Efficient Charge Transport in DNA Diblock Oligomers

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Abstract: The realization of highly efficient photoinduced charge separation across the π-stacked base pairs in duplex DNA remains elusive. The low efficiencies (<5%) typically observed for charge separation over a dozen or more base pairs are a consequence of slow charge transport and rapid charge recombination. We report here a significant (5-fold or greater) enhancement in the efficiency of charge separation in diblock purine oligomers consisting of two or three adenines followed by several guanines, when compared to oligomers consisting of a single purine or alternating base sequences. This approach to wire-like behavior is attributed to both slower charge recombination and faster charge transport once the charge reaches the G-block in these diblock systems.

Introduction

The possibility that the π-stacked base pairs of duplex DNA might function as a conduit for charge transport has stimulated intensive experimental and theoretical investigation during the past two decades.[1] The "molecular wire paradigm" predicts rapid and efficient charge separation over long distances, as has been realized in synthetic donor−bridge−acceptor systems.[2] The occurrence of positive charge (hole) transport over several dozen base pairs in duplex B-DNA has been deduced from studies of photoinitiated oxidative bond cleavage at guanine[3] and from laser transient absorption measurements.[4] Strand cleavage studies have established that hole migration is more efficient in the poly(purine) sequences polyA and poly(AG) than in mixed purine−pyrimidine sequences,[5] presumably due to the lower oxidation potentials of A and G when compared to those of T and C. However, the goal of achieving highly efficient charge separation sequences remains elusive. In the relatively few cases where actual (as opposed to relative) rates and efficiencies have been measured, hole transport over long distances via natural bases has proven to be neither rapid nor efficient.[6,7] However,

significant enhancement in hole transport rates in base sequences incorporating 7-deazaguanine has recently been reported.[8]
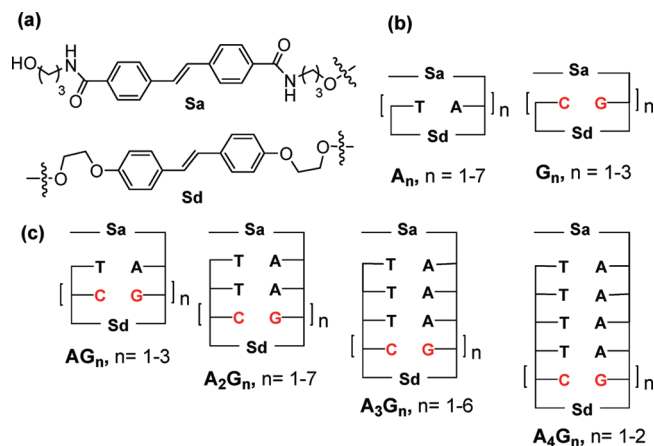
The efficiency of photoinduced charge separation in DNA, like other donor−bridge−acceptor systems, is limited by the competition between hole transport and charge recombination in the initially formed radical ion pair. Several approaches have been taken to avoid energy-wasting charge recombination. Schuster and co-workers have used anthraquinone (AQ), a strong electron acceptor known to undergo rapid intersystem crossing, in their studies of DNA strand cleavage.[9,10] Triplet electron transfer results in the formation of a triplet radical ion pair for which charge recombination would be spin-forbidden. However, quantum yields for the formation of long-lived AQ-DNA triplet charge-separated states have not been determined, and the quantum yields reported for strand cleavage using AQ are very low (<1%). Charge recombination can also be avoided by indirect methods of photochemical hole injection into DNA, including the photochemical cleavage reaction employed by Giese and co-workers.[11] These methods have been effectively employed to study relative yields of stand cleavage reactions but cannot be used to study the dynamics or absolute quantum yields of hole transport.

We have recently developed an experimental protocol that permits the direct determination of both the quantum yields and dynamics for photoinduced charge separation in a DNA-based system,[12−14] information that has not heretofore been available

(1) (a) Murphy, C. J.; Arkin, M. R.; Jenkins, Y.; Ghatlia, N. D.; Bossmann, S. H.; Turro, N. J.; Barton, J. K. *Science* **1993**, *262*, 1025–1029. (b) Schuster, G. B. *Top. Curr. Chem.* **2004**, *236*, 237.

(2) (a) Gust, D.; Moore, T. A.; Moore, A. L.; Lee, S. J.; Bittersmann, E.; Luttrull, D. K.; Rehms, A. A.; Degraziano, J. M.; Ma, X. C.; Gao, F.; Belford, R. E.; Trier, T. T. *Science* **1990**, *248*, 199–201. (b) Davis, W. B.; Svec, W. A.; Ratner, M. A.; Wasielewski, M. R. *Nature* **1998**, *396*, 60–63.

(3) (a) Henderson, P. T.; Johes, D.; Hampikian, G.; Kan, Y.; Schuster, G. B. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 8353–8358. (b) Núñez, M. E.; Hall, D. B.; Barton, J. K. *Chem. Biol.* **1999**, *6*, 85–97.

