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Synthesis and Luminescence Properties of U-Shaped Polycyclic Molecules Containing Syn-Facial Functionalized Quinoxaline Rings

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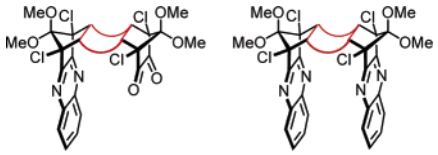
ABSTRACT



Rigid U-shaped molecules containing syn-facially situated quinoxaline rings have been synthesized in three steps, by a combination of the Diels−Alder reaction, the ruthenium-catalyzed oxidation, and the $Zn(OAc)_2$-catalyzed condensation of the resulting bis-α-diketones with benzene-1,2-diamines. The unsymmetric bis-quinoxalines, with electronically different substituents, and the quinoxaline ring-attached α-diketones were also prepared. Their luminescence properties were examined and described.

Rigid and often symmetric polycyclic carbon frameworks are frequently utilized to serve as "spacers" for constructing the U-shaped molecules with specially designed functionality.[1−4] They are used to delineate the intramolecular nonconjugated orbital interactions,[1] to investigate the biologically and possibly the practically important electron and energy transfer phenomena between electronically coupled donor and acceptor groups.[2,3] Recently, intensive research activity has been directed toward making use of their convex−concave topology to demonstrate the formation of host−guest complexes via the processes of molecular recognition manipulated by the noncovalent intermolecular interactions.[4] In connection with our long active synthetic work that employs 1,2,3,4-tetrachloro-5,5-dimethoxycyclopentadiene (**1**)[5] as cyclopentadienone synthon to prepare Diels−Alder (DA) adducts for the construction of polycyclic spacer molecules,[6] we were prompted by a facile ruthenium-catalyzed oxidation procedure of converting vicinal dihaloalkenes to α-diketones recently disclosed by Khan et al.[7] to develop an efficient synthetic approach toward the U-shaped polycyclic compounds having a framework that holds two syn-facially situated quinoxaline rings.

The process, illustrated in Scheme 1, consists of three operations: (1) the DA reactions of **1** with bis-dienophiles to construct *syn*-bis-adducts **A**, (2) the conversion of dichloroetheno-bridges in **A** with use of Khan's protocol to generate bis-α-diketones **B**, followed by (3) the condensation of **B** with benzene-1,2-diamines (BDA's) to produce *syn*-bis-quinoxalines **C**. The versatility of this process is manifested by the presence of two changeable substructures in **C**, the intercalator and the quinoxaline ring. The intercalator originating from bis-dienophilic cycloalkadiene can serve as the

(1) (a) Gleiter, R.; Schafer, W. *Acc. Chem. Res.* **1990**, *23*, 369. (b) Martin, H.-D.; Mayer, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 283.
(2) (a) Chow, T. J.; Chiu, N.-R.; Chen, H.-C.; Chen, C.-Y.; Yu, W.-S.; Cheng, Y.-M.; Cheng, C.-C.; Chang, C.-P.; Chou, P.-T. *Tetrahedron* **2003**, *59*, 5719. (b) Zimmerman, H. E.; Lapin, Y. A.; Nesterov, E. E.; Sereda, G. A. *J. Org. Chem.* **2000**, *65*, 7740.
(3) (a) Smith, T. A.; Lokan, N.; Cabral, N.; Davies, S. R.; Paddon-Row, M. N.; Ghiggino, K. P. *J. Photochem. Photobiol. A* **2002**, *149*, 55. (b) Jolliffe, K. A.; Langford, S. J.; Oliver, A. M.; Shephard, M. J.; Paddon-Row, M. N. *Chem. Eur. J.* **1999**, *5*, 2518.
(4) (a) Klärner, F. G.; Kahlert, B. *Acc. Chem. Res.* **2003**, *36*, 919. (b) Rebek, J., Jr. *Acc. Chem. Res.* **1999**, *32*, 278. (c) Rowan, A. E.; Elemans, J. A. A. W.; Nolte, R. J. M. *Acc. Chem. Res.* **1999**, *32*, 995.
(5) Khan, F. A.; Prabhudas, B.; Dash, J. *J. Prakt. Chem.* **2000**, *342*, 512.
(6) (a) Chou, T.-C.; Lin, G.-H. *Tetrahedron* **2004**, *60*, 7907. (b) Lin, C.-T.; Chen K.-Z.; Chou, T.-C. *Tetrahedron* **2003**, *59*, 1493. (c) Chou, T.-C.; Kuo L.-H.; Liu, K.-F. *J. Chin. Chem. Soc.* **2003**, *50*, 303. (d) Lin, C.-T.; Hsu, H.-C.; Wang, M.-F.; Chou, T.-C. *Tetrahedron* **2000**, *56*, 5383. (e) Chou, T.-C.; Jiang, T.-S.; Hwang, J.-T.; Lin, K.-J.; Lin, C.-T. *J. Org. Chem.* **1999**, *64*, 4874.
(7) Khan, F. A.; Dash, J. *J. Am. Chem. Soc.* **2002**, *124*, 2424.

