Probing the periphery of dendrimers by heterogeneous electron transfer†

K. Krishnamoorthy, Raghunath Reddy Dasari, Arpornrat Nantalaksakul and S. Thayumanavan*

Received (in Austin, TX, USA) 3rd October 2006, Accepted 3rd December 2006
First published as an Advance Article on the web 18th January 2007
DOI: 10.1039/b614236b

The accessibility of the electroactive periphery was studied and compared for dendrimers and linear analogs by heterogeneous electron transfer using microelectrodes.

Incorporation of electroactive functionalities within dendritic architectures has been of interest for two main reasons, biomimetics and sensors.[1] The redox behavior of a functionality incorporated at the focal point of a dendron or at the core of a dendrimer can be very different from that of a fully-solvated small molecule analog.[1,2] Such an encapsulation afforded by dendrimers is often compared to that provided by proteins to electroactive cofactors. While the differences in redox behavior with increase in generation for functionalities at the core of a dendrimer are well-studied,[3] little is known about the dendritic effect at the periphery. Conventional wisdom about dendrimers could suggest that increasing the generation would have little or no effect upon the functionalities at the periphery, since these units are generally considered to be solvent-exposed. We have recently shown, in a systematic study that probed every layer of a dendron, that there is a significant difference in accessibility of the peripheral functionalities with generation using Stern–Volmer quenching experiments.[4] It is useful to understand whether such differences exist even in the case of heterogeneous electron transfer processes. Because, while the nature of the fluorescence quencher also has an effect on the accessibility of the fluorophore,[5] heterogeneous electron transfer will be a direct indication of folding and encapsulation properties and is relevant to applications such as sensing and biomolecular recognition.

In this paper, we report the redox behavior of a diarylaminopyrene unit at the periphery of a dendrimer. The main complication in such a study involves the generation-dependent differences in the number of redox reactions within a single dendrimer molecule.[6] This is because the number of peripheral functionalities doubles with each generation in an AB_2 dendrimer. To circumvent this, we utilize dendrimers that have an identical number of electroactive functionalities independent of generation. These dendrimers are represented as structures **G1–G3** in Chart 1. Since we have recently reported on the syntheses of these dendrimers along with the corresponding fully functionalized analogs (**G1F–G3F**) and the linear analogs (**G1L–G3L**),[7] we make a comparison of these three architectures in the redox behavior.

Department of Chemistry, University of Massachusetts, Amherst 01003, USA. E-mail: thai@chem.umass.edu; Fax: 413-545-4490; Tel: 413-545-1313

† Electronic supplementary information (ESI) available: Experimental details. See DOI: 10.1039/b614236b

The electrochemical experiments were carried out using a Pt microelectrode (25 μm diameter) in argon atmosphere using Ag/Ag^+ as the reference electrode and a Pt wire as the counter electrode with 0.1 M TBAHFP as supporting electrolyte in dichloromethane (DCM). Microelectrodes were used to circumvent issues related to capacitance, polymer formation, and deposition from the electroactive species.[8] An example of a steady state voltammogram (SSV) obtained by sweeping the potential of the microelectrode between 200 mV and 800 mV using diarylaminopyrene model compound **2** as analyte is shown in Fig. 1. The D_0 for the diarylaminopyrene was determined from the data obtained from the chronoamperogram and steady state voltammogram using the microelectrode. The slope from the plot of the ratio of the current in chronoamperometry and steady state voltammetry *vs.* $1/t^{1/2}$ (Fig. 2) was used to calculate the D_0 using the relationship,[9] $i_d(t)/i_{d,ss} = 0.7854 + (\pi^{1/2}/4)a(D_0t)^{-1/2}$, where $i_d(t)$ – current from chronoamperogram, $i_{d,ss}$ – current from the steady state voltammogram, a – radius of the electrode, D_0 – diffusion coefficient, t – time in chronoamperogram.

