π-Extension of heterocycles via a Pd-catalyzed heterocyclic aryne annulation: π-extended donors for TADF emitters†

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We report the annulation of heterocyclic building blocks to access π-extended polycyclic aromatic hydrocarbons (PAHs). The method involves the trapping of short-lived hetarynes with catalytically-generated biaryl palladium intermediates and allows for the concise appendage of three or more fused aromatic rings about a central heterocyclic building block. Our studies focus on annulating the indole and carbazole heterocycles through the use of indolynes and carbazolyne chemistry, respectively, the latter of which required the synthesis of a new carbazolyne precursor. Notably, these represent rare examples of transition metal-catalyzed reactions of N-containing hetarynes. We demonstrate the utility of our methodology in the synthesis of heterocyclic π-extended PAHs, which were then applied as ligands in two-coordinate metal complexes. As a result of these studies, we identified a new thermally-activated delayed fluorescence (TADF) emitter that displays up to 81% photoluminescence efficiency, along with insight into structure–property relationships. These studies underscore the utility of heterocyclic strained intermediates in the synthesis and study of organic materials.

Introduction

Polycyclic aromatic hydrocarbons (PAHs) have had a remarkable impact on materials science due to their desirable electronic and self-assembly properties. A privileged subset of PAHs, heterocyclic PAHs, are highly valued in solar cells,3 electron luminoscent materials1 and organic light emitting diodes (OLEDs)4 (e.g., 1–3, Fig. 1). Indeed, heteroatom incorporation in these systems provides several functional and electronic advantages. This includes the introduction of nitrogen functional handles for synthetic manipulations, capacity for N-coordination to metal centers, the potential for donor–acceptor systems and usage as stimuli-responsive materials.5 Accordingly, concise and diversifiable synthetic methods for accessing heterocyclic PAHs are highly desirable.6

An attractive approach toward heterocyclic PAHs involves assembling fused rings about a central heterocyclic building block through annulative π-extension (APEX).6 A compelling means to achieve this objective involves the use of in situ generated aryynes, although such intermediates were historically avoided because of their high reactivity. However, the strain driven reactivity of aryynes, along with the ability to form multiple bonds in a single step under mild conditions, has prompted the recent usage of aryynes as modular building blocks in a wide array of applications, including in the synthesis of PAHs.7–11 In contrast, heterocyclic aryynes (hetarynes) have only been used sparingly in PAH synthesis. This is in part due to the mild, fluoride-mediated generation of heterocyclic aryynes (hetarynes) only becoming widespread in the past decade.12 Moreover, the ability to access and manipulate indole-derived aryynes (indolynes) and their derivatives differs considerably from that of benzynne chemistry. The pyrrole ring can influence

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Of note, this type of Larock annihilation and permit rapid access to heterocyclic triphenylene derivatives. Three aromatic rings (shown in blue) to important heterocycles, of benzene.

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Hetarynes are rare. Iwayama and Sato have reported [2+2+2] annulations. Additionally, metal-catalyzed transformations that utilize metal-catalyzed trappings of hetaryne structure and reactivity, and its nucleophilicity can often result in side reactions, posing numerous challenges for methodology development. Specifically, the reaction rate of pyrrole in electrophilic aromatic substitution reactions has been approximated to be roughly $3 \times 10^{18}$ times faster than that of benzene. Fig. 2A highlights two recent examples of the generation and capture of indolyne 5, which arises from indolyne silyl triflate precursor 4.16–18

In the present study, we aimed to develop a rapid, convergent approach to access heteroatom-containing PAH scaffolds. In particular, a method was devised that allows for the appendage of multiple aromatic rings to important heterocyclic building blocks in a controlled bimolecular reaction. This reaction provides access to a diverse set of aromatic products with electronic and steric modifications. The sequence we devised, inspired by pioneering studies by Larock, is shown in Fig. 2B. In situ generated hetarynes 9 would be united with bromobiyaryl partners 10 using palladium catalysis to furnish heterocyclic PAHs 11.19 This annulative π-extension of hetarynes would expand on existing applications of hetaryne chemistry, create two new carbon–carbon (C–C) bonds, allow for the addition of three aromatic rings (shown in blue) to important heterocycles, and permit rapid access to heterocyclic triphenylene derivatives. Of note, this type of Larock annulation had not previously been achieved using nitrogen-containing, hetaryne intermediates. Additionally, metal-catalyzed transformations that utilize hetarynes are rare. Iwayama and Sato have reported $[2+2+2]$ reactions of pyridynes.20 Only one study involving metal-catalyzed reactions of electron-rich N-containing hetarynes is available in the literature, as developed by our laboratory.16

Herein, we describe the development of this methodology to access π-extended hetaryne adducts, in addition to a concise synthetic route to a new carbazylene precursor. We also show the utility of our methodology in the synthesis of π-extended ligands, which were utilized in novel two-coordinate metal complexes 12. Rapid access to complexes 12 allowed us to study the influence of extended conjugation on the efficiency of thermally activated delayed fluorescence (TADF) processes, which have received notable interest in recent years in the context of OLEDs.21 As described in Scheme 1, in OLEDs, singlets ($S_1$) and triplets ($T_1$) are generated upon hole and electron recombination. Fluorescence describes prompt decay from the $S_1$ state, whereas phosphorescence describes delayed decay from the $T_1$ state. In TADF emitters, $T_1$ is thermally promoted to the $S_1$ state, followed by radiative decay from $S_1$. We show that extended π-conjugation can influence the performance of the TADF complex by modulating either the steric or electronic features of the ligand. Moreover, our studies permit access to a new TADF emitter that displays up to 81% photoluminescence efficiency.

