with 1 molar equiv of trimethylsilylacetylene to obtain the branch building blocks **9**. The Sonogashira coupling of **9** with **5** followed by desilylation gave the dendron **10**, which was coupled with **4** to afford hexaester **11**. The hydrolysis of **11** eventually afforded first generation fluorescent dendrimer **3** in moderate yield.[15]

The effects of surfactants on the photophysical properties of **1**−**3** were studied. Without the surfactant, compounds **1**−**3** displayed absorption peaks around 370−375 nm. In the presence of the surfactant Triton X-100, these bands were slightly red-shifted to 379−383 nm. The spectral shifts

---

(8) Zhu, X.-J.; Fu, S.-T.; Wong, W.-K.; Guo, J.-P.; Wong, W.-Y. *Angew. Chem., Int. Ed.* **2006**, *45*, 3150–3154.

(9) McQuade, D. T.; Pullen, A. E.; Swager, T. M. *Chem. Rev* **2000**, *100*, 2537. Thomas, S. W.; Joly, G. D.; Swager, T. M. *Chem. Rev* **2007**, *107*, 1339–1386.

(10) (a) Chen, L. H.; Xu, S.; McBranch, D.; Whitten, D. *J. Am. Chem. Soc.* **2000**, *122*, 9302–9303. (b) Gaylord, B. S.; Heeger, A. J.; Bazan, G. C. *J. Am. Chem. Soc.* **2003**, *125*, 896–900. (c) Burrows, H. D.; Lobo, V. M. M.; Pina, J.; Ramos, M. L.; Seixas de Melo, J.; Valente, A. J. M.; Tapia, M. J.; Pradhan, S.; Scherf, U. *Macromolecules* **2004**, *37*, 7425–7427. (d) Kaur, P.; Yue, H; Wu, M.; Liu, M.; Treece, J.; Waldeck, D. H.; Xue, C.; Liu, H. *J. Phys. Chem. B* **2007**, *111*, 8589–8596. (e) Pu, K.-Y.; Pan, S. Y.-H.; Liu, B. *J. Phys. Chem. B* **2008**, *112*, 9295–9300.

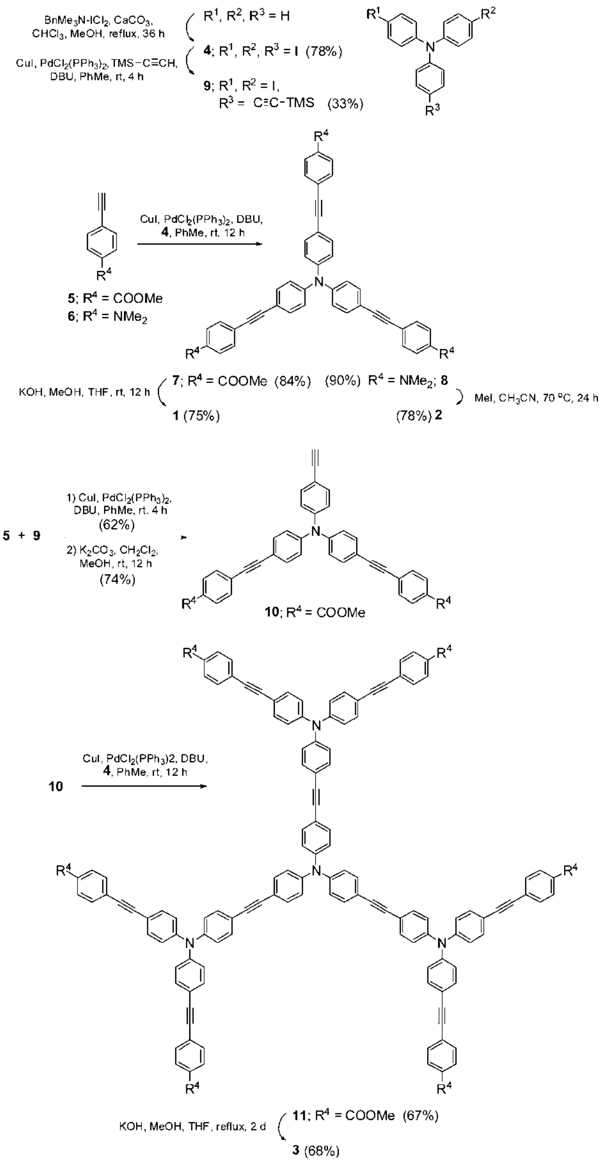
(11) Dalvi-Malhotra, J.; Chen, L. *J. Phys. Chem. B* **2005**, *109*, 3873–3878.

