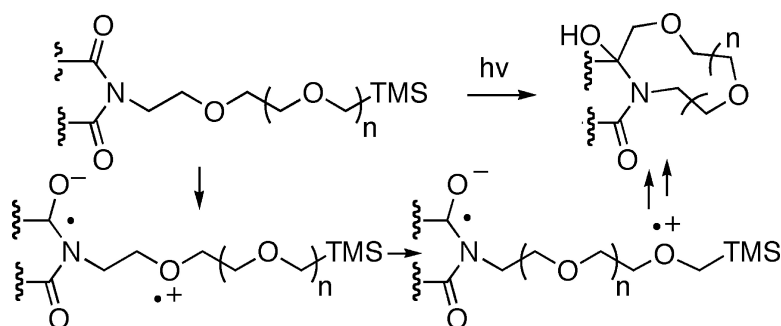


Single Electron Transfer-Promoted Photocyclization Reactions of Linked Acceptor–Polydonor Systems: Effects of Chain Length and Type on the Efficiencies of Macrocyclic Ring-Forming Photoreactions of Tethered α -Silyl Ether Phthalimide Substrates

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Single Electron Transfer-Promoted Photocyclization Reactions of Linked Acceptor–Polydonor Systems: Effects of Chain Length and Type on the Efficiencies of Macrocyclic Ring-Forming Photoreactions of Tethered α -Silyl Ether Phthalimide Substrates

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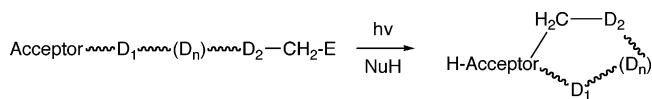
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Abstract: Results of an investigation, aimed at gaining information about the factors governing the efficiencies of single electron transfer (SET)-promoted photocyclization reactions of linked acceptor–polydonor systems, are described. One set of substrates used in this effort includes α -trimethylsilyl ether terminated, polymethylene- and polyethylenoxy-tethered phthalimides and 2,3-naphthalimides. Photocyclization reactions of the polyethylenoxy-linked phthalimides and naphthalimides were observed to take place in higher chemical yields and with larger quantum efficiencies than those of analogs containing polymethylene tethers of near equal length. These findings show that the rates of formation of $1,\omega$ -zwitterionic biradicals that serve as key intermediates in the photocyclization processes are enhanced in substances that contain oxygen donor sites in the chain. The findings suggest that these donor sites facilitate both initial SET to acceptor excited states and ensuing intrachain SET, resulting in migration of the cation radical center to the terminal α -trimethylsilyl ether position. In addition, an inverse relationship was observed between the quantum yields of photocyclization reactions of the tethered phthalimides and naphthalimides and the length of the polyethylenoxy chain. Finally, the roles played by chain type and length in governing photoreaction efficiencies were investigated by using intramolecular competition in photoreactions of polyethylenoxy and polymethylene bis-tethered phthalimides. Mechanistic interpretations and synthetic consequences of the observations made in this study are discussed.

Introduction

In recent investigations, we have used several approaches to gain an understanding of the mechanistic details and synthetic applications of single electron transfer (SET)-promoted photochemical reactions of linked polydonor–acceptor systems (Scheme 1). In earlier work in this area, we showed that phthalimides and maleimides that contain N-linked, α -trimethylsilylmethyl-terminated polyether, polythioether, polysulfonamide, and polypeptide chains undergo chemically efficient SET-promoted photocyclization reactions to produce interesting macrocyclic products.^{1–3} Examples of this synthetic protocol are found in the preparation of macrocyclic polyethers **3** and **4** through photocyclization reactions of α -(trimethylsilyl)methoxy-terminated phthalimides **1** and **2** (Scheme 2).³ The high chemical efficiencies and regiochemical selectivities of these excited-state

Scheme 1



processes are a consequence of efficient intramolecular SET from donor sites in the N-linked chains to the electronically excited phthalimide group. It has been proposed⁴ that the initial excited state SET event in these processes is followed by equilibration of the near equal energy zwitterionic biradicals by way of intrachain SET (ISET). Since silylophilic induced desilylation of the $1,\omega$ -zwitterionic biradicals **6** (Scheme 2) is a rapid process as compared to proton transfer from α -carbons at cation radical centers in the other zwitterionic biradicals,^{5,6} Curtin–Hammett type control guides preferential reaction at the silicon containing terminal positions. This generates $1,\omega$ -biradicals **5** which serve as precursors to the macrocyclic

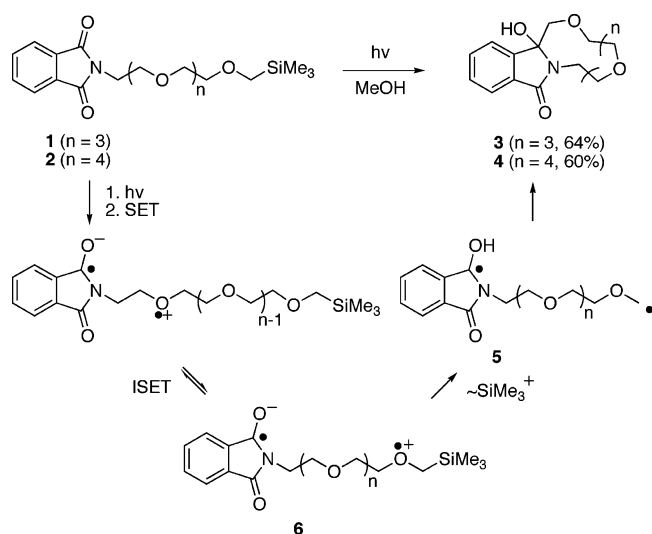
[†] Pusan National University.

[‡] University of New Mexico.

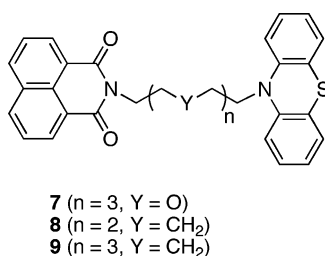
- (1) Yoon, U. C.; Oh, S. W.; Lee, J. H.; Park, J. H.; Kang, K. T.; Mariano, P. S. *J. Org. Chem.* **2001**, *66*, 939.
- (2) Yoon, U. C.; Jin, Y. X.; Oh, S. W.; Park, C. H.; Park, J. H.; Campana, C. F.; Cai, X.; Duesler, E. N.; Mariano, P. S. *J. Am. Chem. Soc.* **2003**, *125*, 10664.
- (3) Yoon, U. C.; Oh, S. W.; Mariano, P. S. *Heterocycles* **1995**, *41*, 2665.