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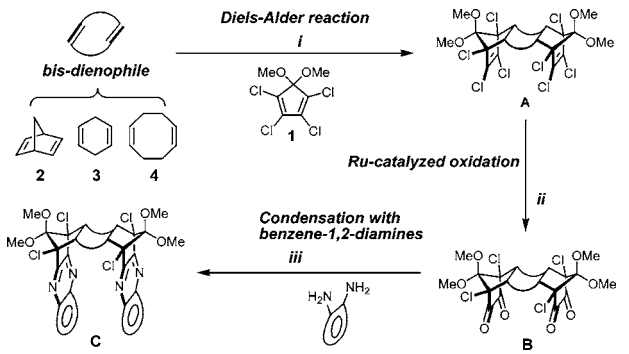
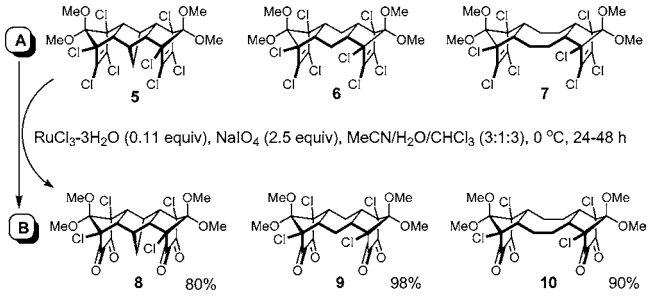
Scheme 1. Synthetic Plan for the Construction of U-Shaped *syn*-Bis-quinoxaline Molecules



controller of the shape and size of polycyclic scaffold, and consequently the distance and stereoalignment between two quinoxaline rings, the motif of which is derived from various BDA's. Furthermore, bis-quinoxalines **C** having two masked ketonic functional groups inherent from **1** should offer the opportunity for further elaboration of molecular architecture.

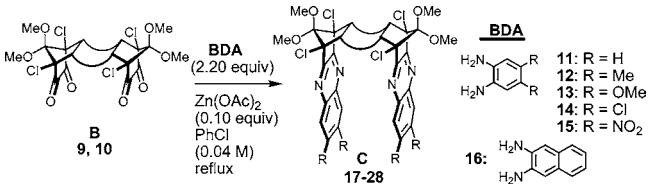
Toward the *syn*-bis-quinoxalines **C** with U-shaped framework, the DA reactions of **1** with cycloalkadienes must proceed stereoselectively to afford *syn*-bis-adducts **A**. The feasibility of the approach is then hinged upon the efficacy of the ruthenium-catalylized oxidation and condensation reactions of the resulting bis-α-diketones **B** with BDA's that are expected to encounter sterically disfavored environment. With this context, we at the outset selected three, structurally well-established *syn*-bis-adducts (**5**, **6**, and **7**) derived from the DA reactions of **1** with norbornadiene (**2**),[8] 1,4-cyclohexadiene (**3**),[9] and 1,5-cyclooctadiene (**4**)[10] as the starting materials to examine the practicality of the synthetic route illustrated in Scheme 1. The oxidation reactions of *syn*-bis-adducts **5**, **6**, and **7** to the corresponding bis-α-diketones **8**, **9**, and **10** were carried out following essentially the procedure reported by Khan et al.[7] and the results are summarized in Scheme 2.