(4) Takada, T.; Kawai, K.; Fujitsuka, M.; Majima, T *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 14002–14006.

(5) (a) Giese, B.; Amaudrut, J.; Köhler, A.-K.; Spormann, M.; Wessely, S. *Nature* **2001**, *412*, 318–320. (b) Liu, C.-S.; Schuster, G. B. *J. Am. Chem. Soc.* **2004**, *125*, 6098–6102.

(6) Williams, T. T.; Dohno, C.; Stemp, E. D. A.; Barton, J. K. *J. Am. Chem. Soc.* **2004**, *126*, 8148–8158.

(7) Kawai, K.; Osakada, Y.; Fujitsuka, M.; Majima, T. *J. Phys. Chem. B* **2008**, *112*, 2144–2149.

(8) Kawai, K.; Kodera, H.; Osakada, Y.; Majima, T. *Nature Chem.* **2009**, *1*, 156–159.

(9) (a) Sanii, L.; Schuster, G. B. *J. Am. Chem. Soc.* **2000**, *122*, 11545–11546. (b) Schuster, G. B. *Acc. Chem. Res.* **2000**, *33*, 253–260.

(10) Liu, C.-S.; Hernandez, R.; Schuster, G. B. *J. Am. Chem. Soc.* **2004**, *129*, 2877–2884.

(11) Giese, B. *Acc. Chem. Res.* **2000**, *33*, 631–636.

(12) Lewis, F. D.; Zhu, H.; Daublain, P.; Cohen, B.; Wasielewski, M. R. *Angew. Chem., Int. Ed.* **2006**, *45*, 7982–7985.

(13) Lewis, F. D.; Daublain, P.; Cohen, B.; Vura-Weis, J.; Shafirovich, V.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2007**, *129*, 15130–15131.

(14) Lewis, F. D.; Daublain, P.; Cohen, B.; Vura-Weis, J.; Wasielewski, M. R. *Angew. Chem., Int. Ed.* **2008**, *47*, 3798–3800.

Chart 1. Structures for Stilbenes Sa and Sd (a) and for Capped Hairpins Possessing Mono- (b) and Diblock (c) Base Pair Sequences

Figure 1. UV/visible absorption spectra of A_2G_n in phosphate buffer (10 mM phosphate, 0.1 M NaCl, pH 7.2). The spectra are normalized at 335 nm.

Figure 2. Circular dichroism spectra of A_2G_n in phosphate buffer (0.1 M NaCl, 10 mM phosphate, pH 7.2).

for a single system. Our initial studies employed capped hairpin structures that possess electron acceptor and donor stilbene chromophores (Sa and Sd, respectively, Chart 1a) separated by polyA-polyT base pair domains consisting of $1-7$ base pairs (A_n, Chart 1b).[12] These studies provided an average efficiency (quantum yield) of ca. 7% and average transport times of ca. 3 ns/base pair for base pair domains consisting of $5-7$ A-T base pairs, hardly qualifying as wire-like behavior.[14] Even lower efficiencies were observed for base pair domains that include AT base sequences.[13] However, introduction of a single G-C base pair near the Sd hole acceptor in A_nGA polypurine sequences (where $n = 2-4$, but not 1) does result in a modest increase in separation efficiency when compared to A_n sequences that have the same total number of base pairs.[14] The requirement of two or three A-T base pairs separating G from the Sa electron acceptor for enhanced charge separation efficiency is reminiscent of our earlier studies of reversible hole transport between G and GG in A_nGAGG polypurine base pair sequences lacking a Sd hole trap.[15] These observations suggested that enhanced charge separation dynamics and efficiency might be achieved in properly designed polypurine sequences.