- (4) Yoon, U. C.; Kwon, H. C.; Hyung, T. G.; Choi, K. H.; Oh, S. W.; Yang, S.; Zhao, Z.; Mariano, P. S. *J. Am. Chem. Soc.* **2004**, *126*, 1110.
- (5) Zhang, X. M.; Yeh, S. R.; Hong, S.; Freccero, M.; Albini, A.; Falvey, D. E.; Mariano, P. S. *J. Am. Chem. Soc.* **1994**, *116*, 4211.
- (6) Su, Z.; Falvey, D. E.; Yoon, U. C.; Oh, S. W.; Mariano, P. S. *J. Am. Chem. Soc.* **1997**, *120*, 10676.

Scheme 2



Scheme 3

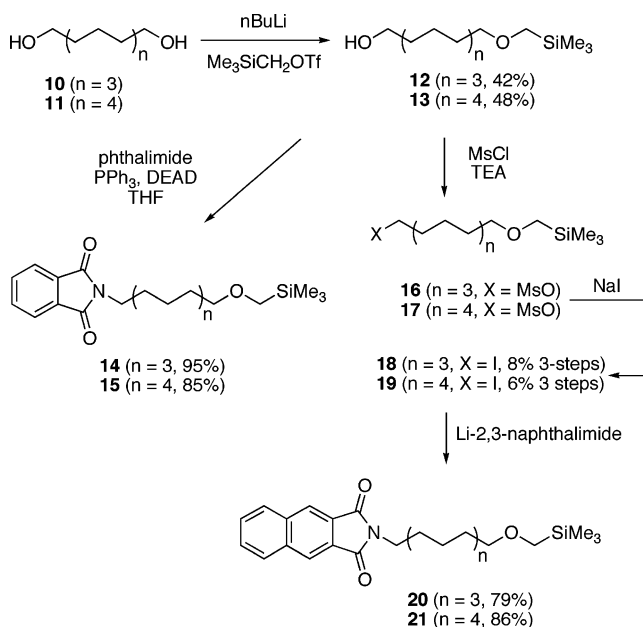


products. Contributing to the high efficiencies of these processes is the fact that the 1, ω -biradicals **5** are formed in these pathways under high-dilution conditions, an advantageous feature of reactions promoted by low flux light sources employed in preparative photochemical reactions.

An intriguing issue that arises from an analysis of the mechanistic route proposed for SET-promoted photocyclization reactions of linked acceptor–polydonor substrates of the type shown in Scheme 2 concerns the factors that govern the rates of the SET processes that lead to production of the reactive 1, ω -zwitterionic biradical intermediates. The rates of these processes should have little effect on chemical yields. However, since the initial SET and subsequent intrachain SET events compete with respective pathways for decay of the excited phthalimide and of zwitterionic biradical intermediates by back-SET (BSET), the rates should greatly influence the quantum efficiencies of the photocyclization reactions.

In an earlier collaborative investigation with Majima and his co-workers,⁷ preliminary information was gained about how long distance SET between linked acceptor–donor pairs is governed by the nature and length of the tether. In this effort, laser flash photolysis (LFP) techniques were employed to measure the rates of formation of terminal zwitterionic biradicals from singlet and triplet excited states of 1,8-naphthalimide–phenothiazine dyads **7** and **9** (Scheme 3) that are linked by near equal length polymethylene and polyethylenoxy chains. The results show that the rates of formation of terminal zwitterionic biradicals are larger in both the singlet and triplet manifold for the polyethylenoxy-linked **7** (S^1 3.5×10^9 s⁻¹, T^1 1.0×10^9 s⁻¹) versus

Scheme 4



the polymethylene linked **9** (S^1 1.0×10^9 s⁻¹, T^1 2.6×10^8 s⁻¹) dyads. In addition, an inverse dependence of polymethylene chain length on the singlet and triplet charge-transfer rates was observed. Accordingly, the rates of formation of terminal zwitterionic biradicals from the singlet and triplet excited states of the eight-methylene-tethered dyad **8** (S^1 4.5×10^9 s⁻¹, T^1 3.8×10^8 s⁻¹) are larger than those of the 11-methylene counterpart **9** (S^1 1.0×10^9 s⁻¹, T^1 2.6×10^8 s⁻¹).

The preliminary findings summarized above stimulated the current investigation aimed at gaining detailed information about how chain type and length govern the quantum efficiencies of SET-promoted photocyclization reactions of linked acceptor–polydonor substrates. These studies were carried out by using α -(trimethylsilyl)methyl ether terminated, polymethylene- and polyethylenoxy-tethered phthalimides and 2,3-naphthalimides. The results of this effort demonstrate that the rates of formation of key 1, ω -zwitterionic biradical intermediates from the excited states of linked donor–acceptor systems are enhanced in substrates which contain intervening oxygen donor sites in the connecting chain and are inversely dependent on the chain length. These findings along with a proposal for the detailed mechanism followed in SET-promoted reactions of linked polydonor–acceptor systems are presented below.

Results

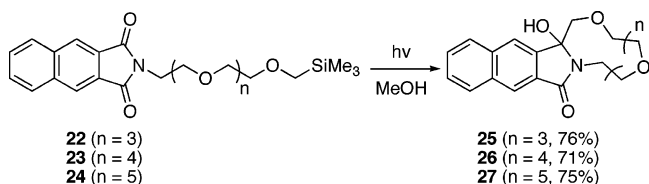
Photocyclization Quantum Yields. The effects of chain type and length on the absolute and relative quantum efficiencies of SET-promoted photocyclization reactions of linked α -silylether phthalimide and 2,3-naphthalimide substrates were determined. The polymethylene-containing substrates **14**, **15**, **20**, and **21** employed in this study were prepared starting with the known^{8,9} diols **10** and **11** by using the sequences shown in Scheme 4. The corresponding polyethylenoxy-linked phthalimides **1** and **2** (Scheme 2) and 2,3-naphthalimides **22**–**24** (Scheme 5) were

(8) Narasimhan, S.; Madhavan, S.; Ganeshwar Prasad, K. *J. Org. Chem.* **1995**, *60*, 5314.