Scheme 2. Preparation of Bis-α-diketones **B** (**8**, **9**, **10**)



The condensation reactions (**B** → **C**, Scheme 1) were initially encountered with lengthy reaction times and unsatisfactory yields, when using commonly practiced procedures. Improvement was finally realized by performing the reactions of bis-α-diketones with BDA's in PhCl at refluxing temperature and in the presence of $Zn(OAc)_2$ as a catalyst. To the best of our knowledge, $Zn(OAc)_2$ was used for the first time in the condensation reaction that involves α-diketones. As shown in Table 1, utilizing this reaction condition, we

Table 1. Synthesis and Fluorescence Wavelengths of *syn*-bis-quinoxalines **C**



entry	**B**	BDA	**C**	time (h)	yield (%)	λ_{em} (nm)[a]
1	**9**	**11**	**17**	15	92	395
2	**10**	**11**	**18**	12	92	390
3	**9**	**12**	**19**	44	88	387
4	**10**	**12**	**20**	18	88	380
5	**9**	**13**	**21**	48	86	390
6	**10**	**13**	**22**	24	88	381
7	**9**	**14**	**23**	30	90	397
8	**10**	**14**	**24**	24	92	391
9	**9**	**15**	**25**	96	85	N/A
10	**10**	**15**	**26**	34	84	N/A
11	**9**	**16**	**27**	18	89	514, 531[b]
12	**10**	**16**	**28**	24	87	479, 485[b]

[a] $CHCl_3$ as solvent. [b] DMSO as solvent.

successfully obtained *syn*-bis-quinoxalines **17**−**28** in yields of more than 80% from the condensation reactions of bis-α-diketones **9** and **10** with various 4,5-disubstituted BDA's, **11**−**16**. However, bis-α-diketone **8** still did not undergo the condensation reaction with benzene-1,2-diamine **11** under this $Zn(OAc)_2$-catalyzed reaction condition.[11]

The fact that bis-α-diketone **8** did not undergo the condensation reaction with diamine **11** and bis-α-diketone **10** took less time than bis-α-diketone **9** to complete the reactions with most of the BDA's implied that the initial nucleophilic addition of BDA's to the carbonyl groups occurs on the concave side (syn to the intercalator) of bis-α-diketones. The monoquinoxaline-attached α-diketones thereby initially formed would then be less reactive toward the second nucleophilic addition of BDA's, particularly in the cases of α-diketones derived from bis-α-diketone **9**. As shown in Table 2, this speculation was verified and permitted us to synthesize α-diketones (**D**, **29**−**34**) and hence the unsym-

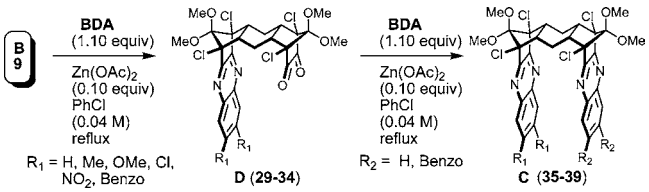
(8) Nelsen, S. F.; Trieber, D. A., II; Wolff, J. J.; Powell, D. R.; Rogers-Crowley, S. *J. Am. Chem. Soc.* **1997**, *119*, 6873.

(9) Chou, T.-C.; Yang, M.-S.; Lin, C.-T. *J. Org. Chem.* **1994**, *59*, 661.

(10) Garcia, J. G.; Fronczek, F. R.; McLaughlin M. L. *Tetrahedron Lett.* **1991**, *32*, 3289.

(11) Both faces of dichloroetheno-bridge in DA adduct **5** are sterically hindered, so are both faces of α-diketone-bridge in bis-α-diketone **8**. However, **5** underwent the Ru-catalyzed oxidation to form **8**, which was not able to undergo the reaction with BDA **11** to afford any condensation products. Presumably, the Ru-catalyzed oxidation of dichloroetheno-bridge in **5** was assisted by the methoxy group to offset the steric hindrance, making the formation of bis-α-diketone **8** feasible. Verification of this speculation is in progress.