We report here the dynamics and efficiencies of charge separation in capped hairpins possessing polyG base pair domains (Chart 1b), diblock base pair domains consisting of $1-4$ adenines followed by $1-7$ guanines (Chart 1c), and several alternating base pair domains. Charge separation efficiencies of ca. 25% over distances as large as 36 Å and the formation of long-lived charge separated states are observed for the diblock systems A_2G_n and A_3G_n possessing two or three adenines and as many as seven guanines, substantially higher than the efficiencies for either homopurine (polyA or polyG) or alternating (AG, CG, or AT) base sequences. Moreover, the rate constants for charge separation are only weakly distance dependent in the longer diblock systems, and charge separation efficiencies are independent of the length of the guanine block. The use of diblock oligomers offers a promising approach to achieving efficient charge separation in synthetic π-stacked systems as well as in DNA. However, the low quantum yields reported for photoinduced charge separation between acridinium and phenothiazine chromophores separated by short A_mG_3
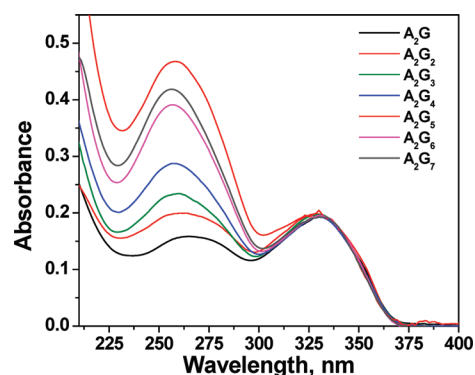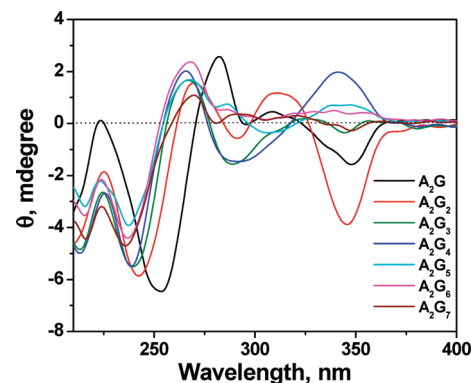
diblock sequences ($m = 0-3$)[7] underscores the necessity of controlling the dynamics of charge separation and charge recombination as well as hole transport in DNA-based systems.

Results

Ultraviolet and Circular Dichroism Spectra. Capped hairpins possessing G_n, AG_n, A_2G_n, A_3G_n, and A_4G_n mono- and diblock sequences (Chart 1b,c) and alternating sequences including AGAGAG, A_2GAGA, and A_2GCGC were prepared and characterized using the methods developed for the A_n conjugates.[16,17] Values of m/z obtained from MALDI-TOF mass spectrometry are reported in Table S1 (Supporting Information). The ultraviolet (UV) spectra of the A_2G_n and A_3G_n conjugates are shown in Figures 1 and S1 (Supporting Information), respectively. These spectra display a long-wavelength band at 330 nm attributed to the overlapping absorption of the Sa and Sd chromophores and a band at shorter wavelength attributed to the overlapping absorption of the base pairs and stilbenes. This band undergoes a blue shift and increase in absorbance as the number of G-C base pairs increases. Thermal dissociation profiles for the A_2G_n and A_3G_n conjugates (Figures S2,3) show incomplete melting upon heating to 90 °C.

The circular dichroism (CD) spectra of the A_2G_n conjugates are shown in Figure 2, and the spectra of the A_3G_n and several other conjugates are shown in Figures S4 and S5 (Supporting Information). The long-wavelength region of the CD spectra

(15) (a) Lewis, F. D.; Liu, J.; Zuo, X.; Hayes, R. T.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2003**, *125*, 4850–4861. (b) Lewis, F. D.; Liu, X.; Liu, J.; Miller, S. E.; Hayes, R. T.; Wasielewski, M. R. *Nature* **2000**, *406*, 51–53.

(16) Lewis, F. D.; Wu, Y.; Zhang, L.; Zuo, X.; Hayes, R. T.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2004**, *126*, 8206–8215.

(17) Lewis, F. D.; Zhu, H.; Daublain, P.; Fiebig, T.; Raytchev, M.; Wang, Q.; Shafirovich, V. *J. Am. Chem. Soc.* **2006**, *128*, 791–800.
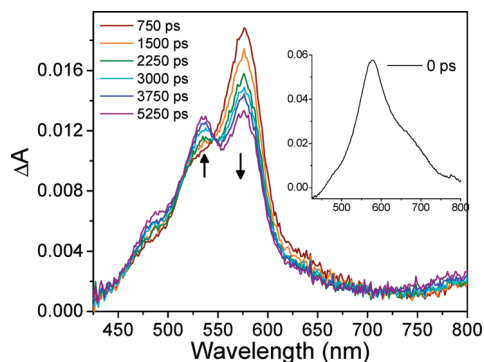
Figure 3. Transient spectra of A_2G_7 from 750 to 5250 ps. The $Sa^{-\bullet}$ radical anion absorbs primarily at 575 nm, while the $Sd^{+\bullet}$ radical cation absorbs at 535 nm. Growth of the $\Delta A_{525nm}/\Delta A_{575nm}$ ratio indicates formation of the fully charge-separated $Sa^{-\bullet}$-A_2G_7-$Sd^{+\bullet}$ state (Figure 5). Inset: Transient spectrum of the $^1Sa^*$ locally excited singlet state immediately after photoexcitation.