Results and discussion

We initiated our synthetic studies by pursuing a Pd-catalyzed annulation reaction of bromobiaryl 13 with $N$-Me-4,5-indolyne precursor 14 (Fig. 3), the latter of which is accessible in a single step from its commercially available $N$–H derivative. In our initial studies, we used 2-bromobiphenyl as the aryl halide coupling partner and examined conditions reported by Larock for the annulation of carboxyclic arynes.22 This led to the formation of 16 in only 43% yield, highlighting the aforementioned challenges associated with using N-containing hetarynes in metal catalyzed reactions, as compared to simpler arynes. In prior studies,24–26 we found that metal-catalyzed trappings of heterocyclic strained intermediates necessitate careful optimization, as such reactions require that a transient strained intermediate be generated at a rate that allows for efficient reaction with an in situ generated organometallic species (i.e., after 13 undergoes oxidative addition with Pd), while minimizing decomposition pathways commonly seen in strained intermediate chemistry. We ultimately found the desired reaction took place more efficiently by employing 5 mol% Pd(db)2, 5 mol% P(o-tolyl)3, a 1 : 1 ratio of co-solvents acetonitrile and toluene, and 10 equivalents of cesium fluoride (CsF). The mixture of co-solvents, in particular, is thought to be important for modulating the rate of hetaryne formation.27 With optimal
conditions, **16** could be accessed in 90% yield. Substituted biaryls could also be employed in the methodology. For example, methoxy- and nitro-substituted biaryls underwent the annulation smoothly to deliver adducts **17** and **18** in 62% and 80% yields, respectively. In these cases, mixtures of regioisomers are formed in roughly equal quantities. We also sought to incorporate additional heteroatoms into the products by employing heterocyclic derivatives of 2-bromobiphenyls. Use of a pyridyl substrate furnished **19** in 76% yield, which is an interesting aza-analog of parent compound **16**. We were also able to replace one of the phenyl rings with pyrrole or indole units, as exemplified by the formation of **20**–**22**. Lastly, we performed the annulation of 2-bromobiphenyl (**23**) with 5,6-indolyne precursor **24**, which delivered adduct **25** in 81% yield. The results shown in Fig. 3 not only provide access to electronically and structurally diverse heteroatom-containing PAHs, but also validate our strategy to achieve the π-extension of heterocyclic building blocks.

Having validated the π-extension of indoles via the use of indolynes, we sought to develop analogous chemistry using the carbazole heterocycle. Carbazoles bear an additional aromatic ring in comparison to their indole counterparts and are valuable in materials-based applications, medicinal chemistry, and natural product total synthesis. However, aryne-derived carbazoles (carbazolynes) have seen sparse use in chemical synthesis. Recent examples involve carbazole generation from the hexadehydro-Diels–Alder reaction, the use of a silyl nonaflate precursor, and via classic dehydrohalogenation chemistry. As silyl triflate precursors to carbazolynes were not known in the literature, we developed the concise approach to carbazolylene precursors **29**–**31** shown in Fig. 4. 3-Bromo-2-hydroxycarbazole (**26**) was treated with HMDS to afford silyl ether **27**, which, in turn, was carried forward in a retro-Brook rearrangement sequence to afford silyl alcohol **28**. Triflation proceeded smoothly to deliver silyl triflate **29** in 69% yield. N-H compound **29** was elaborated to protected derivatives **30** and **31** via methylation and Boc-protection, respectively. N-Me-carbazolylene precursor **30** was employed in our π-extension methodology using our previously optimized conditions. We were delighted to find that reaction of 2-bromobiphenyl (**23**) and N-Me-carbazolylene precursor **30** using Pd-catalysis furnished π-extended carbazole **32** in 86% yield. This is the first example of a transition metal-catalyzed trapping of a carbazolylene intermediate. Notably, this permits the one-step installation of a carbazole moiety into a π-extended system.

We also sought to determine if N-H derivatives of our indole and carbazole annulation products could be accessed using our methodology. It was ultimately found that N-H products were accessible by employing N-Boc protected hetaryne precursors in our methodology (Fig. 5). Subjection of **23** and indolyne precursor **33** to our standard reaction conditions, followed by treatment with trifluoroacetic acid (TFA) to remove the Boc...
protecting group, gave deprotected indole scaffold 34 in 34% yield. Similarly, N-H carbazole adduct 35 was accessed in 65% yield via the corresponding reaction of 23 and N-Boc-carbazolene precursor 31. The ability to access π-extended N-H products (e.g., 34 and 35) is expected to prove generally useful, as the N-position can be easily substituted. PAHs 34 and 35 also proved useful in our subsequent studies (vide infra) pertaining to the synthesis and evaluation of thermally activated delayed fluorescence (TADF) complexes.

