

In Situ Reduction and Functionalization of Polycyclic Quinones

Karl J. Thorley,* Yang Song, Sean R. Parkin, and John E. Anthony



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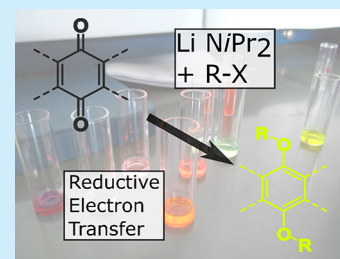


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ABSTRACT: Attempts to functionalize polycyclic quinones using lithium diisopropylamide as a base led to the unexpected formation of acenes. This reaction proceeds by electron transfer from the base to the electron deficient quinone, whose radical anion can react with a variety of electrophiles. Siloxy derivatives synthesized by this method could be easily isolated but showed poor photostability. *In situ* reduced intermediate generation is a convenient approach to functionalization of oxidatively unstable hydroquinones.

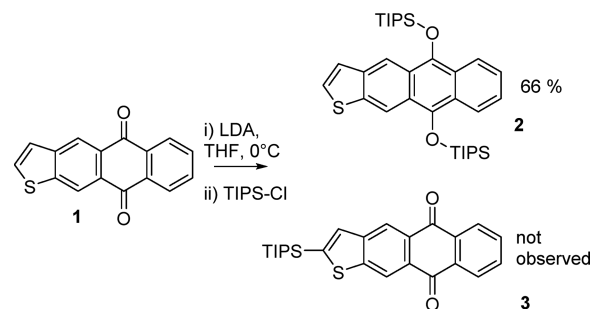


Polycyclic aromatic hydrocarbons (PAHs) have found a multitude of uses in organic materials chemistry and physical organic chemistry. The fundamental molecular properties are based upon the degree of conjugation within their core, (de)localization based on Clar's sextet rule, and the rigidity of their fused multiring scaffolds. The absorption and emission of light, reversible redox chemistry, and charge transport in the solid state have made this class of molecules a stalwart in materials chemistry.¹ Recent applications include use in transistor devices² and singlet fission with an aim to enhance silicon photovoltaic devices.³

To successfully use PAHs in these devices, chemists need to be able to functionalize them with pendant nonconjugated groups to increase their solubility and stability and to control intermolecular interactions and solid-state packing. Ethynylated PAHs are among those most commonly investigated, giving a range of crystal packing motifs to explore.⁴ In photovoltaic materials, alkyl or alkoxy chains are more common⁵ as less crystalline materials are preferable to direct suitable mixing between donor and acceptor phases. Direct conversion of quinones to alkoxy acenes was reported by Brega et al.,⁶ with the resulting products exhibiting properties relevant to oxygen sensing or photodynamic drug delivery. Commonly used as PAH precursors, polycyclic quinones are themselves highly coveted functional materials due to their redox properties and applicability to redox flow batteries.⁷

We recently utilized the facile lithiation of thienoacenes adjacent to sulfur to synthesize functionalized acenes.⁸ In attempts to access functionalized quinones in the same manner (Scheme 1), unexpected reactivity was observed. Reaction of thienoanthracene quinone **1** with lithium diisopropylamide (LDA) at 0 °C was nearly instantaneous, resulting in a green solution. Addition of an electrophile such as triisopropylsilyl chloride caused an overnight color change to a bright yellow fluorescent product, identified as siloxy thienoanthracene **2** by mass spectrometry, NMR analysis, and X-ray diffraction. The reaction proceeded with a yield of 66% with minimal

Scheme 1. Observed Conversion of Thienotetracene Quinone to the Silylated Hydroquinone



purification required. Existing methods for the conversion of quinones to substituted hydroquinones involve the reduction of the quinone using sodium hydrosulfite⁹ or zinc/sodium hydroxide.¹⁰ Both methods require aqueous or biphasic conditions and rigorous exclusion of oxygen and often involve the isolation of potentially unstable hydroquinone. Our new method would allow conversion of quinones to hydroquinone ethers in a single step, using solvents and conditions much more amenable to the functionalization of larger aromatic quinones, and allows the use of water sensitive electrophiles.