(300−375 nm) is assigned to exciton coupling between the two stilbene chromophores. The dependence of the sign and intensity of these bands upon the number of intervening base pairs is similar to that previously observed for capped hairpins and dumbbells having Sa chromophores at both ends of poly(A)-poly(T) base pair domains of variable length.[16,18] The variation in sign and intensity is a consequence of the dependence of exciton-coupled CD spectra upon both the distance between the stilbene chromophores and the dihedral angle between their electronic transition dipoles. The similarity of the exciton-coupled CD spectra for the A_mG_n systems and the previously studied Sa-Sa capped hairpins and dumbbells indicates that these systems have similar B-DNA geometries. The short-wavelength portions (200−300 nm) of the CD spectra for conjugates possessing two or more guanines (Figure 2) are similar to those for the duplexes formed by self-complementary oligonucleotides having alternating G_nC_n diblock sequences.[19] The CD spectra are consistent with the formation of stable capped hairpin structures rather than the G-quadruplex structures favored by single-strand G-tracts.

Transient Absorption Spectra. Femtosecond (fs) time-resolved transient absorption spectra in aqueous buffer were obtained as previously described for the A_n conjugates using 350 nm excitation (which provides selective excitation of Sa) from a Ti-sapphire-based system having a time resolution of ca. 180 fs, a spectral range of 425−800 nm, and a time window of 0−6 ns.[14] The transient spectra for conjugate A_2G_7 shown in Figure 3 are typical of longer diblock systems. Laser excitation initially yields a single absorption band with a maximum at 575 nm assigned to the locally excited $^1Sa^*$ singlet state. Subsequent growth of a 535 nm shoulder is attributed to the formation of the stilbenediamide anion radical $Sa^{-\bullet}$. The stilbenediether radical cation $Sd^{+\bullet}$ has a single strong absorption band at 535 nm, which grows in at later times. Because of the band overlap at 535 nm, charge separation times are determined from plots of the ratio of transient absorbance at 525 and 575 nm (Figure 4). This ratio rises from ∼0.4 for the $Sa^{-\bullet}$-$(A_mGn)^{+\bullet}$-Sd partially charge-separated state to ∼1.0 for $Sa^{-\bullet}$-A_mG_n-$Sd^{+\bullet}$. Neither $A^{+\bullet}$ nor $G^{+\bullet}$ absorbs strongly in this wavelength region.[20] The transient spectra of the longer diblock systems

(18) Lewis, F. D.; Zhang, L.; Liu, X.; Zuo, X.; Tiede, D. M.; Long, H.; Schatz, G. S. *J. Am. Chem. Soc.* **2005**, *127*, 14445−14453.
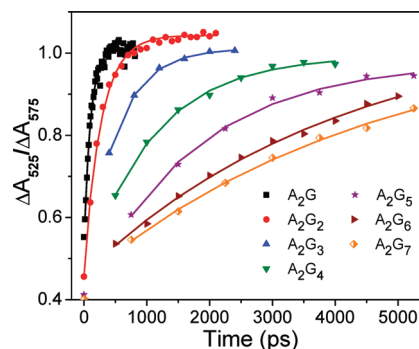(19) Gudibande, S. R.; Jayasena, S. D.; Behe, M. J. *Biopolymers* **1988**, *27*, 1905−1915.

Figure 4. Time-dependent 525/575 nm band intensity ratios for A_2G_n conjugates. The solid lines are single exponential fits to the data obtained following an initial fast rise attributed to reversible hole injection. Fewer data points were taken for longer sequences to avoid sample degradation.
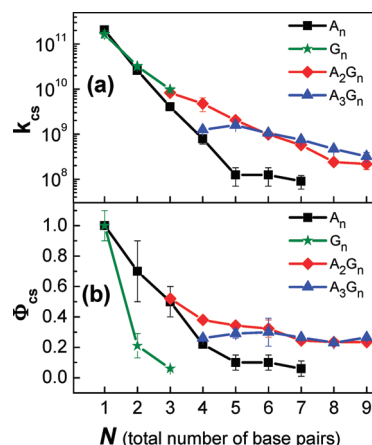

Figure 5. (a) Rate constants and (b) quantum yields for charge separation. In cases where no error bars are shown, the error is smaller than the size of the data marker.

do not decay on the time scale of our measurements, indicative of the formation of long-lived charge-separated states.

Plots of the time dependence of the $\Delta525/\Delta575$ nm ratio for the A_2G_n series (Figure 4) and the other conjugates have fast- and slow-rising components attributed to hole injection ($\tau_i \approx$ 30 ps) and formation of the $Sa^{-\bullet}$-A_mG_n-$Sd^{+\bullet}$ charge-separated state ($\tau_{cs} = 0.12−5$ ns), respectively.[17] Values of τ_{cs} (described as the hole arrival time in our previous publications) were obtained from single exponential fits to the slow-rising components of the $\Delta525/\Delta575$ nm ratio. Quantum yields for charge separation (Φ_{cs}) were estimated by comparing the integrated band intensities of the transient absorption spectra at long delay times with those for A_1 ($\Phi_{cs} = 1$). Values of τ_{cs} and Φ_{cs} for the G_n, AG_n, A_2G_n, A_3G_n, and A_4G_n systems are reported in Table 1 along with our published data for A_n systems.[14] Plots of $\log(k_{cs})$ ($k_{cs} = \tau_{cs}^{-1}$) and Φ_{cs} vs N, the total length of the base pair domain ($N = n + m$), for A_n, G_n, A_2G_n, and A_3G_n are shown in Figure 5. Charge separation times for capped hairpins possessing A_mGAGAG ($m = 1−3$) and A_mGCGC ($m = 1, 2$) sequences are too slow to measure on the time scale of our instrument, and Φ_{cs} values for these sequences are estimated to be <0.05.