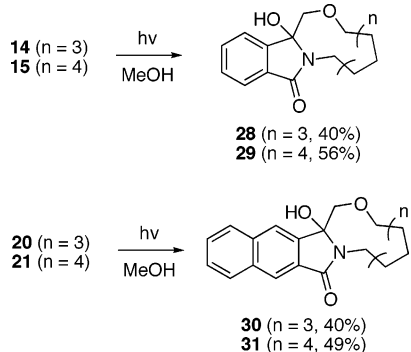
(9) Muller, T.; Grandbarbe, L.; Moraga, E.; Heuschling, P.; Luu, B. *Bioorg. Med. Chem. Lett.* **2004**, *14*, 6023.

(7) Cho, D. W.; Fujitsuka, M.; Sugimoto, A.; Yoon, U. C.; Mariano, P. S.; Majima, T. *J. Phys. Chem. B* **2006**, *110*, 11062.

Scheme 5



Scheme 6



Scheme 7

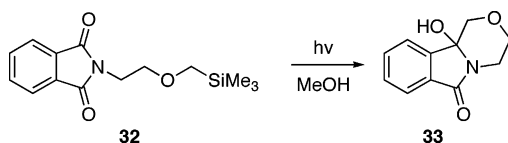


Table 1. Quantum Yield for Photomacrocyclization Reactions of Phthalimides 1, 2, 14, and 15

phthalimide	photoproduct	quantum yield
1	3	0.11
2	4	0.07
14	28	0.04
15	29	0.02

synthesized by the procedures used in our earlier work in this area.^{3,10}

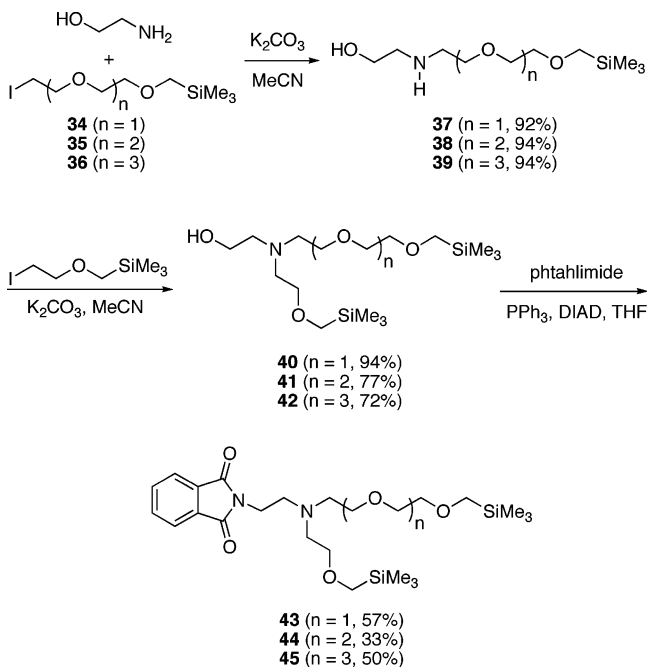
In previous studies,^{3,10} we showed that preparative photoreactions of the polyethylenoxy substrates in methanol take place with high chemical yields to generate the corresponding macrocyclic polyethers (Schemes 2 and 5). In contrast, irradiation (Pyrex $\lambda > 290$ nm) of methanol solutions of the polymethylene analogs **14**, **15**, **20**, and **21** results in formation of the respective macrocyclic amidols **28–31** in only moderate yields (Scheme 6).

Absolute quantum yields for photocyclization reaction of polymethylene and polyethylenoxy-linked phthalimides were determined by using the known¹¹ photoreaction of the (silylmethoxy)ethyl-phthalimide **32** (Scheme 7) as the actinometer ($\Phi = 0.22$). For this purpose, parallel photoreactions were carried out to varying low (5–20%) conversions, which enabled (by extrapolation) the determination of quantum yields at 0% conversion. The results, presented in Table 1, show that quantum efficiencies for formation of the macrocycle polyethers decrease with increasing length of the polyethylenoxy chain. In addition, the nature of the linking chain has a pronounced effect on the quantum efficiencies of photomacrocyclization reactions of the

Table 2. Relative Quantum Yields for Photomacrocyclization Reactions of 2,3-Naphthalimides 20–24

2,3-naphthalimide	photoproduct	rel quantum yield
20	30	0.3
21	31	0.2
22	25	1.0
23	26	0.7
24	27	0.5

Scheme 8



tethered silylether-phthalimide substrates. The latter point is exemplified by the larger quantum yields for formation of the macrocyclic polyethers ($\Phi(1-3) = 0.11$, $\Phi(2-4) = 0.07$) as compared to those of the corresponding phthalimides linked by near equal length, nonelectron donor containing, polymethylene chains ($\Phi(14-28) = 0.04$, $\Phi(15-29) = 0.02$).

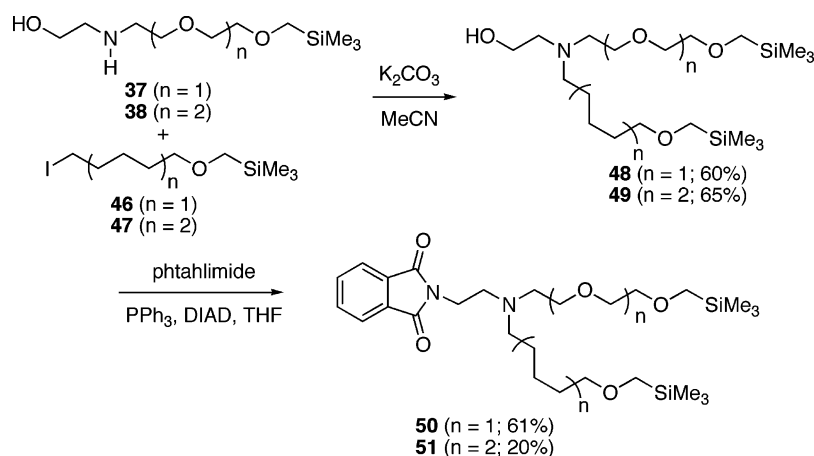
Studies with the related 2,3-naphthalimides **20–24** led to similar results. In these cases, relative quantum yields were determined by using parallel, low conversion photoreactions. For this purpose, the quantum yields for photocyclization reactions of these substances were measured relative to that of **22**, which is arbitrarily assigned a relative quantum yield of 1. The results, given in Table 2, again clearly show that relative quantum efficiencies for macrocyclic product formation decrease as the length of the polyethylenoxy tether increases. Also, the presence of oxygen donor sites in the chain linking the naphthalimide acceptor and α -silylether donor sites enhances the relative quantum efficiencies of the photomacrocyclization reactions.