Table 2. Synthesis and Fluorescence Wavelengths of the Quinoxaline-Attached α-Diketones **D** and Unsymmetric *syn*-Bis-quinoxalines **C**



entry	**B**	BDA (R_1)	**D**	time (h)	yield (%)	λ_{em} (nm)[a]	λ_{CT} (nm)[a]
1	**9**	**11**	**29**	6	98	393	476
2	**9**	**12**	**30**	16	92	373	467
3	**9**	**13**	**31**	10	91	390	475
4	**9**	**14**	**32**	12	96	384	466
5	**9**	**15**	**33**	30	84	365	478
6	**9**	**16**	**34**	8	93	492, 501[b]	

entry	**D**	BDA (R_2)	**C**	time (h)	yield (%)	λ_{em} (nm)[a]
7	**32**	**11**	**35**	40	84	398
8	**32**	**16**	**36**	45	94	488, 497[b]
9	**33**	**11**	**37**	27	80	361
10	**33**	**16**	**38**	37	92	553, 588[b]
11	**34**	**11**	**39**	35	86	479, 483[b]

[a] $CHCl_3$ as solvent. [b] DMSO as solvent.

metrical and electronically different bis-quinoxalines (**C**, **35**−**39**) in excellent yields from bis-α-diketone **9**.[12]

All the U-shaped compounds listed in Tables 1 and 2 gave satisfactory elemental analyses or HRMS data and were characterized by their spectral analyses (^{1}H and ^{13}C NMR, IR, and MS). Particularly, the symmetry-reflected ^{1}H NMR spectrum, which contains a signal at the magnetic field close to or higher than that of TMS, implies that the intercalator unit in each compound adopts more likely a boat conformation in solution.[13] This conformational preference of the intercalator unit is evidently demonstrated in the solid state. As demonstrated by the X-ray single-crystal structures of C_{2v}-symmetric *syn*-bis-quinoxaline **17** (available in the Supporting Information) and *syn*-bis-benzoquinoxaline **27** (Figure 1a), the two face-to-face quinoxaline rings are hung from the boat cyclohexane-intercalated scaffold in an inward (converging) style.[14] The transannular distances between nitrogen atoms and the open ends in **17** are 4.69 and 3.86 Å, respectively. In **27**, however, the corresponding distances are 4.67 and 4.04 Å, and the distance between the open ends is 3.92 Å. These distances indicate that the benzoquinoxaline rings in **27**, though remaining converging, begin to deviate from planarity by bending outward to avoid steric congestion. On the other hand, the molecular structure of *syn*-bis-quinoxaline **18** shown in Figure 1b exhibits two quinoxaline rings facing each other and suspended from the boatlike cyclooctane-intercalated scaffold in an outward (diverging) fashion with an average transannular distance of 7.87 Å between nitrogen atoms and 10.56 Å between two open ends.

That the syn-facially situated quinoxaline units in the cyclohexane- and cyclooctane-intercalated *syn*-bis-quinoxalines are arranged differently (diverging vs converging) with different interplanar distances motivated us to examine the luminescence property of some U-shaped molecules made available in this study. For serving as a reference compound, we synthesized *anti*-bis-benzoquinoxaline **42** following the established synthetic route illustrated in Scheme 1, from the *anti*-bis-adduct **40** of the DA reaction of **1** and 1,5-cyclooctadiene (**4**),[10] via *anti*-bis-α-diketone **41** as shown in Scheme 3.

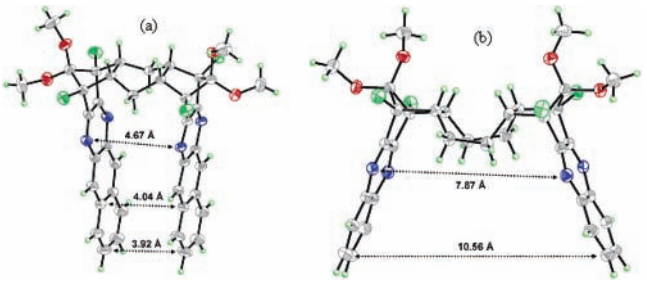
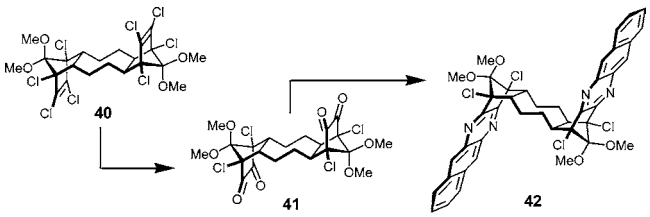


Figure 1. Molecular structure of (a) *syn*-bis-quinoxalines **27** and (b) *syn*-bis-quinoxalines **18**. Thermal ellipsoids are drawn at 30% probability.

