POLARON DYNAMICS

Long-lived photoinduced polaron formation in conjugated polyelectrolyte-fullerene assemblies

Rachel C. Huber,1,2 Amy S. Ferreira,3 Robert Thompson,3 Daniel Kilbride,3 Nicholas S. Knutson,1 Lekshmi Sudha Devi,1 Daniel B. Toso,2 J. Reddy Challa,1 Z. Hong Zhou,2,3 Yves Rubin,1† Benjamin J. Schwartz,1,3† Sarah H. Tolbert1,3,4†

The efficiency of biological photosynthesis results from the exquisite organization of photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this assembly, charge separation and collection could be markedly enhanced. We show that micelle-forming cationic semiconducting polymers can coassemble in water with photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this photoactive elements that promote rapid movement of charge carriers out of a critical recombination range.

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The efficiency of biological photosynthesis results from the exquisite organization of photoactive elements that promote rapid movement of charge carriers out of a critical recombination range. If synthetic organic photovoltaic materials could mimic this assembly, charge separation and collection could be markedly enhanced. We show that micelle-forming cationic semiconducting polymers can coassemble in water with cationic fullerene derivatives to create photoinduced electron-transfer cascades that lead to exceptionally long-lived polarons. The stability of the polarons depends on the organization of the polymer-fullerene assembly. Properly designed assemblies can produce separated polaronic charges that are stable for days or weeks in aqueous solution.

In biological photosynthetic systems, energy cascade structures promote the spatial separation of photogenerated charges created at the reaction center, preventing their recombination. These energy cascade structures require close proximity of the electron donors and acceptors, on the scale of ~1 nm, and the corresponding electron transfer (ET) processes take only a few picoseconds (1). Similarly, photoexcitation in artificial organic photovoltaic (OPV) cells generates dissociated charges at a donor-acceptor interface on subpicosecond time scales. However, OPVs suffer a large degree of recombination because they rely on phase separation of the conjugated polymer donor and fullerene acceptor into domains on the length scale of 10 to 20 nm to facilitate efficient exciton diffusion and charge transfer (2, 3). The high charge densities present in OPVs, coupled with the low dielectric constant of organic materials, favor carrier recombination before the charges can be extracted through external electrodes. If OPVs could be designed to use ET cascades that are reminiscent of photosynthetic complexes, it should be possible to greatly improve charge separation and reduce recombination losses (4).

Here we describe how molecular self-assembly can enable dissolved OPV materials (conjugated polymers and fullerenes) in aqueous solution to mimic the ET cascade structures of biological complexes and allow us to “spatially” control photogenerated charges. We demonstrate efficient long-time charge separation following photoexcitation: The ET cascade produces separated polarons that are exceptionally stable for weeks, a lifetime that is unprecedented for OPV materials. Although long polaron lifetimes have been observed in covalently linked donor-acceptor dyads and triads (5) and micellar structures (6), our use of standard organic photovoltaic materials sets this work apart. In addition, our use of self-assembly provides potential future advantages in reproducibility and scalability, both of which are major hurdles for conventional OPVs with kinetically controlled structures (7–9). Finally, the photoinduced charge separation we achieve takes place in water, opening possibilities for the “green” production of artificial photosynthetic devices.

The particular materials used in this study are a combination of a conjugated polyelectrolyte, poly(fluorene-alt-thiophene) (PFT) (10), and several regioisomers of the charged fullerene derivatives C60-N,N-dimethylpyrroloidinium iodide [C60(PF3)2], where n is the number of charged pyrroloidinium iodide groups (11) (Fig. 1A to C). PFT is a water-soluble semiconducting polyelectrolyte whose bis-alkylated sp3-hybridized fluorenyl carbon forms a wedge-shaped monomer that facilitates the assembly of the charged polymer into rod-like micelles (Fig. 1B); details of how this polymer assemblies have been published previously (10). Because of the charged nature of the polymer, the electron acceptor(s) must also carry cationic charges to avoid heterocoagulation. The synthesis of C60(PF3)n, depending on the reaction conditions, produced multiaadducts with n ranging from 2 to 5, including multiple regioisomers for each n. To avoid confusion, we will refer to C60(PF3)n with n = 3 to 5 as “higher” adducts and fullerenes with n = 2 as “mixed-bis” adducts.