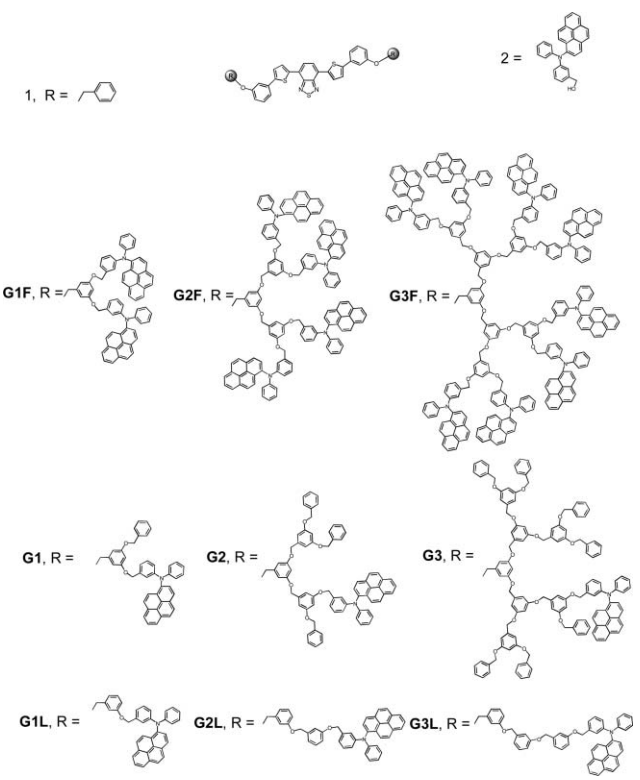

Chart 1 Structures of **2**, **G1–G3**, **G1F–G3F** and **G1L–G3L**.

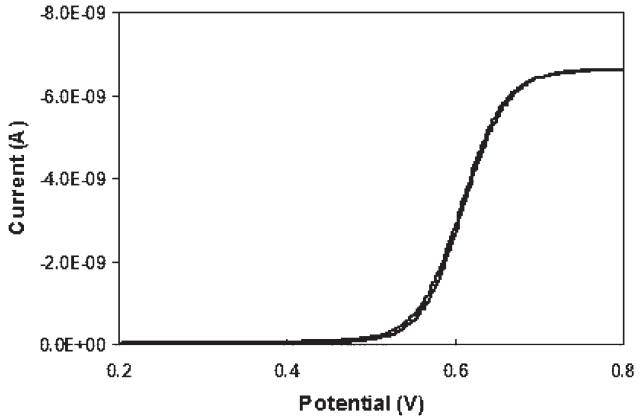

Fig. 1 Cyclic voltammogram of **2** using 25 μm Pt disk at a scan rate of 10 mV s^{-1}.

The D_0 thus obtained was substituted in the steady state equation to obtain "n" using the relationship, $i = 4nFaD_0C$, where n – number of electrons transferred, F – Faraday constant, a – radius of the electrode, C – concentration of the analyte. The n was found to be 1 for model compound **2**. In order to obtain D_0 and k^0 for the dendrimers and linear molecules from the experimental data points, it is necessary that we know the number of electrons transferred from the macromolecules. The cyclic voltammogram recorded using a macroelectrode showed a single redox wave for all the **F** dendrimers suggesting that there are no interactions among the multiple redox centres at the periphery. Therefore, the 'n' calculated for each of the dendrimers was taken to be equal to the number of diarylaminopyrene units present in the molecule.[10] The k^0 for all the molecules was calculated by following the reported procedure.[11] The k^0 for the dendrimers **G1** and **G2** did not vary significantly, but the **G3** dendrimer exhibits a rate constant that is four-times lower. The k^0 decrease in **G3** is likely due to the encapsulation of diarylaminopyrenes substituted on the periphery of the third generation dendrimer.

If this is really due to the presumed dendritic effect, then one would expect that the rate constants with the linear analogs of the dendrimers do not change with generations. This indeed was the case. The linear molecules, **G1L**, **G2L** and **G3L**, all exhibited similar k^0, as noted in Table 1. On the other hand, it is also possible that the little change in electrochemical behavior from

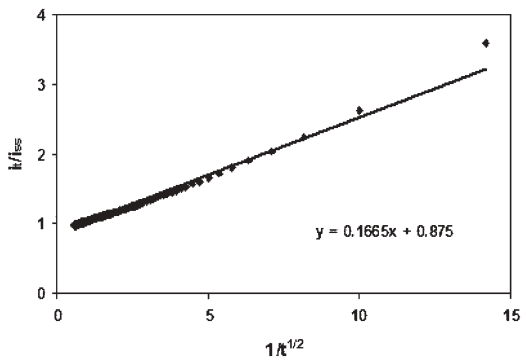

Fig. 2 Plot of the experimental ratio i_t/i_{ss} against inverse square root of time for the oxidation of **2** with a 25 μm Pt disk electrode.