Scheme 3. Synthesis of *anti*-Bis-benzoquinoxalines **42** by the Process Illustrated in Scheme 1



The UV spectra of bis-benzoquinoxaline **27**, **28**, and **42** in $CHCl_3$ (available in the Supporting Information) contain two major bands in the regions of 250−300 ($S_0 \rightarrow S_2$) and 325−380 nm ($S_0 \rightarrow S_1$), characteristic of benzoquinoxaline chromophore.[15] Interestingly, as shown in Figure 2a, the fluorescence spectra of **28** and **42** in $CHCl_3$ are identical, showing a broad and structureless band peaking at 479 nm.

(12) Under the same reaction condition, bis-α-diketone **10** underwent the condensation reaction with 1 equiv of BDA **11** to give a mixture of mono- and bis-quinoxaline adducts.

(13) This signal arises from the inward-oriented methylene hydrogens of the intercalator unit, which experience a strong, distance-dependent anisotropic shielding effect from quinoxaline rings. For example, in the cases of cyclohexane-intercalated *syn*-bis-quinoxalines (**17**, **19**, **21**, **23**, **25**, and **27**), these typical multiplets were found to center at about δ −1.15 ppm. The corresponding methylene hydrogens in cyclooctane-intercalated *syn*-bis-quinoxalines (**18**, **20**, **22**, **24**, **26**, and **28**) were centered at δ ~0.43 ppm.

(14) Crystallographic data (excluding structure factors) for **17**, **18**, and **27** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 222195, CCDC 222196, and CCDC 278625, respectively. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK [fax +44(0)-1223-336033 or e-mail deposit@ccdc.cam.ac.uk].

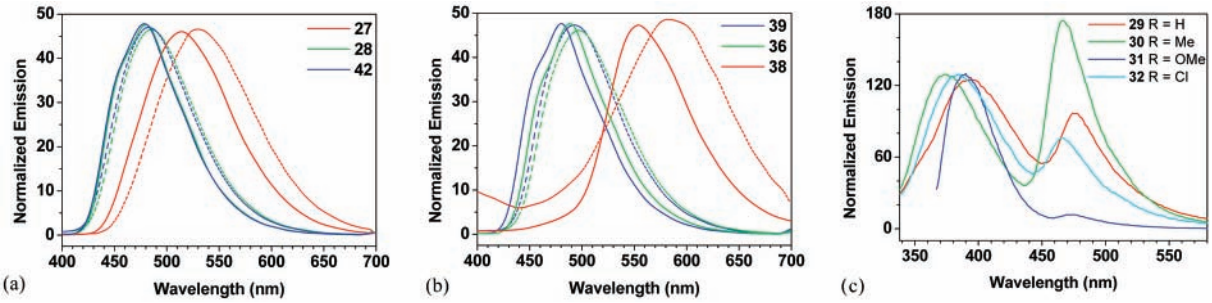


Figure 2. Fluorescence emission spectra of (a) bis-benzo-quinoxalines **27**, **28**, and **42**, (b) unsymmetrical bis-quinoxalines **36**, **38**, and **39**, and (c) mono-quinoxalines **29**−**32** in $CHCl_3$ (solid line) and DMSO (dash line); $c = 1.0 \times 10^{-5}$ M; λ_{ex} = absorption λ_{max}. The intensity was normalized.