We achieved control over the solution-phase aggregation of these materials by exploiting the different solubility properties of the conjugated polyelectrolyte and charged fullerene derivatives. Mixed-bis adducts show limited solubility (without PFT) in aqueous solution, whereas higher adducts are water soluble at high concentration. This difference suggests that the mixed-bis adducts should coassemble in aqueous solution with PFT, a result we confirmed by cryogenic electron microscopy (cryoEM), small-angle x-ray scattering (SAXS), and luminescence quenching studies. CryoEM images of pure PFT, PFT-mixed-bis adducts, and PFT-high adducts contributed by A. Holland (OK), C. Eisenger (CD), T. Kropatsch (WY), J. Arnehm (IN), T. Tomastik (OH), S. Platt (PA), L. Alfred (UT), M. Berry (UT), A. Wickert (TK), and I. Van-Vliet (CEU). This project used earthquake data from the ANSS Comprehensive Catalog. The well data used in this study are available as supplementary materials on Science Online.

SUPPLEMENTARY MATERIALS

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Materials and Methods

Fig. S1 to S18

Tables S1 to S4

References (28–46)

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are shown in Fig. 1, D to F. Pure PFT samples self-assemble into branched micelles that are roughly 4 ± 0.5 nm in diameter and 30 to 50 nm in length. CryoEM images of PFT assembled with mixed-bis adducts are visually similar to the pure PFT, indicating association of the C60(P)2 with the PFT micelles. In contrast, cryoEM images of PFT:high adducts appear blurry because these solutions contain separate PFT and fullerene agglomerates.

This interpretation of coassembly of PFT with mixed-bis adducts is also supported by SAXS measurements (Fig. 2, A and B). We radially averaged the SAXS data and fit it to a power law to extract the exponent $\alpha$, which is related to the polymer fractal structure (12, 13). Values of $\alpha = 1$, 2, and 4 correlate to rigid rod, lamellar, and spherical structures, respectively, although interactions between molecules cause deviations from these ideal slopes. Analysis of SAXS data for pure PFT yielded $\alpha = 1.5$ at low $q$ (rod-like at large size), increasing to $\alpha = 3.7$ at high $q$ (sphere-like at small size). Deviation from $\alpha = 1$ arose from the branched network seen by cryoEM (Fig. 1D) (14). SAXS power-law slopes for C60(P)2 high-adducts correspond to a percolation network at low $q$ and rod-like behavior at high $q$, indicating aggregation (12, 15). SAXS data from the combined PFT:high adducts solution was well approximated as the mass-scaled sum of the pure PFT and pure fullerene scattering, suggesting a nonassembled mixture, similar to that seen by cryoEM. By contrast, mass-scaled SAXS from solutions of PFT and mixed-bis adducts is nearly identical to the pure PFT. These results provide strong evidence that C60(P)2 and PFT coassemble into a single micellar aggregate.

Finally, electronic interactions in the polymer-fullerene assemblies were confirmed with luminescence quenching, which provides an indirect measure of the photoinduced charge transfer from the polymer to the fullerenes (16). Solutions of PFT:high adducts showed relatively little photoluminescence (PL) quenching, presumably because the donors and acceptors were not in close physical proximity, but aqueous solutions of PFT with the mixed-bis adducts had substantial PL quenching, indicating both physical and electronic contact (Fig. 3A). The data indicate that >75% of the PFT excitations were quenched in the presence of the mixed-bis adducts.

We determined the dynamics of charge separation in these donor-acceptor assemblies using ultrafast broadband transient absorption spectroscopy on dilute aqueous solutions of coassembled PFT with mixed-bis adducts (17). Representative transient absorption spectra at different probe delays following excitation at 470 nm are shown in Fig. 3B. We assigned the negative transient absorption peak near 520 nm to stimulated emission, as the spectral features and the lifetime (Fig. 3C) matched the fluorescence emission. Interestingly, the 690-nm absorption of the PFT hole polaron ($P^-$) appeared on a subpicosecond time scale after photoexcitation (18, 19). This ultrafast appearance of $P^-$ confirmed that the C60(P)2 adducts must be coassembled with PFT, because other geometries would require diffusion or other structural rearrangements that could not occur so quickly. Once formed, about 75% of the PFT polarons in these dilute samples decayed back to the ground state in ~200 ps (Fig. 3C). The remaining polarons survived past the nanosecond time scale.