Table 1 Electrochemical parameters for diarylaminopyrene in **G*n***, **G*n*L** and **G*n*F** series using Pt microelectrode

Molecules	n	$E_{1/2}$	D_0 (cm^2 s^{-1})[a]	k^0 (cm s^{-1})[a]
G1	2	658	$(1.0 \pm 0.1) \times 10^{-5}$	$(1.3 \pm 0.1) \times 10^{-3}$
G2	2	664	$(4.6 \pm 0.5) \times 10^{-6}$	$(1.4 \pm 0.1) \times 10^{-3}$
G3	2	685	$(2.4 \pm 0.2) \times 10^{-6}$	$(3.7 \pm 0.05) \times 10^{-4}$
G1L	2	607	$(8.3 \pm 0.1) \times 10^{-6}$	$(2.1 \pm 0.1) \times 10^{-3}$
G2L	2	609	$(6.6 \pm 0.5) \times 10^{-6}$	$(1.7 \pm 0.1) \times 10^{-3}$
G3L	2	612	$(4.4 \pm 0.2) \times 10^{-6}$	$(2.1 \pm 0.3) \times 10^{-3}$
G1F	4	660	$(5.9 \pm 0.2) \times 10^{-6}$	$(9.3 \pm 0.2) \times 10^{-4}$
G2F	8	664	$(4.9 \pm 0.1) \times 10^{-6}$	$(1.2 \pm 0.1) \times 10^{-3}$
G3F	16	667	$(1.7 \pm 0.1) \times 10^{-6}$	[b]

[a] The error values were calculated from four independently fabricated Pt microelectrodes. [b] Calculation of k^0 was not possible, (see the text for explanation).

G1L through **G3L** may also be due to a relatively minimal increase in molecular weight across this series. The situation was slightly different in the case of the fully decorated dendrimers **G1F–G3F**. In these molecules, **G1F** and **G2F** exhibit similar k^0, which is similar to that observed with the difunctionalized dendrimers **G1** and **G2**. We were not able to estimate the rate constant for **G3F**, since we were not able to fit the data into the quasi-reversible model that is used for the k^0 estimation.[11]

Similarly, we compared the $E_{1/2}$ values for each of these dendrimers. The $E_{1/2}$ of **G1** is about 658 mV and increases slightly to 664 mV for **G2**. However, when the generation increases from **G2** to **G3**, this number increases significantly (by 21 mV). From the kinetic data (k^0), we understand that the diarylaminopyrene unit is more encapsulated in **G3** compared to **G2**. If this were the case, the encapsulated electroactive unit would be in a different microenvironment compared to the bulk solvent. Since this environment is partially influenced by the dendrimer backbone containing aryl functionalities, it is likely that the polarity experienced by the electroactive unit is less than that of the electrolyte-containing solvent medium. It is reasonable to expect that the radical cation of the diarylaminopyrene is less stable in a less polar environment and we suggest that this translates into the 21 mV difference in $E_{1/2}$.

It is intriguing to note that the redox potential of **G3F** did not change significantly from **G2F**. It could be deceiving to think that this result suggests that there is no encapsulation in **G3F**, relative to **G2F** especially because the diarylaminopyrene units are larger than just the benzyl ether functionalities and therefore the effect is in fact expected to be higher. We attribute this to the accessibility of the electroactive functionalities to the electrode surface. In the case of **G1F–G3F**, the electrode surface has access to electroactive units in a variety of microenvironments, since some of these units are likely to be encapsulated, partially encapsulated, or fully solvent exposed. The electron transfer reaction would then happen at the most kinetically accessible (likely the most solvent exposed ones) diarylaminopyrene unit. Therefore, the redox potential of this reaction could be equivalent in both **G2F** and **G3F**. In the case of **G1–G3** on the other hand, the electrode is likely to feel a true average of the possible conformations that the dendrimer is likely to adopt with respect to the diarylaminopyrene unit (see Fig. 3 for a cartoon illustration). Therefore, the redox potential obtained here is a real average representation of the encapsulation of the peripheral units. An alternate and perhaps a less likely possibility is that the more electron rich diarylaminopyrene units around a