(20) Yamagami, R.; Kobayashi, K.; Tagawa, S. *J. Am. Chem. Soc.* **2008**, *130*, 14772−14777.

Table 1. Quantum Yields for Charge Separation (Φ_{cs}) and Charge Separation Times (τ_{cs}) for Capped Hairpins Having a Total of N Base Pairs[a–c]

N	A_n	Φ_{cs}	τ_{cs}, ps	G_n	Φ_{cs}	τ_{cs}, ps	AG_n	Φ_{cs}	τ_{cs}, ps	A_2G_n	Φ_{cs}	τ_{cs}, ps	A_3G_n	Φ_{cs}	τ_{cs}, ps
1	A	1.0	5	G	1.0	6									
2	A_2	0.80	39	G_2	0.21	31	AG	0.70	32						
3	A_3	0.50	250	G_3	0.06	100	AG_2	0.40	100	A_2G	0.52	120			
4	A_4	0.23	1300				AG_3	0.15	250	A_2G_2	0.38	220	A_3G	0.26	760
5	A_5	0.10	4500							A_2G_3	0.34	490	A_3G_2	0.29	630
6	A_6	0.09	9000							A_2G_4	0.32	1000	A_3G_3	0.30	910
7	A_7	0.06	12000							A_2G_5	0.25	1700	A_3G_4	0.27	1300
8										A_2G_6	0.24	4200	A_3G_5	0.23	2100
9										A_2G_7	0.24	4600	A_3G_6	0.27	3100

[a] Structures for capped hairpins shown in Chart 1. Data shown are the average of at least two separate measurements. Errors are <10%. [b] Data for A_n series from ref 10. [c] Capped hairpins A_4G and A_4G_2 have values of Φ_{cs} = 0.16 and 0.15, respectively, and values of τ_{cs} = 945 and 1400 ps, respectively.
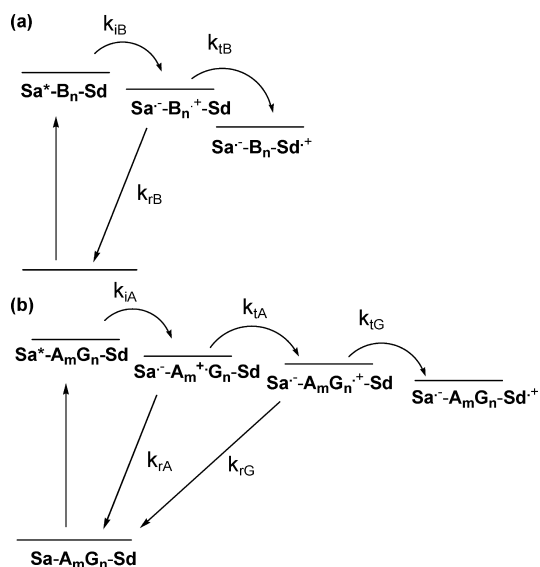

Figure 6. Simplified mechanisms for charge separation in (a) homo(purine) sequences (B = adenine or guanine) and (b) in A_mG_n diblock sequences. Within longer blocks, the positive charge could move by either a localized hopping or delocalized polaron mechanism.

Discussion

Charge Separation via Homopurine Sequences. As previously reported, the rate constants and quantum yields for charge separation in the A_n capped hairpins (Chart 1b) are strongly distance dependent at short distances ($N < 5$, Figure 5) but only weakly distance dependent at longer distances. The distance dependence of the charge separation rates was attributed to a crossover in charge separation mechanism from single-step tunneling at shorter distances to multistep hopping at longer distances;[17] however, the mechanism for charge separation in our systems remains a topic of active investigation.[21] A simplified hopping mechanism for charge separation via poly(A) or poly(G) is shown in Figure 6a. Hole injection from singlet Sa* into either A or G is highly efficient, and thus Φ_{cs} for the oligomers A_n and G_n is determined by the competition between the rate constants for hole transport (k_{tB}) and charge recombination (k_{rB}), and the charge separation time is determined by the sum of these rate constants (eq 1). We note that $\tau_{cs}^{-1} \sim k_{tB}$

when $k_{tB} \gg k_{rB}$. Previous studies of A-tract hole transport using either guanine or Sd as the hole trap have established that both k_{tB} and k_{rB} decrease as the A-tract becomes longer.[17,22,23]

$$\Phi_{cs} = k_{tB}/(k_{tB}+k_{rB}) \qquad \tau_{cs} = (k_{tB}+k_{rB})^{-1} \qquad (1)$$