Commercially available anthraquinone **4** behaved in the same manner as thienoanthracene quinone **1** and was thus used to further investigate the scope of the reaction (Table 1). Reactions performed with commercial LDA solutions provided the same reactivity as freshly prepared LDA. Similarly, lithium

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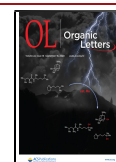
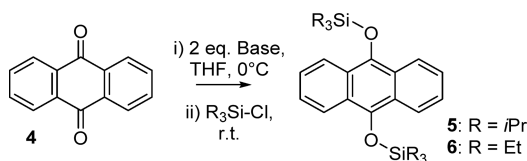


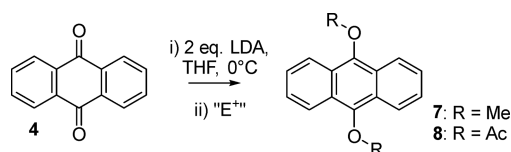
Table 1. Reaction Conditions toward Anthracene Silyl Ethers

base	R	R-Cl (equiv)	yield (%)
LDA	<i>i</i> Pr	4	82
fresh LDA	<i>i</i> Pr	4	83
LiTMP	<i>i</i> Pr	4	80
LHMDS	<i>i</i> Pr	4	13
LDA	<i>i</i> Pr	2	45
LDA	<i>i</i> Pr	2 (reflux)	70
LDA	Et	2	95

tetramethylpiperidide caused an immediate color change upon addition to **4**, ultimately producing the same TIPS-substituted product **5** in 82% yield. Addition of lithium hexamethyldisilazide to **4** gave no obvious color change, and anthracene **5** was isolated in a much lower yield (13%), a majority of the material being recovered quinone. Although similar in basicity, LDA and LiTMP are known to undergo single-electron transfer reactions, which are uncommon for LHMDS. Absorption spectra of the intermediate formed by adding an excess of LDA to **4** resemble those of the electrochemically generated radical anion.¹¹ This intermediate confirms an electron transfer mechanism but also suggests that a second reduction to the dianion is not possible. The persistent radical anion first must react with an electrophile, before a second electron transfer can occur. The resulting anion can then react with a further electrophile molecule to yield product **5**. The observation of LDA acting as an electron donor has been documented.^{12,13} Perhaps the most relevant report comes from the Scott group, who observed that ketones underwent reduction by electron transfer, subsequently following a variety of reaction pathways.¹⁴ However, this reactivity has not found widespread use as a useful synthetic protocol.

The minimum amount of TIPS-Cl for complete reaction at room temperature was found to be 4 equiv. Using only 2 equiv, the reaction did not go to completion after the mixture had been stirred overnight at room temperature, as observed by the red coloration of the reaction mixture due to the radical anion, and the reduced yield. Heating at reflux after the addition of 2 equiv of TIPS-Cl resulted in conversion within a few hours, minimizing the amount of excess TIPS-OH being produced upon quenching but at the cost of a yield lower than for the room-temperature reaction. Silyl chlorides with primary alkyl chains [R = Et (Table 1)] required only 2 equiv and resulted in complete reaction in <1 h at room temperature in excellent yield.

In attempts to install a range of simple alkyl chains (Table 2), only anthraquinone **4** was recovered. For electrophiles with protons adjacent to the leaving group, a competing E2 reaction is a plausible explanation for the lack of desired reactivity. However, electrophiles such as benzyl bromide and allyl bromide also yielded only anthraquinone **4**. Alternatively, the intermediate may react through a radical pathway, resulting in hydroquinone formation and eventually reoxidation to quinone **4**. An exception was the reaction with either iodomethane or dimethyl sulfate, which proceeded in good yield to methyl

Table 2. Reaction Conditions with Carbon-Based Electrophiles

E ⁺	R	conditions	yield (%)
BuBr	Bu	8 equiv, 55 °C, HMPA, 5 days	0
BuBr	Bu	4 equiv, 55 °C, K ₂ CO ₃	0
MeI	Me	2 equiv, 55 °C	67
Me ₂ SO ₄	Me	2 equiv, rt	80
Ac ₂ O	Ac	2 equiv, rt	49

ether hydroquinone **7**. Acyl-derivatized product **8** could also be obtained rapidly and cleanly by use of acetic anhydride.

Silyl ether side groups induce a larger red-shift of absorption and emission and smaller oxidation potentials than alkoxy or acyl groups (Figure 1). This shift is explained by stronger lone

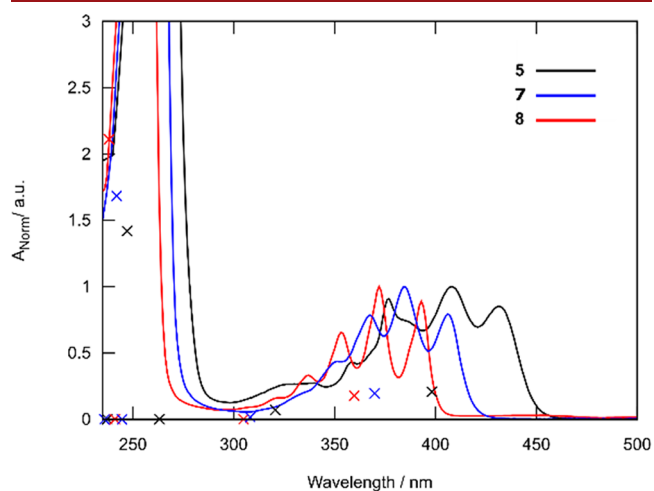


Figure 1. Normalized absorption spectra of anthracene derivatives **5**, **7**, and **8** in a dilute solution (CH₂Cl₂, 10⁻⁶ M). Crosses indicate time-dependent density functional theory-predicted excitation wavelengths and oscillator strengths.