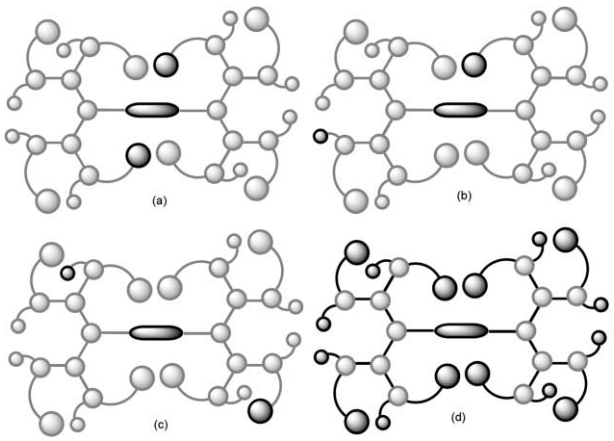

Fig. 3 Possible conformations of difunctionalized dendrimers (a–c) and fully decorated dendrimers (d). The schematic is to indicate that the peripheral functionalities in the difunctionalized dendrimers can be more exposed in one conformation compared to the other. The fully functionalized dendrimers, on the other hand, could always have some of the functionalities exposed and therefore results from these molecules could be misleading. Difunctionalized dendrimers represent the true average of the possible conformations.

radical cation in the **G3F** provide a better stabilization than the bare benzyl ether moieties in **G3**. The inherently lower $E_{1/2}$ values of the linear molecules **G1L–G3L** could be attributed to a much greater solvent exposure. However, we do not understand the large difference in magnitude even at the first generation stage between the dendrimers and the linear molecules.

In summary, we have shown that the electroactive units substituted at the periphery can be encapsulated significantly enough at higher generations to exhibit differences in electron transfer rates and radical ion stabilities. We have also shown that attempts to discern this information using the more classical, fully decorated dendrimers such as **G1F–G3F** could be deceiving. This study is likely to have implications not only in areas such as electrochemical sensing using dendrimers, but also in interpreting the polyvalent effects in biomolecular recognition using dendrimer scaffolds.[12] The results here show that the ligands at the periphery are not likely to be equally available for binding of dendrimers at higher generations. Therefore, the results from the polyvalent dendrimers have to be interpreted with this possibility in mind.

We thank the National Science Foundation for a CAREER award.

Notes and references

1 W. Ong, M. Gómez-Kaifer and A. E. Kaifer, *Chem. Commun.*, 2004, 1677; F. Diederich and B. Felber, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 4778; J. R. Aranzaes, C. Belin and D. Astruc, *Angew. Chem., Int. Ed.*, 2006, **45**, 132; C. Valério, E. Alonso, J. Ruiz, J.-C. Blais and D. Astruc, *Angew. Chem., Int. Ed.*, 1999, **38**, 1747; D. K. Smith and F. Diederich, *Chem. Commun.*, 1998, 2501; Y. Wang, C. M. Cardona and A. E. Kaifer, *J. Am. Chem. Soc.*, 1999, **121**, 9756; S. Hecht and J. M. J. Fréchet, *Angew. Chem., Int. Ed.*, 2001, **40**, 74; H. D. Abrüna, *Anal. Chem.*, 2004, **76**, 310A.