Product Distributions in Photoreactions of Bis-Tethered Substrates. Another approach used to probe the effects of chain length and type on the efficiencies of SET-promoted photomacrocyclization reactions of linked acceptor-donor systems focuses on product distributions arising in reactions of bis-tethered phthalimides **43–45** (Scheme 8) and **50** and **51** (Scheme 9). The substrates used in this effort contain polymethylene and polyethylenoxy chains of different lengths. In SET-promoted photochemical reactions of these substrates, relative quantum efficiencies for intramolecularly competitive reactions

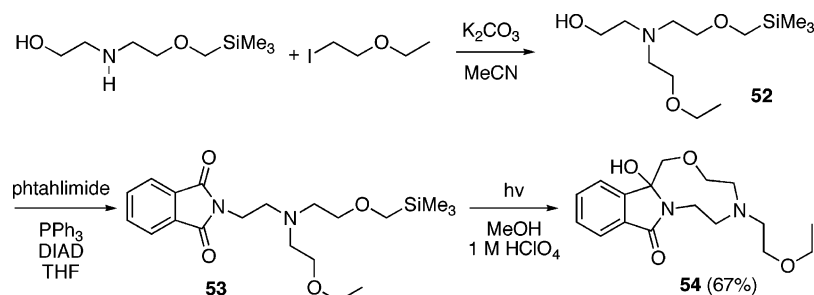
(10) Wang, R.; Zhao, Z.; Mariano, P. S.; Choi, K. H.; Kim, S. H.; Yoon, U. C. *J. Photochem. Photobiol., A: Chem.* **2005**, *175*, 232.

(11) Yoon, U. C.; Kim, J. W.; Ryu, J. Y.; Cho, S. J.; Oh, S. W.; Mariano, P. S. *J. Photochem. Photobiol., A: Chem.* **1978**, *106*, 145.

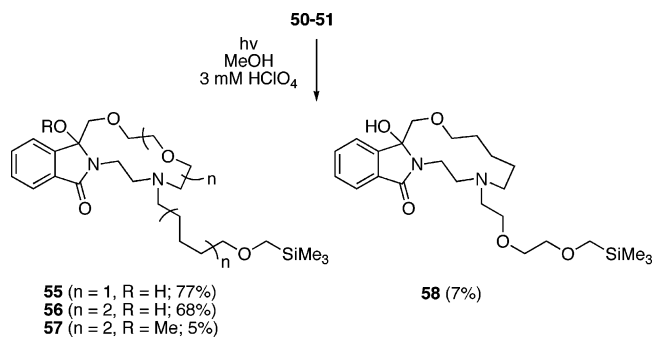
Scheme 9



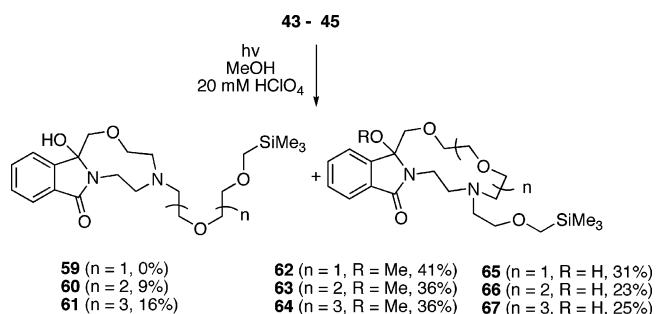
Scheme 10



Scheme 11



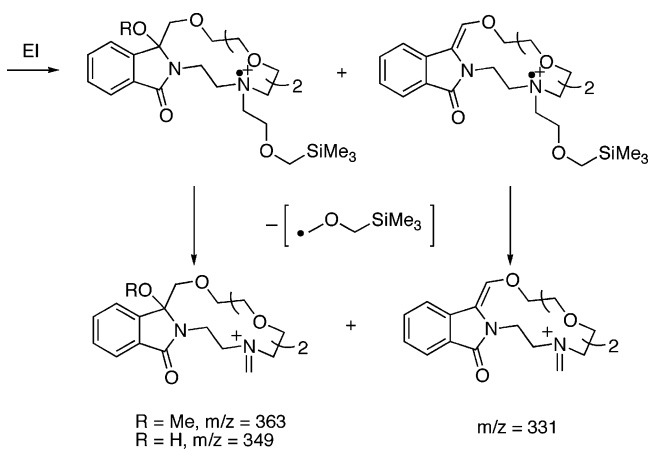
Scheme 12



taking place by way of formation and desilylation of two different terminal α -silyl ether cation radicals are reflected in the relative yields of two possible macrocyclic products.

Preparation of the bis(polyethylenoxy) analogs, starting with ethanolamine and the known³ iodo polyethers **34**–**36**, followed the sequences given in Scheme 8. The mixed polyethylenoxy–polymethylene-substituted phthalimides **50** and **51** were synthesized from the known¹² iodoalkyl ethers **46** and **47** by using

Scheme 13



amino alcohols **37** and **38** and the two-step routes shown in Scheme 9. Finally, to confirm that reactions of the bis-tethered phthalimides follow the general trend that cation radical desilylation takes place more rapidly than α -deprotonation,^{5,6} we studied the photochemistry of the unsymmetric bis(ethylenoxy)-branched phthalimide **53**. This substance was prepared by using the sequence shown in Scheme 10.

Photoreaction of each substrate was promoted by irradiation (Pyrex, $\lambda > 290$ nm) of a methanol solution containing HClO_4 . The presence of acid in each solution results in protonation of the tertiary amine moiety, thus preventing undesired SET from this donor site.⁴ Photomacrocyclization reactions of the bis-tethered phthalimides result in formation of the products and isolated yields given in Schemes 10–12. Accordingly, the cyclic

(12) Yoon, U. C.; Oh, J. H.; Lee, J. S.; Kim, D. U.; Lee, J. G.; Kang, K. T.; Mariano, P. S. *Bull. Korean Chem. Soc.* **1992**, *13*, 166.