Values of τ_{cs} for G_1 and G_2 are similar to those for A_1 and A_2 (Table 1). However, the value of τ_{cs} for G_3 is smaller than that for A_3, and the quantum yields for charge separation for G_2 and G_3 are substantially smaller than those for A_2 and A_3 (Figure 5b). Charge recombination is expected to be more rapid for G_n vs A_n systems as a consequence of the smaller energy gap for charge recombination from the $Sa^{-\bullet}/G^{+\bullet}$ versus $Sa^{-\bullet}/A^{+\bullet}$ radical ion pair.[24] Faster charge recombination results in smaller values for τ_{cs} and substantially less efficient charge separation in G_3 versus A_3 systems. The low value of Φ_{cs} for G_3 is consistent with a recent report from Kawai et al., who were unable to detect charge separation between acridinium and phenothiazine chromophores separated by three guanines.[7]

Charge Separation via Diblock Purines. Quantum yields and rate constants for charge separation in the A_mG_n diblock systems (Table 1) are dependent upon the length of both purine blocks. A simplified hopping mechanism for charge separation in diblock systems is shown in Figure 6b. We expect hole transport from the A to G blocks to be essentially irreversible on the 0−6 ns time scale of our measurements (Figure 4). Thus, Φ_{cs} will be determined by the product of the quantum yields Φ_{csA} and Φ_{csG} for the sequential formation of the $Sa^{-\bullet}-A_m-G_n^{+\bullet}-Sd$ and the $Sa^{-\bullet}-A_mG_n-Sd^{+\bullet}$ charge-separated states (eq 2). The values of Φ_{cs} for A_2G_n and A_3G_n sequences with two or more G's are substantially larger than the values for A_m sequences having the same total number of base pairs N (ca. 0.25 vs 0.06 for $N = 7$, Figure 5b). In addition, Φ_{cs} for these diblock systems is only weakly distance dependent, suggesting that moderately efficient charge separation could be observed using even longer G-blocks. Other sequences were less effective: values of Φ_{cs} = 0.15 for A_4G and A_4G_2 (Table 1, footnote c) are intermediate between the values for A_n and A_3G_n systems having the same total number of base pairs, and values of Φ_{cs} for AG_n and several alternating base sequences, including A_mGAGAG ($m = 1-3$) and A_mGCGC ($m = 1, 2$), are lower than those for A_n sequences having the same total number of base pairs.

(21) (a) Park, J.-H.; Choi, H.-Y.; Conwell, E. M. *J. Phys. Chem. B* **2004**, *108*, 19483–19486. (b) Grozema, F. C.; Tonzani, S.; Berlin, Y. A.; Schatz, G. C.; Siebbeles, L. D. A.; Ratner, M. A. *J. Am. Chem. Soc.* **2008**, *130*, 5157–5166. Siriwong, K.; Voityuk, A. A. *J. Phys. Chem. B* **2008**, *112*, 8181–8187.

(22) Lewis, F. D.; Wu, T.; Zhang, Y.; Letsinger, R. L.; Greenfield, S. R.; Wasielewski, M. R. *Science* **1997**, *277*, 673–676.

(23) Lewis, F. D.; Zhu, H.; Daublain, P.; Sigmund, K.; Fiebig, T.; Raytchev, M.; Wang, Q.; Shafirovich, V. *Photochem. Photobiol. Sci* **2008**, *7*, 534–539.

(24) Lewis, F. D.; Kalgutkar, R. S.; Wu, Y.; Liu, X.; Liu, J.; Hayes, R. T.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2000**, *122*, 12346–12351.

$$\Phi_{cs} = \Phi_{csA}\Phi_{csG} = [k_{tA}/(k_{tA}+k_{rA})][k_{tG}/(k_{tG}+k_{rG})] \quad (2)$$

All four of the rate constants in eq 2 are expected to be dependent upon the length of the purine blocks, complicating interpretation of the kinetic data for diblock systems. Our previous studies of Sa-linked hairpins having A_mG ($m = 1-4$) sequences but lacking a Sd hole trap have shown that both k_{tA} and k_{rG} are strongly distance dependent.[22] The value of k_{rG} for AG sequences is particularly large (ca. 1×10^{10} s^{-1}), thus accounting for the low values of Φ_{cs} for AG$_n$ systems. In A_2G_n hairpins ($n = 1-3$) lacking a Sd hole trap, k_{tA} is independent of n, but k_{rG} decreases with increasing n,[25] indicating that slower charge recombination as well as faster G-tract hole transport can contribute to the high efficiency of charge separation in the A_mG_n diblock systems. For the longer A_mG_n diblock systems we estimate a transport time of $0.5-1$ ns/base pair, faster than our estimate of ca. 3 ns/base pair for A_n sequences.[12]