To mimic biological charge-separation systems, coassembly and rapid charge separation are required, but if they are followed by rapid recombination, the charges cannot be extracted. A fullerene acceptor that is optimized for charge separation thus needs to contain one class of compounds that can assemble intimately with the PFT for efficient charge transfer, and a second class of compounds that can assemble more loosely, allowing us to pull the electron away from the PFT and prevent recombination. Fortunately, both types of compounds were already available within our mixed-bis sample, and their properties could be examined simply by separating C60(P)2 regioisomers. Our mixed-bis samples were primarily composed of four isomers (10% trans-1, 38% trans-2, 44% trans-3,

Fig. 1. PFT and charged fullerene structure and assembly. PFT structure (A); cartoon of a PFT micelle (B); charged fullerenes (C). CryoEM images of pure PFT (D), PFT:mixed-bis adducts (E), and PFT:high adducts (F).

Fig. 2. SAXS data for PFT and PFT/fullerene mixtures. (A) Data for PFT:high-adducts are reasonably approximated by a sum of PFT + high-adducts. (B) The PFT:mixed-bis profile overlap mass-scaled PFT data. (C) Raw scattering data for all PFT and PFT:bis-fullerene samples are similar. (D) Distance distribution functions, $P(r)$, obtained by Fourier transformation of the data in (C) show different fullerene environments for trans-1,2 and trans-3,4, with PFT:mix-bis corresponding to the sum of the two.
and 7% trans-4). Structures of each of the isomers are shown in Fig. 4, A to D. We partially separated these isomers by silica gel column chromatography of the neutral pyrrolidine precursors (prior to quaternization), producing fractions that we refer to as trans-1,2 (29% trans-1 and 71% trans-2) and trans-3,4 (14% trans-2, 74% trans-3, and 12% trans-4). The full characterization of all of these materials is found in figs. S1 to S22 of the supplementary materials (17). The trans-1,2 fullerenes have charges on nearly opposite sides of the buckyball and can be viewed as isotropically charged molecules that should not easily insert into a PFT micelle. By contrast, the angle between charges in trans-3 is ~145° and that between charges in trans-4 is 103°, suggesting more amphiphilic molecules that could insert into the PFT micelle.

The coassembly of PFT with trans-1,2 and trans-3,4 was examined via SAXS. Raw scattering data for all of the samples looked similar to the data for pure PFT (Fig. 2C), but Fourier analysis using cylindrical boundary conditions showed subtle variations. In Fig. 2D, PFT and PFT:trans-3,4 showed similar probability distributions, supporting the model of insertion of fullerene into the PFT micelle. PFT:trans-1,2 shows two peaks, reminiscent of a polymer micelle with a partial “shell” of fullerenes surrounding the outside. The PFT:mixed-bis data were well fit by a simple linear combination of the PFT:trans-1,2 and PFT:trans-3,4 probability distributions, further supporting the idea that trans-3,4 assembles on the inside of the polymer micelle, whereas trans-1,2 surrounds the outside. The relative locations of the two different sets of fullerenes were also confirmed via solvatochromic absorption measurements (fig. S25). These measurements show that the ultraviolet absorption of trans-1,2 fullerenes assembled with PFT matches that of the fullerenes in pure water, indicating that trans-1,2 sits outside of the PFT micelle. In contrast, the absorption of the trans-3,4 fullerenes assembled with PFT matches that of the fullerenes in organic solvents, indicating that trans-3,4 sits in a lower dielectric environment than the micelle interior.

Figures 4, F and G, show luminescence quenching measurements that further support the idea that different isomers of C_{60}P_{12} assemble in different places in the PFT micelle. The luminescence decays shown in Fig. 4G were taken with a Kerr-gated time-resolved fluorescence setup using C_{60} as the gate medium, providing a time resolution of ~1 ps (20). Clearly, the PFT fluorescence is quenched nearly to the instrument limit in concentrated solutions when assembled with trans-3,4 fullerenes, verifying that the photoinduced charge transfer to these fullerenes is ultrafast. In contrast, there is almost no fast quenching of the PFT emission with an equal amount of trans-1,2 fullerenes, reflecting their assembled position predominantly on the outside of the micelle, out of range for fast ET. Figure 4F shows steady-state luminescence measurements on these same samples. Consistent with the time-resolved data, assemblies of PFT with trans-1,2 fullerenes showed little luminescence quenching, whereas PFT assembled with trans-3,4 fullerenes had strong quenching. These quenching results suggested that not only can we selectively associate fullerenes with polymer micelles using the number of charges, we can also control the position of the fullerene within the micelle by the placement of the charges (Fig. 4E).