Table 3. Major Fragment Ions in the EI Mass Spectra of Photoproducts Generated by Irradiation of Bis-Tethered Phthalimides **43–45**, **50**, and **51**

photoproduct	fragment ions			
	<i>m/z</i> obsd (% rel intens)	<i>m/z</i> calcd/molec form	<i>m/z</i> obsd (% rel intens)	<i>m/z</i> calcd/molec form
55	305.1493 (32)	305.1464/C ₁₆ H ₂₁ N ₂ O ₄	287.1398 (100)	287.1406/C ₁₆ H ₁₉ N ₂ O ₃
56	349.1771 (40)	349.1773/C ₁₈ H ₂₅ N ₂ O ₅	331.1664 (100)	331.1666/C ₁₈ H ₂₃ N ₂ O ₄
57	363 (22)		331 (100)	
58	303.1707 (48)	303.1706/C ₁₇ H ₂₃ N ₂ O ₃	285.1609 (100)	285.1610/C ₁₇ H ₂₁ N ₂ O ₂
60	261 (37)		243.1136 (50)	243.1135/C ₁₄ H ₁₅ N ₂ O ₂
61	261 (23)		243 (100)	
62	319 (34)		287 (100)	
63	363 (32)		331.1657 (60)	331.1657/C ₁₈ H ₂₃ N ₂ O ₄
64	407 (79)		375 (80)	
65	305 (67)		287 (100)	
66	349.1763 (80)	349.1763/C ₁₈ H ₂₅ N ₂ O ₅	331 (100)	
67	393 (78)		375 (73)	

amidol **54** is generated as the exclusive macrocyclic product upon irradiation of the bis-tethered phthalimide **53** (Scheme 10). In addition, macrocyclic amido–alcohols **55** and **58** are formed in the photoreaction (MeOH, 3 mM HClO₄) of the mixed-tethered phthalimide **50** in respective yields of 77% and 7% (Scheme 11). In contrast, irradiation of the longer chain mixed polyethylenoxy–polymethylene phthalimide **51** gives rise to the exclusive formation of amido–alcohol **56** and amido–ether **57**. Similarly, irradiation of the bis(polyethylenoxy)-tethered phthalimides **43–45** in MeOH containing 20 mM HClO₄ brings about formation of product mixtures comprised of macrocyclic amido–alcohols and amido–ethers (Scheme 12). In all cases, the amido–ethers originate from the corresponding amido–alcohols by way of a documented acid-catalyzed methanol–water exchange process taking place under the conditions used for these photoreactions.⁴

Structure assignments to the products formed in these photomacrocyclization reactions are complicated in most cases by ambiguities associated with the interpretation of NMR data. Specifically, although the existence of the phthalimide-derived amido alcohol and amido ether groups in these substances is easily demonstrated by the presence of characteristic ¹H and ¹³C NMR resonances, except for **54**, it is difficult to distinguish between the formed ring and residual side chain groups in the photoproducts by employing these or any other spectroscopic methods. Further retarding structure assignments is the fact that these substances resist crystallization. As a result, we have resorted to an old method employing electron-impact (EI) mass spectrometry to characterize the products generated in photocyclization reactions of the bis-tethered phthalimides. It is well-known that the major fragmentation reaction of amine nitrogen centered cation radicals, generated by EI-ionization, is β -cleavage to produce iminium ions and neutral radicals (Scheme 13). Thus, EI-promoted cleavage of the external β -carbon–carbon bond in the photoproducts should occur efficiently to yield iminium ions having *m/z* values that are characteristic of the nature of formed-ring and external-side chain moieties.

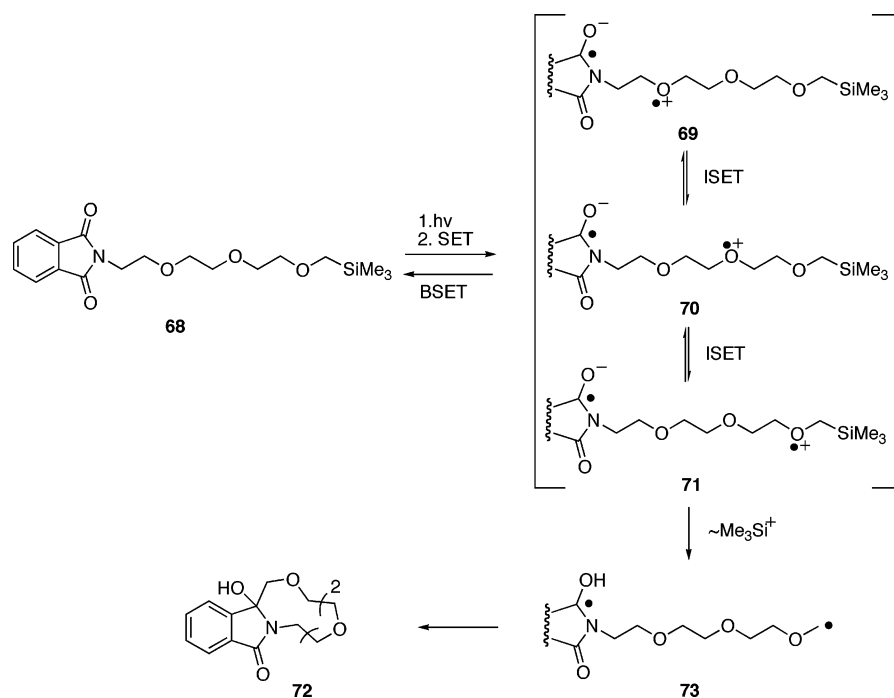
The results (Table 3) of EI-mass spectrometric analysis of the photoproducts of the reactions shown in Schemes 11 and 12 fully support the structure assignments made. For example, photoproducts **63** and **66**, formed in respective 36% and 23%

yields by irradiation of bis-tethered phthalimide **44**, show major peaks in their EI-mass spectra at *m/z* values that correspond to iminium ions generated by loss of the ((trimethylsilyl)methoxy)-methyl radical. Since it is well documented that loss of methanol or water takes place readily in substances of this type under mass spectrometric conditions,⁴ the mass spectra of **63** and **66** contain major charged fragments at *m/z* values (relative intensities) of 363 (32%) and 331 (60%) and at 349 (80%) and 331 (100%), respectively (Table 3). In contrast, the minor photoproduct **60** formed from **44** has an EI-mass spectrum which contains major peaks at *m/z* 261 (37%) and 243 (50%), corresponding to ions that arise by loss of the (((trimethylsilyl)methoxy)ethylen)oxy)methyl radical from the parent ion before and after loss of water. In addition, high-resolution measurements on selected fragment ions confirm that they have atomic compositions expected for iminium ions arising by loss of the side chain radicals from the parent ion directly or after loss of water or methanol. Similar observations/conclusions are made in analyzing the EI-mass spectra of the other products generated in photocyclization reactions of the bis-tethered phthalimides.

