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Charge separation and recombination at polymer-fullerene heterojunctions: Delocalization and hybridization effects

Gabriele D'Avino,[†] Luca Muccioli,[§] Yoann Olivier[†] David Beljonne^{†,}*

[†] Laboratory for Chemistry of Novel Materials, University of Mons, 7000 Mons, Belgium.

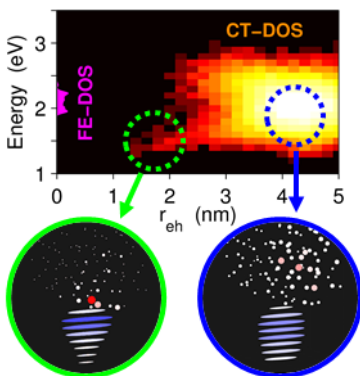
[§] Laboratoire de Chimie des Polymères Organiques, UMR 5629, University of Bordeaux, 33607 Pessac, France.

* David.Beljonne@umons.ac.be

ABSTRACT

We address charge separation and recombination in polymer/fullerene solar cells with a multiscale modelling built from accurate atomistic inputs and accounting for disorder, interface electrostatics and genuine quantum effects on equal footings. Our results show that bound localized charge transfer states at the interface coexist with a large majority of thermally accessible delocalized space-separated states that can be also reached by direct photoexcitation, thanks to their strong hybridization with singlet polymer excitons. These findings reconcile the recent experimental reports of ultrafast exciton separation (“hot” process) with the evidence that high quantum yields do not require excess electronic or vibrational energy (“cold” process), and show that delocalization, by shifting the density of charge transfer states towards larger effective electron-hole radii, may reduce energy losses through charge recombination.

TOC GRAPHICS



KEYWORDS

organic photovoltaics, polymer-fullerene solar cells, multiscale modelling, exciton dissociation, charge recombination

Motivated by the prospects for high-efficiency organic solar cells, there have been considerable efforts to unveil the mechanisms of charge separation at donor/acceptor (D/A) heterojunctions.^{1,2} Though this is still a very much debated question, there is growing evidence that, in the best devices, almost quantitative charge photogeneration from relaxed charge-transfer (CT) states occurs without the need for excess electronic or vibrational energy,³⁻⁵ possibly assisted by an entropic gain ensured by the three-dimensional character of the fullerene acceptors.^{6,7} This seems to imply that exciton dissociation proceeds through weakly bound CT states, a mechanism supported by microelectrostatic calculations of model interfaces.⁸⁻¹⁰ On the other hand, a recent report on charge separation occurring within a 40 fs time window over distances of a few nm in fullerene-based bulk heterojunctions,¹¹ and other evidences of ultrafast phenomena,¹²⁻¹⁴ point instead to the combined role of delocalization effects and vibrationally-“hot” states in pulling charges apart.¹⁵⁻¹⁷ Yet, how do we reconcile these two nearly opposite pictures of charge separation with the massive recombination of photogenerated charges, which has been identified as the main responsible for open-circuit voltage losses¹⁸ and that drastically limits the power conversion efficiency of organic solar cells?

To address this question, we resort to a full atomistic theoretical description of charge pairs at polymer-fullerene interfaces that accounts on an equal footing for electrostatic, disorder, and delocalization effects. Our modelling reveals the presence of distinct populations of CT states that mediate charge separation (CS) and charge recombination (CR). Namely, while CR takes place from a small set of bound interfacial CT states, CS may occur both as a thermally activated process and by direct photoexcitation of space-separated CT states acquiring oscillator strength due to strong mixing with resonant polymer singlet excitons. Interestingly, we further show that

charge delocalization should reduce CR also in the cold scenario by shifting the density of CT states towards larger effective electron-hole (e-h) radii.