Hole Transport Mechanism. The simplified mechanisms shown in Figure 6 do not specify the method of hole transport through A- or G-tract sequences consisting of more than one base pair. The mechanism of hole transport in DNA continues to be a topic of active investigation and debate among proponents of single-step superexchange, multistep hole hopping, and polaron drift mechanisms.[26] The weak distance dependence of τ_{cs} and the lack of distance dependence for Φ_{cs} in systems having multiple base pairs (Figure 5) are consistent with a hole hopping or polaron drift mechanism.[17] However, charge separation in short A_n systems and charge recombination over longer distances in A_n and other systems may occur via a single-step superexchange mechanism.[27] The extent of hole delocalization also continues to be an issue of debate between proponents of localized vs delocalized holes or polarons.[28] The results of our recent studies of charge separation and spin dynamics in DNA hairpins possessing the strong oxidant perylenediimide as a base pair surrogate are indicative of polaron formation in hairpins having three or four consecutive adenines adjacent to perylenediimide.[29]

Our present results, particularly the requirement of two or more bases in both blocks of the diblock systems and the increase in both Φ_{cs} and k_{cs} for A_3G_n systems with $n = 1-3$ (Figure 2), are consistent with hole delocalization over A- and G-blocks consisting of two or more base pairs. We expect that modeling of our results for diblock systems will present a challenging problem as a consequence of reversible hole injection in Sa-A_n systems and the competition between charge recombination and hole transport and trapping in both the A- and G-blocks.

Comparisons with Other Studies. When comparing our results to those from other studies of DNA hole transport, it is important to keep in mind that direct measurement of both charge separation dynamics and efficiencies has not been realized in other systems. A recent investigation by Kawai et al. of charge separation between acridinium (Acr$^+$) and phenothiazine (Ptz) chromophores separated by A_mG_3 ($m = 1-3$)[7] would appear to be most similar to our studies. However, the choice of Acr$^+$ as the excited-state acceptor is puzzling in view of previous studies by Fukui and Michel-Beyerle, which established that singlet Acr$^+$ is not a sufficiently strong singlet-state oxidant to oxidize A and only oxidizes G by a superexchange mechanism that is strongly distance dependent.[30] Thus, it is not surprising that values of τ_{cs} for the Acr$^+$-Ptz systems are too short for measurement by nanosecond transient absorption spectroscopy, and values of Φ_{cs} decrease from 0.062 for Acr$^+$-A_1G_3Ptz to 0.018 for Acr$^+$-A_3G_3Ptz (small, when compared to our value of 0.30 for A_3G_3).

We note that values of k_{cs} for both A_n and diblock systems decrease with each additional base pair (Figure 5a), whereas the values of Φ_{cs} remain essentially constant at longer distances (Figure 5b). Thus, we would caution against the use of relative yields of strand cleavage or fluorescence as surrogates for rate constants, particularly when the measured quantum yields for these processes are very low. Unfortunately, this practice continues to be widely employed in the DNA electron transfer literature, as does the selective use of kinetic data from other laboratories to convert relative yields to rate constants.[31] A comparison of our results and those of Kawai et al.[7] for Acr$^+$-A_mG_3Ptz systems that seemingly are closely related should be sufficient to call into question such practices.

It is also important to note that, whereas hole transport in alternating sequences including A_nGAGA is slow on the $0-6$ ns time scale of our experiments, it may be rapid relative to the much slower reactions leading to oxidative strand cleavage processes.[10,32] Both Geise[33] and Schuster[34] and their co-workers have employed photochemical methods that eliminate charge recombination as a process competing with hole migration in their studies of the relative efficiencies of strand cleavage at GG or GGG steps separated by poly(A) or repeating mixed A and G polypurine base sequences. These studies should provide reliable relative rate constants for hole migration vs strand cleavage. However, as these investigators have consistently reported, their studies do not provide absolute rate constants for either process. Finally, we note that there is no evidence for periodicity in either their data for the relative efficiency of hole transport or our quantum yield data. Neither is there evidence for periodicity in either our kinetic data or that of Takada and co-workers.[35]

Concluding Remarks

In summary, we observe efficiencies of ca. 25% for photo-induced charge separation in DNA capped hairpin systems

(25) Lewis, F. D.; Liu, X.; Liu, J.; Hayes, R. T.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2000**, *122*, 12037–12038.

(26) (a) Jortner, J.; Bixon, M.; Langenbacher, T.; Michel-Beyerle, M. E. *Proc. Natl. Acad. Sci. U.S.A.* **1998**, *95*, 12759–12765. (b) Berlin, Y. A.; Burin, A. L.; Ratner, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 260–268. Renger, T.; Marcus, R. A. *J. Phys. Chem. A* **2003**, *107*, 8404–8419. (c) Conwell, E. M. *Proc. Natl. Acad. Sci. U.S.A.* **2005**, *102*, 8795–8799. Conwell, E. M.; Basko, D. M. *J. Phys. Chem. B* **2006**, *110*, 23603–23606.