Discussion

The results presented above provide interesting information about mechanistic pathways involved in SET-promoted photocyclization reactions of linked acceptor–polydonor substrates. In addition, the findings give insight into factors that govern the quantum efficiencies of these processes. To set a framework to discuss the observations made and conclusion drawn, it is necessary to consider the possible mechanistic routes that can be followed in photocyclization reactions of acceptor–polydonor substrates. The (trimethylsilyl)methoxy-terminated, triethylenoxy-linked phthalimide **68** will be used for the purpose of illustration (Scheme 14). The possible pathways for conversion of the excited state of **68** to the macrocyclic polyether product **72** all share a common ending that involves generation and desilylation of the 1, ω -zwitterionic biradical **71**, leading to formation of the 1, ω -biradical **73** which then undergoes cyclization. In one limiting mechanism, the 1, ω -zwitterionic biradical **71** is generated directly by long-range SET from the terminal oxygen donor site in **68** to the phthalimide excited state. Alternatively, several stepwise routes initiated by SET

Scheme 14



from the less distant ether oxygen donors are also possible. In these cases, the initial SET event is followed by intrachain SET (ISET) to yield an equilibrating mixture of zwitterionic biradicals **69**–**71**. As mentioned above, product formation in these pathways is driven by Curtin–Hammett controlled desilylation of **71**.⁴ All three of the zwitterionic biradicals **69**–**71** can decay to the ground state of **68** by back single electron transfer (BSET). As a result, the quantum efficiency for photocyclization of **68** is governed by the relative rates of (1) formation of the zwitterionic biradicals by SET versus other modes of decay of the phthalimide excited state and (2) formation and desilylation of the $1,\omega$ -zwitterionic biradical **71** versus BSET from **69**–**71**.

As discussed above, significant differences exist between the quantum efficiencies of photocyclization reactions of polyethylenoxy- and polymethylene-tethered phthalimides and 2,3-naphthalimides. In all cases, the polyethylenoxy substrates react to form the corresponding macrocyclic products in higher chemical yields and quantum efficiencies than those of polymethylene-analogs having tethers of near equal length. If the reasonable assumption is made that these differences are due to enhanced rates of formation rather than desilylation or back-SET decay of the $1,\omega$ -zwitterionic biradical intermediates, the results show that the limiting mechanism involving direct SET from the terminal α -silylether donor site to the phthalimide excited-state is not the most quantum efficient pathway responsible for photocyclization reactions of the polyethylenoxy substrates. Potentially more efficient routes for these processes are those in which initial SET takes place from more closely positioned oxygen donor sites within the chain. As expected, on the basis of a wealth of previous observations made in studies of distance dependencies of intramolecular SET,^{13–16} the rates

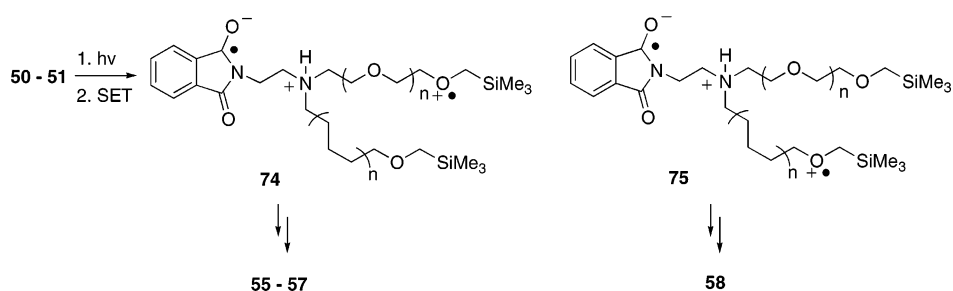
SET from oxygen donor sites in the chain should decrease dramatically as their distances from the phthalimide chromophore increase. For product formation to take place in photoreactions initiated by SET from close oxygen donor sites, intrachain SET¹⁷ leading to eventual generation of the $1,\omega$ -zwitterionic biradicals (e.g., **71**) must be competitive with BSET from the initially and subsequently formed zwitterionic biradical intermediates (e.g., **69** and **70**). The fact that the quantum efficiencies for photocyclizations of polyethylenoxy-tethered substrates are higher suggests that this is the case. However, as the number of intervening oxygen donor sites in the interconnecting chain increases, back-SET from the intermediate zwitterionic biradicals increasingly limits the fraction of the initially formed zwitterionic biradicals that are transformed to the key $1,\omega$ -zwitterionic biradical in the product forming pathway.¹⁹

In summary, the higher quantum efficiencies associated with photomacrocyclization reactions of trimethylsilylmethyl-terminated, polyethylenoxy-tethered phthalimides and 2,3-naphthalimides are a consequence of the fact that these processes can be initiated by short distance SET from near oxygen donor sites and that formation of the key $1,\omega$ -zwitterionic biradicals can take place by intrachain-SET. This mechanistic proposal gains additional support from observations made in studies with the bis-tethered phthalimides **50** and **51**. In these systems, photocyclization reactions can take place via two competitively