The description of the electronic structure at the length scale pertaining to charge separation at organic heterojunctions is a formidable task that we tackle with a multiscale approach grounded on a site-based model Hamiltonian fed with atomistic inputs. Our starting point is the realistic P3HT/PCBM interface in Figure 1a obtained from molecular dynamics simulations,⁹ which defines molecular sites and their disordered connectivity. The electronic Hamiltonian is represented on a diabatic basis of localized states including the neutral state $|0\rangle$, singlet Frenkel excitons (FE) $|i\rangle$, and singlet-coupled CT states $|i, j\rangle$ with i and j running on D and A sites, respectively. We consider explicitly the three low-lying unoccupied orbitals of fullerene derivatives, so j is actually a composite index labelling A sites and orbitals. On this basis the Hamiltonian reads:

$$H = H_{CT} + H_{FE} + H_{CT-FE} \quad (1)$$

$$H_{CT} = \sum_{i,j} \varepsilon_{ij}^{CT} |i, j\rangle\langle i, j| + \sum_j \sum_{(i,i')} J_{ii'}^h |i, j\rangle\langle i', j| + \sum_i \sum_{(j,j')} J_{jj'}^e |i, j\rangle\langle i, j'| + \sum_{(i,j)} J_{ij}^g |0\rangle\langle i, j| \quad (2)$$

$$H_{FE} = \sum_i \varepsilon_i^{FE} |i\rangle\langle i| + \sum_{(i,i')} J_{ii'}^x |i\rangle\langle i'|; H_{FE-CT} = \sum_{(i,j)} J_{ij}^s |i\rangle\langle i, j| \quad (3)$$

Where H_{CT} accounts for the energy of electrostatically interacting CT states (diagonal energies ε_{ij}^{CT}), for hole and electron transfer (CT couplings $J_{ii'}^h$ and $J_{jj'}^e$), and for ground-state charge transfer couplings (J_{ij}^g) that are also responsible for CR. H_{FE} is the traditional Frenkel exciton model with site energies ε_i^{FE} and energy transfer couplings $J_{ii'}^x$, and finally H_{FE-CT} mixes Frenkel and CT excitons via the exciton splitting coupling J_{ij}^s .

While similar models have been already proposed^{15,19,20}, our approach goes beyond ideal lattices of reduced dimensionality in favor of the realistic three-dimensional morphology of a

polymer/fullerene interface,⁹ and Hamiltonian 1 is fully parameterized against robust atomistic calculations (see Experimental Section).

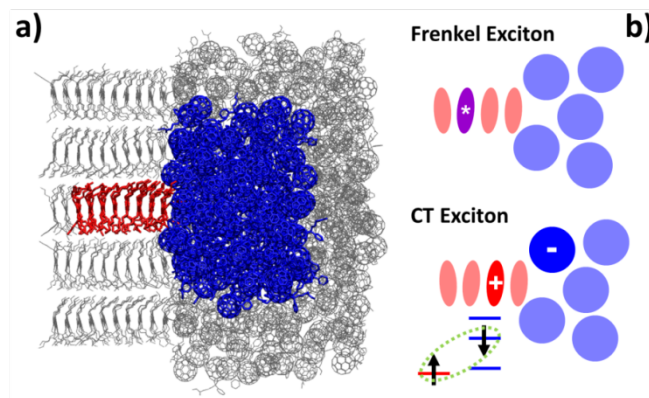


Figure 1. a) Snapshot of the P3HT/PCBM interface considered in this study; the colored region represents the subsystem described by Hamiltonian (1). b) Sketch of the molecular Frenkel exciton and singlet-coupled charge transfer states.

We start our discussion from *pure* CT states, i.e. the eigenstates of H_{CT} in Equation 2 that do not present any mixing with FEs. Our calculations confirm a very small CT in the ground state with less than 0.01 electrons of net charge on the D or A subsystem,²⁰ which corresponds to a negligible vacuum level shift (<5 meV) across the interface. The effect of charge delocalization on the energy landscape of CT states is addressed in Figure 2, where we compare the density of CT states (CT-DOS) computed according to three scenarios: (i) fully localized holes and electrons ($J^h = J^e = 0$), (ii) delocalized electrons with localized holes ($J^h = 0$), and (iii) fully delocalized holes and electrons. The average energy profile in the localized picture (Figure 2a) points to two populations of CT states: a low-energy tail of states with $r_{eh} < 2$ nm that are electrostatically bound by 0.3-0.4 eV, and a dominant fraction of states featuring larger e-h radii and characterized by a rather flat energy profile.⁹