Given this degree of control, the next step was to examine long-lived excitations in assemblies of PFT and mixed-bis adducts containing both intimately assembled trans-3,4 and more isotropically charged trans-1,2 fullerenes. Ideally, this coassembly should permit rapid photoinduced electron transfer from PFT to the trans-3,4 fullerenes, followed by a second ET step to the trans-1,2 fullerenes. If this type of directed ET cascade occurs, electrons on the trans-1,2 fullerenes would then be stabilized in the high-dielectric environment of the water surrounding the micelle, preventing recombination with the PFT. Indeed, we found that photoexcitation of aqueous PFT:mixed-bis adduct solutions caused a dramatic color change from yellow to dark green over time (Fig. 3D); once the solution was exposed to light, the color change was essentially permanent, lasting days to weeks. Dilute solutions, like those used to collect the data in Fig. 3, B and C, required extensive light exposure (fig. S24), but when higher concentrations were used, the color change took place in just a few seconds under room lights, indicating that the quantum yield for long-lived charge separation is much higher than the ~25% in dilute solutions (compare Fig. 3B).

PFT is a blue-absorbing polymer with an absorption maximum at 430 nm in water and little to no absorbance above 550 nm (10). The color change from yellow to green was confirmed to arise from the appearance of the PFT hole polaron (P⁺) by comparing steady-state data (Fig. 3D) with transient absorption data (Fig. 3B) and absorption from PFT oxidized with iodine, both of which show absorption in the sub-gap region.
Fig. 4. Spectroscopic evidence for long-lived charged species in solution. Chemical structures of trans-1 bis (A), trans-2 bis (B), trans-3 bis (C), and trans-4 bis (D) fullerene derivatives with color emphasizing the hydrophobic regions. Cartoon depicting the assembly of trans-1,2 (orange) and trans-3,4 (purple) bis fullerenes with PFT (red). Photoexcitation of the PFT backbone leads to charge transfer first to trans-3,4 and then to trans-1,2, where the electron remains due to stabilization by the reorganization of water. The hole (green, h\(^+\)) remains on PFT (E). PL of PFT, PFT:mixed-bis, PFT:trans-3,4 bis, and PFT:trans-1,2 bis (F). Time-resolved luminescence for assembled concentrated PFT:trans-3,4 bis and PFT:trans-1,2 bis samples (G).

Final confirmation that the long-lived separated charges resulted from a self-assembled ET cascade comes by examining the details of absorption and luminescence for a range of samples in different solvents. As discussed above, aqueous solutions of PFT and PFT:trans-1,2 fullerenes show little PL quenching (Fig. 4, F and G), but they did briefly turn green during the course of the dissolution, indicating polaron formation (possibly from disordered polaron that transiently allowed the fullerene to partly insert into the micelle). By contrast, despite the efficient luminescence quenching in solutions of PFT coassembled with the trans-3,4 fullerenes (Fig. 4, F and G), the solutions did not turn green and ultrafast experiments (data not shown) indicate that polarons are formed on subpicosecond time scales (as in Fig. 3B), but recombine with 100% yield over the next few hundred picoseconds. These results indicate that controlling the spatial position of the fullerenes can dramatically affect carrier dynamics. Moreover, photoexcitation of green-colored PFT:mixed-bis fullerene solutions results in increased luminescence quenching because PFT excitons are further quenched by P*-polarons (Fig. 3F). However, when tetrahydrofuran (THF), which is known to disassemble the polymer micelles (27), was added to the coassembled green system, the luminescence signal regained its intensity, indicating a fully reversible system (Fig. 3F). These results further support the idea that intimate assemblies with well-controlled molecular positions are required to facilitate a charge transfer cascade and avoid recombination. When nanoscale architecture is optimized, the result is stable polarons that could potentially be applied to improve organic photovoltaic cells via suppression of charge recombination.

REFERENCES AND NOTES
17. See supplementary materials on Science Online for details.

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