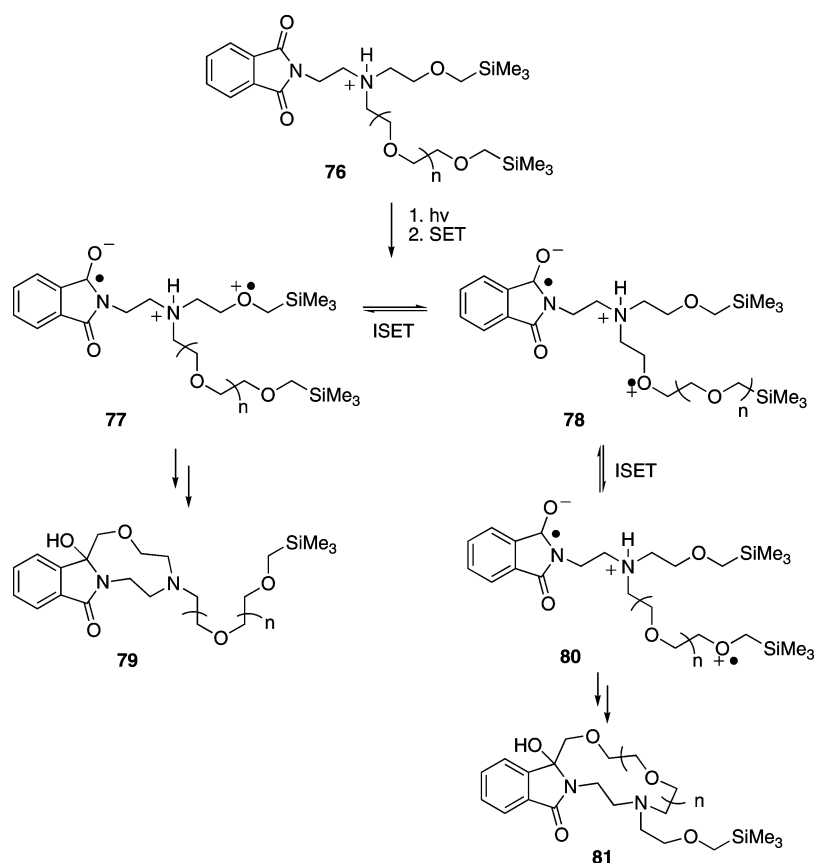
- (13) Larsson, S.; Volosov, A. *J. Phys. Chem. B* **1986**, *85*, 2548.
 (14) Oevering, H.; Paddon-Row, M. N.; Heppener, M.; Oliver, A. M.; Cotsaris, E.; Verhoeven, J. W.; Hush, N. S. *J. Am. Chem. Soc.* **1987**, *109*, 3258.
 (15) Yonemoto, E. H.; Saupe, G. B.; Schmehl, R. H.; Hubig, S. M.; Riley, R. L.; Iveson, B. L.; Mallouk, T. E. *J. Am. Chem. Soc.* **1994**, *116*, 4786.

- (16) 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.
 (17) Theoretical studies by Robb and his co-workers¹⁸ have shown that this type of cation radical translocation in 1,2-diamines can take place by either an orbital overlap or through-bond mechanism.
 (18) Blancafort, L.; Jolibois, F.; Olivucci, M.; Robb, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 722.
 (19) This phenomenon is analogous to the decreasing rates of formation of $1,\omega$ -zwitterionic biradicals in polypeptide-linked electron donor–acceptor pairs (for examples, see refs 20–24).
 (20) Symons, M. C. *Free Radical Biol. Med.* **1997**, *22*, 1271.
 (21) Gray, H. B.; Winkler, J. R. *Ann. Rev. Biochem.* **1996**, *65*, 537.
 (22) Shin, Y. K.; Newton, M. D.; Isied, S. S. *J. Am. Chem. Soc.* **2003**, *125*, 3722.
 (23) Schanze, K. S.; Sauer, K. *J. Am. Chem. Soc.* **1988**, *110*, 1180.
 (24) Schanze, K. S.; Cabana, L. A. *J. Phys. Chem.* **1990**, *94*, 2740.

Scheme 15



Scheme 16



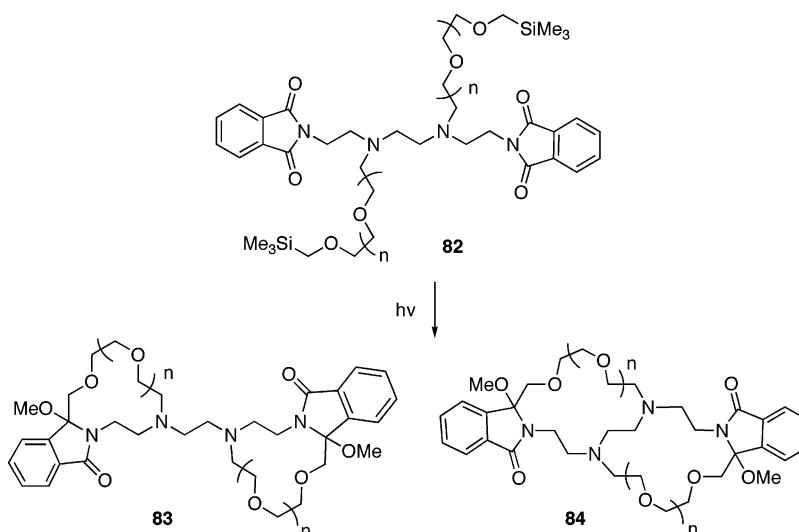
formed 1, ω -zwitterionic biradicals, one (**75**, Scheme 15) at the end of a polymethylene chain and the other (**74**) at the end of a near equal length polyethylenoxy tether. The availability of the more efficient indirect route for formation of **74**, initiated by short distance SET and driven by intrachain SET, is reflected in the exclusive or predominant formation of macrocyclic polyether products (e.g., **55–57** promoted by irradiation of **50** and **51**, Scheme 11).

As alluded to above, the inverse relationship observed between quantum efficiencies and the length of the polyethylenoxy chain in photoreactions of phthalimides **1** and **2** and 2,3-naphthalimides **22–24** is a consequence of increasingly competitive back-SET processes of intervening oxygen-centered zwitterionic biradical intermediates. In light of this proposal, the results arising from investigations with the bis(polyethylenoxy)-tethered phthalimides **43–45** are intriguing. At the outset, it was anticipated that irradiation of these substrates, which contain silyl ether-terminated polyethylenoxy chains of different lengths, would bring about regioselective production of products resulting from cyclization involving the shorter

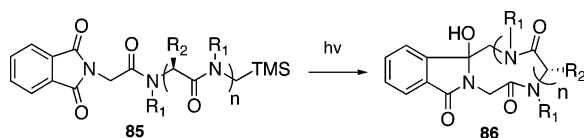
chain. Instead, photoreactions of the bis-tethered phthalimides result in either exclusive (for **43**, Scheme 12) or predominant (for **44** and **45**) formation of the larger ring containing products. The most dramatic example of this counterintuitive finding is seen in the photoreaction of **45** where competition takes place within chains containing one versus four oxygen donor sites. On the basis of the quantum yields of photoreactions of monotethered phthalimides that contain mono- and tetraethylenoxy chains, i.e., **32** ($\phi = 0.22$) and **1** ($\phi = 0.11$), we expected that reaction of **45** would form the small ring product **61** in a higher yield than that for the large ring products **64** and **67**. In fact, the combined yields of **64** and **67** (61%) are much higher than that of **61** (19%).