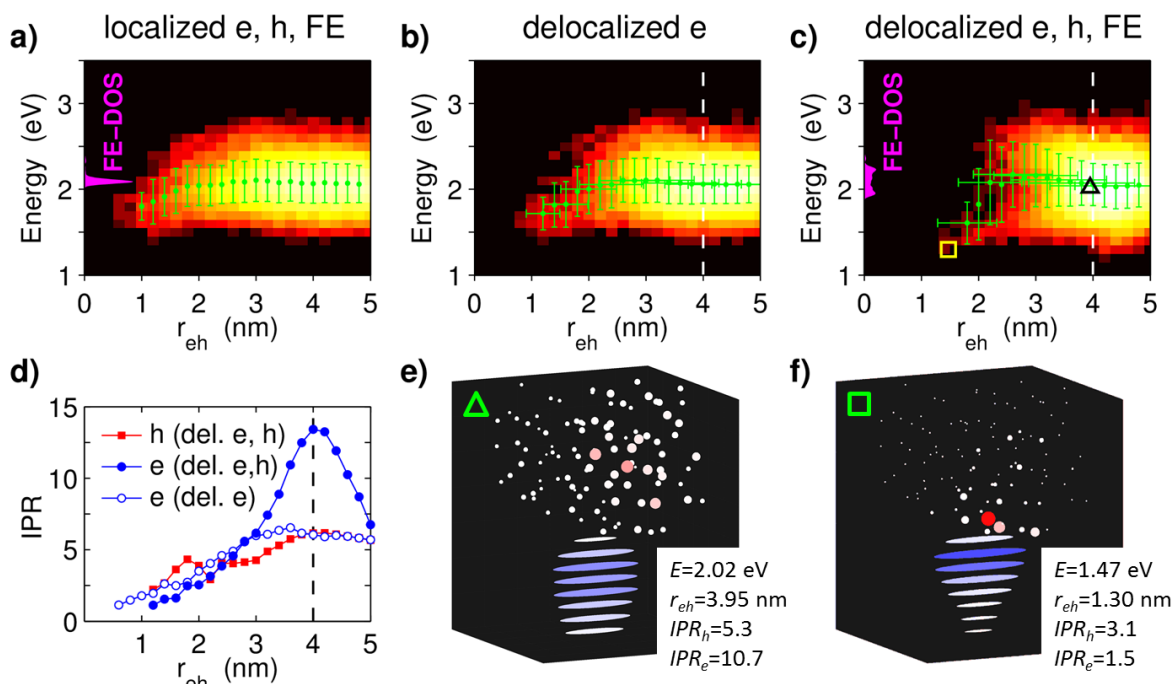


Figure 2. a-c) Density of pure CT states (heat map, logarithmic color scale) as a function of e-h distance and energy for localized and delocalized carriers. Green dots show the energy profile averaged in intervals of r_{eh} , vertical (horizontal) error bars report the standard deviation of energy (e-h mean spread) within each interval. Magenta areas in panel a) and c) show the DOS of pure localized and delocalized FEs, respectively. d) Average inverse participation ratio (IPR) as a function of r_{eh} . e-f) Rendering of representative CT states, triangle and square recall panel c).

The CT-DOS changes substantially when accounting for delocalization, especially when both electrons and holes can spread on multiple molecules. The remarkable difference between the CT-DOS in Figure 2b and 2c attests the importance of accounting for the delocalization of both carriers, at least for neat interfaces to large polymer crystallites; however many polymer/fullerene blends present disordered intermixed regions where we expect the actual scenario to be comprised between the pictures in Figure 2b and 2c. Delocalization has a favorable effect on charge separation, as it stabilizes less Coulombically bound CT states at large e-h distance and shifts the CT-DOS to larger r_{eh} . Both charge carriers can in fact delocalize towards their respective transporting materials, leading to an increase of the average e-h distance,

although many delocalized CT states have tails extending down to the interface. Charge delocalization, quantified by the inverse participation ratio (IPR, see Figure 2d), increases with r_{eh} , leading to CT states whose electronic clouds spread on average over ~ 13 fullerenes at $r_{eh} \sim 4$ nm, like the one rendered in Figure 2e. Nevertheless, a small population of more localized and bound CT states at small r_{eh} persists even when both electrons and holes are allowed to delocalize (square in Figure 2c and Figure 2f).