pair donation from the more electron rich oxygen atoms of the polarized Si–O bond. There is also significant hyperconjugation donation from the Si–O bond into the acene system, as observed by natural bond orbital¹⁵ analysis (see the Supporting Information). Electron donation affects both HOMO and LUMO levels, but the stronger influence on the HOMO results in a narrowing of the frontier orbital gap. All of these changes are described well by density functional theory calculations (see the Supporting Information).

Given the ease of isolating the silyl hydroquinones, the scope of functionalizing a variety of quinones with TIPS groups was explored (Figure 2). The synthesis of substituted tetracene **9** was successful, but reaction of pentacene quinone failed to yield the desired acene product, likely due to the insolubility of the quinone and the instability of the final product. Thiophene-containing quinones undergo reaction without substitution adjacent to sulfur (Figure 2, **10–12**), indicating the faster reaction by electron transfer than by deprotonation. The good yield of substituted benzodithiophene **10** is particularly relevant given its use in donor–acceptor polymers

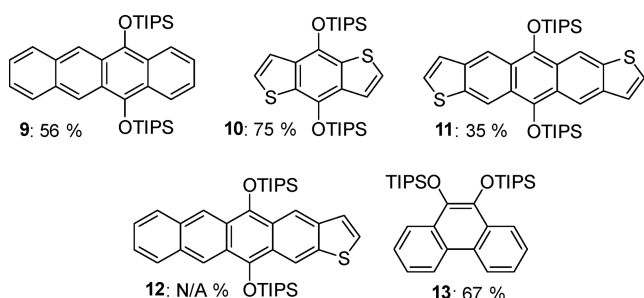


Figure 2. Products from reactions of a range of quinones with LDA and TIPS-Cl.

and small molecules for photovoltaics.¹⁶ Yields of products tend to mirror the size of the acene system, and the corresponding expected decrease in stability of the final products. Thienotetracene **12** was the largest system that could be synthesized, although the crystalline material decomposed even in the absence of light over a period of weeks. It was not possible to obtain a clean NMR spectrum of **12**; therefore, its purity is questionable, and a yield could not be determined. Reaction with 1,2-diones was also successful, with phenanthrene derivative **13** being isolated in reasonable yield.

Molecular properties were investigated by absorption and emission spectroscopy, showing the expected progressive red-shift with an increase in acene size. Addition of a thiophene ring resulted in a shift of ~ 50 nm, while addition of a benzenoid ring resulted in shifts of 100 nm, in line with observations of other derivatized acene families (Figure 3).¹⁷

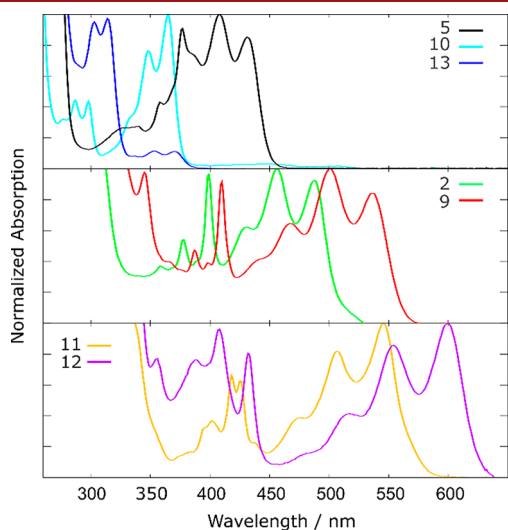


Figure 3. Normalized solution absorption spectra (CH_2Cl_2 , 10^{-6} M) of TIPS-substituted acenes.

Following this trend, the long wavelength absorption of thienotetracene **12** is representative of the depicted structure, although some absorption toward the UV region could originate from decomposition products such as endoperoxide. All of the TIPS-substituted acenes exhibit fluorescence spectra with the mirror image of the $S_1 \leftarrow S_0$ excitation, showing that despite the close energy of the S_1 and S_2 states, these materials still conform to Kasha's rule.¹⁸ Cyclic voltammetry showed a reversible oxidation peak in most cases, with no reduction peaks observed within the solvent window. Experimental HOMO energies increase with an increase in acene size and

are reproduced well by density functional theory calculation of ionization potentials.