However, the broad structureless emission band of **27** is red-shifted by 1420 cm^{-1} to 514 nm. Also shown in Figure 2a and Table 1 is the solvent effect on the excimer formation, in which the resulting fluorescence emission bands when measured in polar solvent DMSO are red-shifted, relative to those measured in $CHCl_3$, by 17, 6, and 4 nm for **27**, **28**, and **42**, respectively. The difference in fluorescence behavior between **27** and **28** (**42**) suggests that excimer formation is strongly dependent on the mutual orientation and interchromophore distance. In **27**, the two benzoquinoxaline units are arranged face-to-face in a converging manner and in close proximity with a distance of only about 4 Å (Figure 1a), giving rise to the intramolecular excimer interaction between these two chromophores, and consequently a significant solvent-dependent red-shifted emission band as compared with **28** (**42**). In addition, the emission band for **27** is slightly broader and about one-third less intensive than that for **28** and **42**, further indicating the fluorescence of **27** is intramolecularly self-quenched via π,π-interaction.

As the intramolecular π,π-interaction was strongly suggested in the cyclohexane-intercalated **27**, the unsymmetrical and electronically different bis-quinoxalines **36**, **38**, and **39**, in which one of benzoquinoxaline units in **27** is respectively replaced by a dichloroquinoxaline, dinitroquinoxaline, and quinoxaline ring, were next examined. The fluorescence spectrum of **39** is similar to those of the cyclooctane-intercalated *syn*- and *anti*-bis-benzoquinoxalines (**28** and **42**), suggesting the intramolecular π,π-interaction between quinoxaline and benzoquinoxaline rings in **39** is insignificant (Figure 2b). However, the π,π-interaction becomes evident in **36** and **38**. As shown in Figure 2b and Table 2, compounds **36** and **38** exhibit a broad and structureless excimer emission band peaking at 488 and 553 nm, which are red-shifted by 385 and 2794 cm^{-1}, respectively, with respect to that of **39** (λ_{max} = 479 nm). When solvent was changed to DMSO, red-shifts by only 9 and 4 nm were observed respectively for **36** and **39**, and were comparable to the cases of **28** and **42**. However, a large red-shifted solvent effect was observed for **38**, by a magnitude of about 35 nm and twice of that in the case of **27**, indicating significant energy transfer between chromophores in the process of excimer formation.

The 1,2-dione group can act as the acceptor in intramolecular energy and electron-transfer processes.[16] The synthetic accessibility of donor−{cyclohexane}−acceptor systems, in which the quinoxaline ring and 1,2-dione group are uniquely situated face-to-face and in close proximity with an estimated distance of only about 4−5 Å, intrigued us to study the luminescence property of these systems. As shown in Figure 2c and Table 2, the di-X-quinoxaline−{cyclohexane}−α-dione systems, where X = H (**29**), Me (**30**), MeO (**31**), and Cl (**32**), display fluorescence spectra of distinctive pattern (so are UV spectra, see the Supporting Information). Besides the emission band at 350−400 nm due to each disubstituted quinoxaline unit, α-diketo-quinoxalines **29**, **30**, **31**, and **32** each displayed a new emission band at 450−500 nm. In each case, the new emission band is separated from the short-wavelength one by more than 80 nm and can be attributed to the consequence of a rapid charge-transfer process between electron-donating quinoxaline and electron-accepting diketone units.

In summary, an efficient three-step synthetic approach (Scheme 1) to the U-shaped polycyclic compounds containing face-to-face aligned quinoxaline rings has been implemented. Examination of the luminescence property of the cyclohexane-intercalated quinoxaline systems has disclosed significant intramolecular excimer interaction between chromophores. The results suggest that the strategy appears practical for developing configurationally different systems with electronically different quinoxaline-based chromophores, for the purpose of devising molecules that may prove to possess specific functions of interest, such as electron/energy transfer phenomena and host−guest complexation. Further work toward these aims is underway in this laboratory.

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Supporting Information Available: Experimental procedures with characterization data for all new compounds, absorption/emission spectra for compounds **17**−**39** and **42**, molecular structure for **17**, and X-ray crystallographic data for **17**, **18**, and **27** (CIF format). This material is available free of charge via the Internet at http://pubs.acs.org.

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(15) Waluk, J.; Grabowska A.; Pakulstroka, B. *J. Lumin.* **1980**, *21*, 277.
(16) Lokan, N.; Paddon-Row, M. N.; Smith, T. A.; La Rosa, M.; Ghiggino, K. P.; Speiser S. *J. Am. Chem. Soc.* **1999**, *121*, 2917.