With a realistic description of the CT-DOS at hand, we can now turn our attention to FEs. Because of the strong energy transfer couplings between P3HT decamers ($J^x \approx 80$ meV), pure FEs ($H_{FE-CT} = 0$) spread over the polymer stack leading to very different FE-DOS in the localized ($J^x = 0$ in Equation 3, magenta area in Figure 2a) and delocalized picture (Figure 2c). The nature of the electronic excitations radically changes upon switching on the coupling with CT states (H_{FE-CT}), which leads to strong FE-CT *hybridization* as measured by their fractional FE (CT) character v_{FE} (v_{CT}). We quantify the number of excited states of nearly pure FE character ($v_{FE} > 0.9$) to be only the 32% of that of (pure and localized) basis FEs. While these numbers are specific to our model interface and system-size dependent, we point out that the disappearance of pure FE in the close proximity of an interface is instead a general result, as also suggested by many-body Bethe-Salpeter calculations on bimolecular complexes.²¹ The weight of FEs of interfacial polymer chains is therefore dispersed in the manifold of CT states, which, due to their much larger number, maintain mostly $v_{CT} \sim 1$.

Strongly hybridized excitations should efficiently mediate the ultrafast conversion of pure FE generated in the polymer bulk in high-energy CT states, but also strongly affect the optical properties of the D/A interface. Figure 3a shows the absorption cross section calculated for our

P3HT/PCBM interface, which resembles the P3HT H-aggregate absorption associated with FEs, plus a weak low-energy tail due to the intrinsic CT absorption. The intense polymer absorption is polarized along the backbone axis, while CT features have also an out-of-plane component. While this is fully consistent with optical measurements,³ our modelling further reveal that much of the absorption intensity comes from states with a large CT character borrowing their intensity from bright FEs: for our P3HT/PCBM interface the 62% of the integrated cross-section is provided by states with $v_{CT}>0.5$. Moreover, most of this absorption corresponds to CT states with an effective e-h distance larger than 3 nm and that are resonant with FE. This is better shown by the r_{eh} -resolved absorption spectrum of hybrid CT states in Figure 3b, which reveals the correlation between absorption frequency and the effective distance between the photo-generated e-h pair.

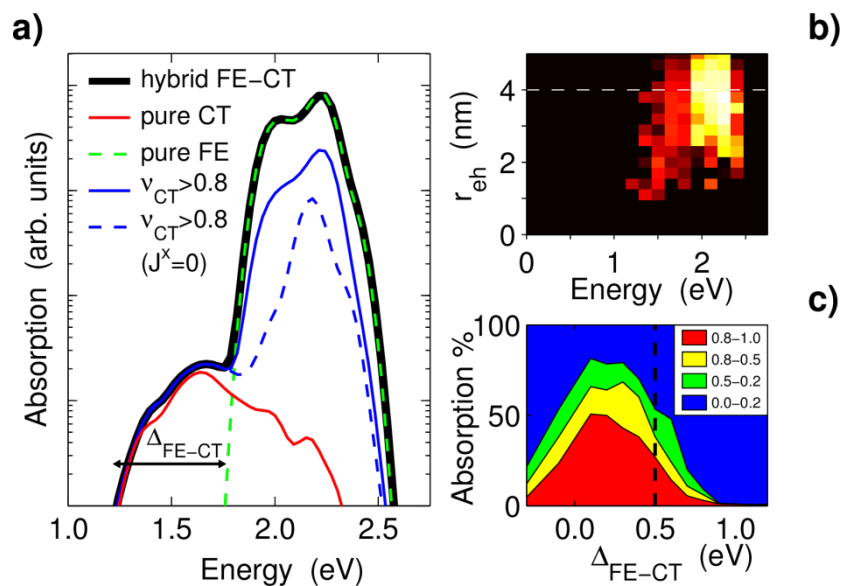


Figure 3. a) Absorption spectrum of the P3HT/PCBM interface computed with different models (see text). b) Absorption spectrum of hybrid CTs resolved in energy and e-h distance, showing that most of CT transitions mainly yields space separated charges. c) Participation of states of different CT character (v_{CT} in the caption) to the total absorption cross-section as a function of Δ_{FE-CT} . The vertical line at $\Delta_{FE-CT}=0.5$ corresponds to P3HT/PCBM. For $\Delta_{FE-CT}\sim 0.2$ half of the total absorption corresponds to states with $v_{CT}>80\%$.