(12) (a) Kim, I.-B.; Dunkhorst, A.; Gilbert, J.; Bunz, U. H. F. *Macromolecules* **2005**, *38*, 4560–4562. (b) Kim, I.-B.; Bunz, U. H. F. *J. Am. Chem. Soc.* **2006**, *128*, 2818–2819. (c) Kim, I.-B.; Phillips, R.; Bunz, U. H. F. *Macromolecules* **2007**, *40*, 814–817.

(13) Kajigaeshi, S.; Kakinami, T.; Moriwaki, M.; Fujisaki, S.; Maeno, K.; Okamoto, T. *Synthesis* **1988**, 545–546.

(14) (a) Devadoss, C.; Bharathi, P.; Moore, J. S. *J. Am. Chem. Soc.* **1996**, *118*, 9635–9644. (b) Pesak, D.; Moore, J. S. *Macromolecules* **1997**, *30*, 6467–6482. (c) Nantalaksakul, A.; Dasari, R. R.; Ahn, T.-S.; Al-Kaysi, R.; Bardeen, C. J.; Thayumanavan, S. *Org. Lett.* **2006**, *8*, 2981–2984. (d) Zhang, X.; Ren, X.; Xu, Q. H.; Loh, K. P.; Chen, Z. K. *Org. Lett.* **2009**, *11*, 1257–1260.

Scheme 1. Synthesis of **1**, **2**, and **3**



observed in the emission spectra were in the opposite direction and of more significance. The emission peaks of **1**, **2**, and **3** were at 454, 485, and 489 nm in the absence of Triton X-100. The surfactant caused the emission bands to blue-shift by 20, 47, and 68 nm, respectively (Table 1).

The blue shift and increase in fluorescence quantum yields (Φ_F) suggested that the deaggregation of **1**−**3** was caused by the addition of the surfactants. The enhancement of Φ_F of **3** was greater than that of **1** implied that compound **1**, a smaller molecule, was only partially deaggregated.

We also investigated the fluorogenic behaviors of **1**−**3** in the presence of metal ions in the +2 oxidation state, such as Cr^{2+}, Fe^{2+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Cd^{2+}, Hg^{2+}, and Pb^{2+}. Without the surfactant, the fluorescence signal of **3** can be quenched by Hg^{2+} ions (Figure 2a), whereas there are no significant effects on the signals of **1** and **2**. With Triton X-100, the fluorescence signal of **1** was quenched by all metal ions listed above, but the signal of **2** was not affected. On the other hand, the fluorophore **3** still exhibited a selective quenching by Hg^{2+} ions.

A Stern−Volmer plot was made in order to access a quantitative measurement of fluorescence quenching. K_{sv} for the system with Triton X-100 was 33,700 M^{-1}, whereas it was only 5,800 M^{-1} for the system without Triton X-100 (Figure 3). It is clear that Triton X-100 could amplify this selective quenching effect.

The nonselective quenching of **1** suggested that positively charged metal ions reduce the electrostatic repulsion between

Table 1. Photophysical Properties of **1**−**3** in 50 mM Phosphate Buffer (pH 8.0) without and with Triton X-100

	absorption		fluorescence	
compd	λ_{max} (nm)	ε (M^{-1} cm^{-1})	λ_{max} (nm)	Φ_F^{a}
		Without Triton X-100		
1	374	5900	454	0.097
2	370	26823	485	0.14
3	375	63500	489	0.037
		With Triton X-100		
1	383	9592	434	0.47
2	382	21310	438	0.46
3	379	49820	421	0.65

[a] Quinine sulfate in 0.1 M H_2SO_4 (Φ_F = 0.45) was the reference.