Although at first site surprising, the results arising from studies with **43–45** provide additional information about intricacies associated with SET-promoted photoreactions of acceptor–polydonor-linked reactants. The question here is why does formation of the larger chain 1, ω -zwitterionic biradical, the precursor of the larger ring products, occur more efficiently in SET-promoted photoreactions of the bis(polyethylenoxy)-

Scheme 17



Scheme 18



tethered phthalimides. Plausible answers to this question must take into account the actual ionization state of the substrates that participate in these reactions and how this affects the energetic changes associated with the initial and subsequent SET events. Since these reactions are conducted under strongly acidic conditions, the actual reactants are the corresponding ammonium salts **76** (Scheme 16). As a result, direct excited-state and subsequent intrachain SET processes produce cationic rather than zwitterionic biradicals. Consequently, the key intermediates in the competing photocyclization pathways are the $1,\omega$ - and $1,\omega'$ -cation biradicals **77** and **80** which undergo irreversible desilylation to produce biradical precursors of the respective small and large ring products. Importantly, there is no reason to believe that the rates of desilylation of **77** and **80** will be different. If anything, our earlier findings^{5,6} suggest that the higher energy content of **77**, caused in this case by the proximity of the two positively charged centers, would translate into more rapid methanol promoted desilylation of **77**. Consequently, the relative efficiencies of large and small ring forming photoreactions must be a consequence of the relative rates of formation of the cation biradical intermediates **77** and **80** versus their decay by back- or intrachain-SET.

When viewed from this perspective, several potential causes for the unexpected regiochemical courses followed in photoreactions of **43**–**45** become apparent. The first arises from a consideration of the rates of initial SET from the oxygen donor center in the short chain and the closest oxygen site in the longer chain. The charge repulsion caused, high-energy contents of cation radicals **77** and **78** should have a deleterious effect on the rate of their formation by direct SET to the phthalimide excited state. In contrast, SET from more remotely positioned oxygen donor sites in the longer polyoxygen-containing tethers would not be subject to this energetic/rate effect.

An alternate view of the effect of charge repulsion focuses on intrachain SET processes that occur subsequent to initial SET events. Charge repulsion in the proximal cation biradicals **77** and **78** should have a marked effect on the energetics associated with intrachain SET induced equilibration of all of the cation biradical intermediates. Specifically, owing to its high-energy content, the rate of formation of $1,\omega$ -cation biradical **77** from other cation biradicals in the equilibrating mixture could be much smaller than that of desilylation of the $1,\omega'$ -cation biradical **80**.⁴ If so, Curtin–Hammett type control would not be operable and reactions proceeding by formation and desilylation of **80** would predominate. Of course, as the length of the longer polyethylenoxy tether increases, the efficiencies for formation of the $1,\omega'$ -cation biradicals will decrease (see above). This is in accord with the experimental observations (Scheme 12) which show that photocyclization reactions taking place in the shorter tether of the bis-tethered substrates become increasingly competitive when the length of the longer polyethylenoxy chain increases.

Conclusions

The studies described above show that SET-promoted photoreactions of linked acceptor–polydonor substrates can take place through mechanistic pathways that involve indirect routes for production of key $1,\omega$ -zwitterionic biradical intermediates. Studies with phthalimides and 2,3-naphthalimides linked to α -(trimethylsilyl)methyl ether donors via polyethylenoxy versus polymethylene chains show that the availability of close oxygen donor sites and intrachain SET pathways causes photocyclization reactions of the polyethylenoxy-tethered substrates to occur in higher chemical yields and quantum efficiencies. Also, the results demonstrate that an inverse relationship exists between photocyclization efficiencies and the length of the polyethylenoxy tether. In polyethylenoxy polymethylene bis-tethered substrates, the enhanced efficiencies are reflected in highly regioselective reactions in which cyclizations via the polyethylenoxy chains greatly predominate.

In addition to mechanistic information, this effort has provided a foundation for synthetic applications of photoreactions of acceptor–polydonor substrates. One example of this is found

in the results of a parallel investigation²⁵ probing a new methodology for crown ether synthesis involving photocyclization reactions of bis(phthalimides) **82** (Scheme 17). Consideration of the chain length dependence of photocyclization reaction efficiencies observed in the current effort led to the prediction that irradiation of the bis(phthalimides) **82** would lead to formation of the bis(crown ethers) **83** rather than cryptand type products **84**. In fact, photocyclization reactions of these substrates are highly regioselective, yielding bis(crown) products exclusively. Another example of photocyclization reactions of acceptor–polydonor substrates that are driven by sequential short distance and intrachain SET comes from an earlier study² probing photochemical methods for the preparation of cyclic polypeptide analogs **86** starting with phthalimides **85** that contain α -silylamide donors linked by polypeptide chains (Scheme 18). In these cases, the highly structured nature of the polyamide tethers should inhibit direct SET from the silylamide donor site to the phthalimide excited state. In spite of this limitation,

(25) Sung, N. K.; Cho, D. W.; Choi, J. H.; Choi, K. W.; Yoon, U. C.; Maeda, H.; Mariano, P. S. *J. Org. Chem.* **2007**, *72*, 8831.

photocyclization reactions of **85** take place efficiently, most likely due to the availability of pathways in which initial SET occurs from close amide donors followed by intrachain SET transferring the cation radical center to the reactive terminal position.

We anticipate that the results of the investigations described above will be applicable to the mechanistic analysis and preparative applications of SET photochemical reactions of a variety of different types of linked acceptor–polydonor systems.

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Supporting Information Available: Experimental and NMR spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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