This result confirms the possibility that primary photoexcitations in organic heterojunctions consist in space-separated CT states as suggested by Ma and Troisi for a model two-dimensional D/A interface.¹⁹ The efficient optical generation of space-separated carriers requires delocalized CT states extending down to interface where these can mix with the FEs,¹⁹ but also other material parameters play a key role. The offset between CT and FE absorptions, which can vary much in polymer/fullerene heterojunctions, is in fact also crucial. Its effect is addressed in Figure 3c, where we show that the amount of absorption intensity transferred to CT states is maximized for an optimal overlap between CT and FE DOSs. The delocalization of FEs is also very important, as it mediates the coupling between CT states and FEs of the inner polymer chains. Consequently, the absorption intensity of CT states is expected to drop in systems featuring localized excitations, as illustrated in Figure 3a where we compare the cross section of the excited states of prevailing CT character ($v_{CT} > 0.8$) in the case of delocalized (full blue line) and localized FEs ($J^x = 0$, blue dashed line).

We next address the critical aspect of charge recombination (CR), which is responsible for voltage losses up to 0.7 eV in organic solar cells.¹⁸ Despite several theoretical attempts to compute CR rates,^{22–26} the role of delocalization has been overlooked so far. Here, radiative and nonradiative CR rates from all the excited states have been calculated in both cases of localized and delocalized carriers. In the localized picture nonzero CR rates are found only for the few CT states corresponding to D/A pairs in close contact at the interface, while sizeable rates are found also for delocalized states with $r_{eh} \geq 3$ nm. Following Burke *et al.*,¹⁸ we assume thermal equilibrium between Coulombically bound CT states and space-separated delocalized charges,

both described within our model, and compute Boltzmann averaged (non)radiative rates (\bar{k}_{NR}) \bar{k}_{RAD} that are given in Table 1. Our results are in overall accordance with experimental values^{18,27} and confirm that the nonradiative pathway is the dominant one. Delocalization is found to reduce \bar{k}_{NR} by three orders of magnitudes due to the dilution of interfacial localized CT states into the dense manifold of low-energy space separated charges. This result also follows from the rather flat energy landscape of our P3HT/PCBM interface (Figure 1a), while charge delocalization has little effect when a substantial energy gap separates bound and delocalized states (see SI).

Table 1. Thermally averaged radiative and nonradiative CR rates in s^{-1} computed for the P3HT/PCBM interface for localized and delocalized carriers.

	Localized e and h	Delocalized e	Delocalized e and h
\bar{k}_{RAD}	$1.1 \cdot 10^6$	$5.9 \cdot 10^5$	$2.3 \cdot 10^5$
\bar{k}_{NR}	$3.0 \cdot 10^{10}$	$2.2 \cdot 10^{10}$	$4.8 \cdot 10^7$

To conclude, our modelling reveals the presence of states of different nature at organic D/A heterojunctions, namely bound localized CT states at the interface and a large majority of delocalized space-separated states; pure molecular FEs barely exist in the close proximity of the interface and their absorption intensity is largely transferred to resonant CT states. This provides a key for interpreting the early branching in the fate of photogenerated CT states observed for several polymer/fullerene blends^{12,27} and reconciles the observations of charge separation in the ultra-fast and thermally activated regime, while showing that charge delocalization may slow down charge recombination. The emerging picture confirms the crucial role of CT states and their energetics that is largely governed by electrostatic interactions and morphology. High-

energy CT states, mostly superimposed to the polymer absorption, are pivotal for achieving high charge yields, minimizing at the same time voltage losses.

EXPERIMENTAL SECTION

Parameters in Equations 1-3 are obtained from calculations performed on the structures of the MD-simulated P3HT/PCBM interface in Ref. 9. CT states energies include the effect of electrostatic interactions and account for dielectric screening at the microscopic level,^{9,10,28} while FE energies and charge and energy transfer couplings are evaluated at the semiempirical INDO/S level. \bar{k}_{NR} is computed with a Marcus-Levich-Jortner formula suitably modified to account for delocalization,²⁹ \bar{k}_{RAD} is computed assuming spontaneous emission. Results have been obtained for ten supramolecular clusters similar to that in Figure 1a, sampling the whole interface of Ref. 9.

ASSOCIATED CONTENT

Supporting Information. Comprehensive computational details. Distribution of charge and energy transfer couplings. Energetics of localized CT states. System size effects. Additional results. The following files are available free of charge.

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