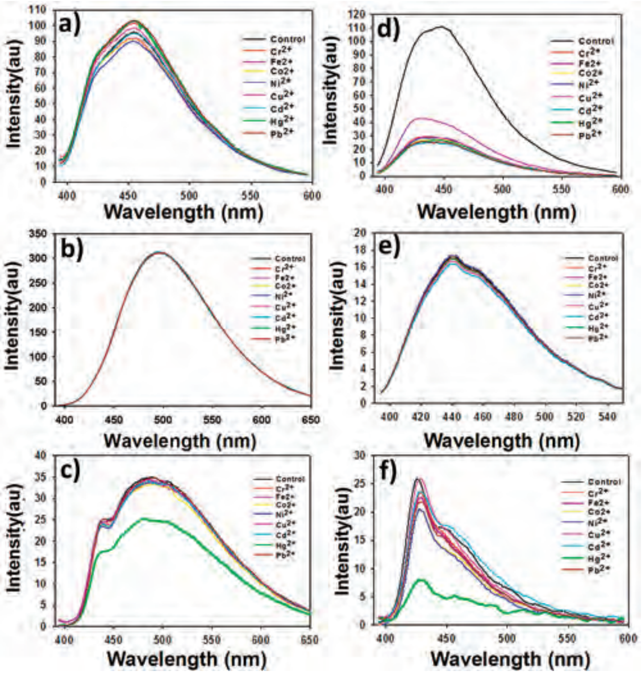


Figure 2. Emission spectra of the solutions of **1**−**3** (10 μM) upon the addition of metal ions (40 μM): without Triton X-100 for (a) **1**, (b) **2**, and (c) **3**; with 0.1 mM Triton X-100 for (d) **1** (1 μM), (e) **2** (0.1 μM), and (f) **3** (0.1 μM).

---

(15) The spectroscopic data (^{1}H and ^{13}C NMR, MALDI-TOF MS, and ESI-MS spectra) of every compound are available in Supporting Information.

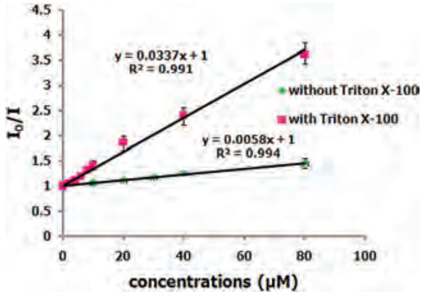


Figure 3. Stern−Volmer plots for fluorescence quenching of **3** (0.1 μM) with and without of Triton X-100 (0.1 mM).

the partially deaggregated negatively charged fluorophores **1**, resulting in the enhancement of self-quenching. Conversely, the charge repulsion among positively charged fluorophore **2**, having a comparable molecular size to **1**, cannot be reduced by the metal ions and therefore exhibits no enhancement of the self-quenching effect.

The selective fluorescence quenching of **3** by Hg^{2+} is more complicated and difficult to rationalize. With the high selectivity for Hg^{2+}, the common metal ion enhanced self-quenching mechanism is unlikely to play the key role. The quenching effect may involve selective formation of $\mathbf{3}\cdot Hg^{2+}$ complex and efficient energy transfer between the fluorescent units in **3** to this complex at the periphery.[16] To test if the proposed complex could be reversed, a strong chelator, EDTA, was added. The addition of 2.5 molar equiv of EDTA could restore the fluorescent signal of **3** to its original level (Figure 4). The result supports the above hypothesis to some extent.

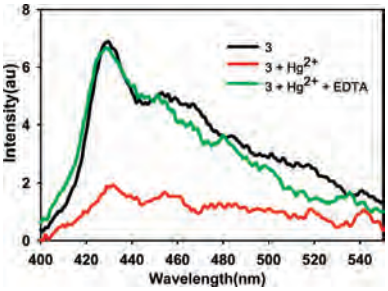


Figure 4. Emission spectra of **3** (0.1 μM) upon the addition of Hg^{2+} (40 μM) and EDTA (100 μM).

In summary, a series of diphenylacetylene dendritic compounds containing negatively and positively charged peripheral groups were successfully synthesized through a convergent approach. We have demonstrated that these diphenylacetylene based dendritic molecules with a charge decorated periphery constitute a new intriguing class of fluorophores useful for sensing applications in aqueous media. The quantum efficiencies of the fluorophores in water were considerably enhanced by the nonionic sufactant Triton X-100. In the presence of Triton X-100, the fluorescent signal of the first generation dendrimer containing a carboxylate periphery could be selectively quenched by Hg^{2+}. A wide linear fluorescence quenching response to Hg^{2+} concentration was observed in the range of 2−80 μM (0.4−16 ppm). Other applications along this line are currently under investigation, and the results will be disclosed in due course.

Acknowledgment. This work is supported by the Thailand Research Fund (TRF) and the 90th Anniversary of Chulalongkorn University Fund (Ratchadaphiseksomphot Endowment Fund). The measurement of fluorescent spectra was performed in the laboratory of Prof. Thawatchai Tuntulani.

Supporting Information Available: Spectroscopic data and detailed experimental procedures. This information is available free of charge via the Internet at http://pubs.acs.org.

OL900929G

---

[16] (a) Sandanaraj, B. S.; Demont, R.; Aathimanikandan, S. V.; Savariar, E. N.; Thayumanavan, S. *J. Am. Chem. Soc.* **2006**, *128*, 10686–10687. (b) Jiwpanich, S.; Sandanaraj, B. S.; Thayumanavan, S. *Chem. Commun.* **2009**, 806–808.