(27) Blaustein, G. S.; Demas, B.; Lewis, F. D.; Burin, A. L. *J. Am. Chem. Soc.* **2009**, *131*, 400–401.

(28) (a) Barnett, R. N.; Cleveland, C. L.; Joy, A.; Landman, U.; Schuster, G. B. *Science* **2001**, *294*, 567–571. (b) Conwell, E. M.; Bloch, S. M.; McLaughlin, P. M.; Basko, D. M. *J. Am. Chem. Soc.* **2007**, *129*, 9175–9181. (c) Hatcher, E.; Balaeff, A.; Keinan, S.; Venkatramani, R.; Beratan, D. N. *J. Am. Chem. Soc.* **2008**, *130*, 11752–11761.

(29) Zeidan, T. A.; Carmieli, R.; Kelley, R. F.; Wilson, T. M.; Lewis, F. D.; Wasielewski, M. R. *J. Am. Chem. Soc.* **2008**, *130*, 13945–13955.

(30) (a) Fukui, K.; Tanaka, T. *Angew. Chem., Int. Ed.* **1998**, *37*, 158–161. (b) Davis, W. B.; Naydenova, I.; Haselberger, R.; Ogrodnik, A.; Giese, B.; Michel-Beyerle, M. E. *Angew. Chem., Int. Ed.* **2000**, *39*, 3649–3652. (c) Hess, S.; Götz, M.; Davis, W. B.; Michel-Beyerle, M. E. *J. Am. Chem. Soc.* **2001**, *123*, 10046–10055.

(31) (a) Schuster, G. B., Ed. *Long-Range Charge Transfer in DNA*; Springer-Verlag: Berlin, 2004; Vols. *236–237*. Wagenknecht, H. A. *Charge Transfer in DNA*; Wiley-VCH: Weinheim, 2005. (b) O'Neill, M. A.; Barton, J. K. *J. Am. Chem. Soc.* **2004**, *126*, 11471–11483.

(32) Takada, T.; Kawai, K.; Fujitsuka, M.; Majima, T. *Chem. Eur. J.* **2005**, *11*, 3835–3842.

(33) Giese, B. *Top. Curr. Chem.* **2004**, *236*, 27–44.

(34) Schuster, G. B.; Landman, U. *Top. Curr. Chem.* **2004**, *236*, 139–161.

(35) Takada, T.; Kawai, K.; Cai, X.; Sugimoto, A.; Fujitsuka, M.; Majima, T. *J. Am. Chem. Soc.* **2004**, *126*, 1125–1129.

possessing diblock A_nG_m poly(purine) base sequences having as many as nine base pairs. This represents a substantial improvement over the highest values we have observed for poly-A or alternating base pair sequences[13,14] or those reported by other workers. Efficient charge separation is attributed to the ability of the diblock sequences to facilitate charge separation while retarding charge recombination. Hole transport within the longer G-blocks is both efficient and relatively rapid, behavior approaching that characteristic of molecular wires. Further enhancement in the efficiency of photoinduced charge separation in DNA will require reduction in the competition from energy-wasting charge recombination processes (k_{rA}, k_{rG}, Figure 6b). Fast charge separation may also be possible in sequences possessing chemically modified purines or pyrimidines.[8]

It is interesting to speculate that the complementary poly-(pyrimidine) strand in a diblock A_nG_m system might conduct negative charge (electrons) in the opposite direction, as a consequence of the higher electron affinity of thymine vs cytosine.[36] Thus, diblock poly(purine) sequences may function as both positive and negative charge carriers in appropriately designed systems. While enhanced charge transport within DNA may itself find application in such fields as sensors, diagnostics, and perhaps molecular electronics, the fundamental principles governing long-distance charge transport that are gleaned from these systems will more generally prove valuable in designing a wide variety of specialized charge transport oligomers.[29,37]

Supporting Information Available: Materials and Methods section, MALDI-TOF analysis for capped hairpins, UV and circular dichroism spectra, thermal dissociation profiles, transient spectra for A_2G_2, A_3G, and A_3G_6 systems, and kinetic fits for A_3G_n systems. This material is available free of charge via the Internet at http://pubs.acs.org.

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(36) Lyngdoh, R. H. D.; Schaefer, H. F. *Acc. Chem. Res.* **2009**, *42*, 563–572.

(37) (a) Rathore, R.; Abdelwahed, S. H.; Guzei, I. A. *J. Am. Chem. Soc.* **2003**, *125*, 8712–8713. (b) Zeidan, T. A.; Wang, Q.; Fiebig, T.; Lewis, F. D. *J. Am. Chem. Soc.* **2007**, *129*, 9848–9849.