2 C. M. Cardona and A. E. Kaifer, *J. Am. Chem. Soc.*, 1998, **120**, 4023; K. N. Jayakumar and S. Thayumanavan, *Tetrahedron*, 2005, **61**, 603; C. B. Gorman, J. C. Smith, M. W. Hager, B. L. Parkhurst, H. Sierzputowska-Gracz and C. A. Haney, *J. Am. Chem. Soc.*, 1999, **121**, 9958; C. B. Gorman and J. C. Smith, *Acc. Chem. Res.*, 2001, **34**, 60; C. S. Cameron and C. B. Gorman, *Adv. Funct. Mater.*, 2002, **12**, 17; D. L. Stone, D. K. Smith and P. T. McGrail, *J. Am. Chem. Soc.*, 2002, **124**, 856; P. R. Ashton, V. Balzani, M. Clemente-Leon, B. Colonna, A. Credi, N. Jayaraman, F. M. Raymo, J. F. Stoddart and M. Venturi, *Chem.–Eur. J.*, 2002, **8**, 673; F. E. Appoh, D. S. Thomas and H. Kraatz, *Macromolecules*, 2005, **38**, 7562; C. Turrin, J. Chiffre, D. Montauzon, G. Balavoine, E. Manoury, A. Caminade and J. Majoral, *Organometallics*, 2002, **21**, 1891; C. Chi, J. Wu, X. Wang, X. Zhao, J. Li and F. Wang, *Macromolecules*, 2001, **34**, 3812.

3 C. Valério, J. Fillaut, J. Ruiz, J. Guittard, J. Blais and D. Astruc, *J. Am. Chem. Soc.*, 1997, **119**, 2588; M. Suzuki, R. Nakajima, M. Tsuruta, M. Higuchi, Y. Einaga and K. Yamamoto, *Macromolecules*, 2006, **39**, 64; M. Daniel, J. Ruiz and D. Astruc, *J. Am. Chem. Soc.*, 2003, **125**, 1150; J. Palomero, J. A. Mata, F. González and E. Peris, *New J. Chem.*, 2002, **26**, 291; C. A. Nijhuis, F. Yu, W. Knoll, J. Huskens and D. N. Reinhoudt, *Langmuir*, 2005, **21**, 7866; S. Sengupta and S. K. Sadhukhan, *Organometallics*, 2002, **21**, 1891; B. González, I. Cuadrado, C. M. Casado, B. Alonso and C. J. Pastor, *Organometallics*, 2000, **19**, 5518; M. R. Bryce, W. Davenport, L. M. Goldenberg and C. Wang, *Chem. Commun.*, 1998, 945; C. F. Hogan, A. R. Harris, A. M. Bond, J. Sly and M. J. Crossley, *Phys. Chem. Chem. Phys.*, 2006, **8**, 2058.

4 K. Sivanandan, S. V. Aathimanikandan, C. G. Arges, C. J. Bardeen and S. Thayumanavan, *J. Am. Chem. Soc.*, 2005, **127**, 2020.

5 A. V. Sivakumar, S. B. Sandanaraj, C. G. Arges, C. J. Bardeen and S. Thayumanavan, *Org. Lett.*, 2005, **7**, 2809.

6 F. Marchioni, M. Venturi, P. Ceroni, V. Balzani, M. Belohradsky, A. M. Elizarov, H. Tseng and J. F. Stoddart, *Chem.–Eur. J.*, 2004, **10**, 6361.

7 A. Nantalaksakul, R. R. Dasari, T. Ahn, R. Al-Kaysi, C. J. Bardeen and S. Thayumanavan, *Org. Lett.*, 2006, **8**, 2981.

8 G. N. Kamau, T. M. Saccucci, G. Gounili, A. E. F. Nassar and J. F. Rusling, *Anal. Chem.*, 1994, **66**, 994; D. O. Wipf, E. W. Kristensen, M. R. Deakin and R. M. Wightman, *Anal. Chem.*, 1988, **60**, 306.

9 G. Denuault, M. V. Mirkin and A. J. Bard, *J. Electroanal. Chem.*, 1991, **308**, 27.

10 S. Nlate, J. Ruiz, V. Sartor, R. Navarro, J. Blais and D. Astruc, *Chem.–Eur. J.*, 2000, **6**, 2544; J. B. Flanagan, M. Shlomo, A. J. Bard and F. C. Anson, *J. Am. Chem. Soc.*, 1978, **100**, 4248.

11 M. V. Mirkin and A. J. Bard, *Anal. Chem.*, 1992, **64**, 2293.

12 M. L. Wolfenden and M. J. Cloninger, *J. Am. Chem. Soc.*, 2005, **127**, 12168; E. K. Woller and M. J. Cloninger, *Org. Lett.*, 2002, **4**, 7; D. Page and R. Roy, *Bioconjugate Chem.*, 1997, **8**, 714.