While the TIPSO-acene series could be characterized by optical spectroscopy, the larger members of the series showed poor light stability in dilute solution. In direct sunlight, solutions of tetracene **9** are bleached in <10 min, with the resulting UV–visible spectra showing no absorption in the visible region. Samples of **9** freshly prepared from crystalline material exhibit a clean ^1H NMR spectrum. After light exposure, these original resonances disappear and peaks resembling literature spectra⁶ for the endoperoxide decomposition product are observed (see the Supporting Information). Drop-cast films showed improved photostability over dilute solutions but were eventually bleached in direct sunlight over tens of hours. Single crystals are more stable and could be safely handled under ambient conditions. Structural factors concerning the photostability of the siloxy acenes are under further investigation in our lab.

Crystals suitable for X-ray diffraction analysis could be grown in most cases. Several common trends were observed in the packing. Most derivatives show the *anti* conformation of the oxy substituents (Figure 4, top). In gas phase calculations

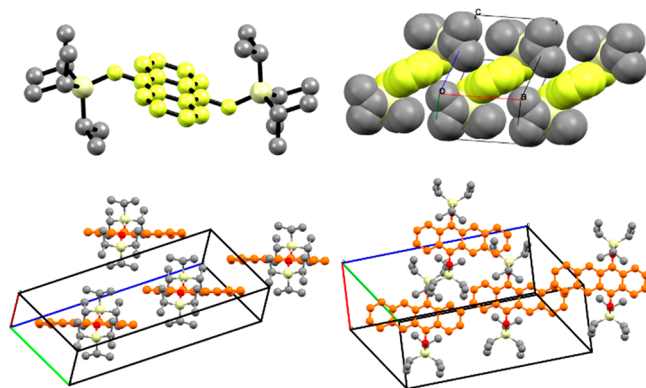


Figure 4. Crystal structures of anthracene **5** (top, yellow) and tetracene **9** (bottom, orange).

(see the Supporting Information), the *syn* and *anti* conformers are almost equal in energy regardless of the substituent. In the crystalline solid, the *anti* conformation may be favored as it allows for the construction of extended molecular stacks, while the *syn* conformation molecules are limited to pairwise interactions. In most cases, there are few close contacts between atoms of adjacent acene cores, meaning electronically and optically isolated chromophores with single crystals all exhibit solid-state emission. Acyl anthracene **8** does show significant spatial overlap between anthracene cores, although transfer integral calculations suggest that electronic communication is still minimal between adjacent molecules. Crystals of **9** show minimal overlap between the long ends of the tetracene core of two molecules arranged in opposing directions (Figure 4, bottom). Despite minimal spatial overlap, calculated transfer integrals show a moderate coupling of 45 meV between LUMOs. Although these materials are not suited to n-type transport due to high-energy LUMOs, the fact that some orbital overlap is possible is promising with respect to future attempts to crystal engineer p-type materials for solid-state charge transport through solubilizing group size and PAH core dimension.

In conclusion, a straightforward synthesis of functionalized PAHs directly from their parent quinones has been discovered using common laboratory reagent LDA. Compared to alternative literature procedures, this new method is extremely straightforward to perform, is sometimes complete in minutes or can be left for prolonged periods in the absence of light without any side reaction, and results in high yields of product, which are easily isolated. The *in situ* generation of intermediates allows the reaction of otherwise unstable hydroquinones to be realized. This work also serves as a reminder that use of LDA as a base with electron deficient systems can lead to unexpected reactivity.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.orglett.0c02529>.

Synthetic and computational details and experimental spectra (PDF)

Accession Codes

CCDC 2020003–2020007 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

■ AUTHOR INFORMATION

Corresponding Author

Karl J. Thorley – Department of Chemistry and Center for Applied Energy Research, University of Kentucky, Lexington, Kentucky 40506, United States; orcid.org/0000-0003-0665-3363; Email: karl.thorley@uky.edu

Authors

Yang Song – Department of Chemistry, Centre College, Danville, Kentucky 40422, United States; orcid.org/0000-0002-5901-5739

Sean R. Parkin – Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506, United States

John E. Anthony – Department of Chemistry and Center for Applied Energy Research, University of Kentucky, Lexington, Kentucky 40506, United States; orcid.org/0000-0002-8972-1888

Complete contact information is available at: <https://pubs.acs.org/doi/10.1021/acs.orglett.0c02529>

Notes

The authors declare no competing financial interest.

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