A potential application of indole- and carbazole-based PAHs is in organic light emitting diodes (OLEDs), which are crucial for high-performance display technologies and solid-state lighting applications. Specifically, the recent development of TADF complexes of the general structure donor–M–acceptor, where M is Cu(I), Ag(I), or Au(I), and where the donor and acceptor are amide and carbene ligands, respectively, (e.g., 36 and 37, Fig. 6) has allowed access to emissive dopants with high photoluminescence efficiencies (ΦPLQY up to 100% in both solution and in the solid state) and short-lived excited states (τ < 1 μs). These compounds also offer potential economic advantages over Ir- or Pt-centered phosphorescent dopants.

The photophysical properties of these two-coordinate complexes can be manipulated by altering either the donor or acceptor ligands. For example, compounds 36 and 37 have the same amide donor ligand (carbazolyl) but different acceptor carbene ligands. Consequently, the energy for the interligand charge transfer (ICT) transition is different in each complex. Compound 36, with the carbene BZI (1,3-bis(2,6-diisopropylphenyl)-1-H-benzo[d]imidazole-2-ylidene) as an acceptor ligand emits at 432 nm when doped in polystyrene (PS) films whereas 37, which has MAC (1,3-bis(2,6-diisopropylphenyl)-5,5-dimethyl-4-keto-tetrahydropyridylidene) as an acceptor, emits at 506 nm in the same media. The difference in energy for the ICT state is due to the poorer electrophilicity of BZI (36, Ered = −2.82 V vs. Fe+/Fe) relative to MAC (37, Ered = −2.50 V). The low electron affinity of BZI raises the energy of the τICT state such that it is near resonant with that of the locally excited triplet state (τLE) of carbazolyl (τLE = 415 nm). It follows that altering the nature of the amide donor will also modify the energy of the ICT state, and consequently the photophysical properties of the complex.

Previous studies on carbazolyl donor ligands have focused on electronic modifications of carbazole using electron-donating or withdrawing groups, steric hindrance, and structural flexibility, leading to important structure–property relationships. Moreover, extending the conjugation in aromatic π-systems by benzannulation has been shown to impact relative HOMO and LUMO energy levels in ways that sometimes lead to counterintuitive changes in emission color. Thus, the effect of similar π-extension on the photophysical properties of donor–M–acceptor complexes may not be obvious. Heterocyclic PAHs accessible by our π-extension methodology provide an opportunity to study and compare new π-extended TADF complexes.

Two-coordinate donor–Au–acceptor complexes were prepared by treatment of 34 or 35 with sodium tert-butoxide in the presence of the NHC–Au–Cl complex (Fig. 7A). The metal complexes evaluated in the present study (Fig. 7B) are Au complexes due to their superior stability compared to Ag or Cu analogs. Complexes 36+π and 37+π were obtained in 68% and 78% yields, respectively, whereas the respective indolyl complexes 38 and 38+π were prepared in 60% and 45% yields using this protocol. Complexes 36+π and 37+π enable comparison of the new π-extended phenanthrocarbazolyl donors to their respective carbazolyl counterparts, 36 and 37. The methylindolyl (38) and phenanthroindolyl (38+π) derivatives allow us to assess the impact of π-extension within a new indole series of complexes, as well as compare the carbazolyl and indolyl complexes.

The photophysical properties of the π-extended carbazolyl-based complexes, 36+π and 37+π, were examined in different
media (Fig. 8) and compared to data of the parent carbazole-containing complexes 36 and 37 (Table 1).\textsuperscript{36,48,49} The UV-visible absorption spectra of 36+\(\pi\) and 37+\(\pi\) display a strong solvent-independent band at 320 nm attributed to a \(\pi-\pi^*\) transition localized on the phenanthrocarbazolyl ligand. Weaker bands at lower energy are more structured and display a pronounced negative solvatochromism (e.g., 36+\(\pi\) at 416 nm in MeCy and 382 nm in MeTHF; 37+\(\pi\) at 460 nm in MeCy and 417 nm in MeTHF). This band is assigned to the ICT transition between the \(\pi\)-extended carbazole donor and carbene acceptor ligand that is overlapped with \(\pi-\pi^*\) transitions on the phenanthrocarbazolyl ligand.

The UV-visible absorption spectra of 36+\(\pi\) and 37+\(\pi\) are narrow, red-shifted and independent of solvent polarity. Radiative (\(k_r\)) and non-radiative (\(k_{nr}\)) rate constants are calculated using the relationship 
\[ k_r = \Phi_{PL}/\tau, \]
where \(\Phi_{PL} = k_r/(k_r + k_{nr})\). The radiative rate for emission from 36 is rapid (\(k_r = 3.0 \times 10^7\) s\(^{-1}\) in MeTHF) as opposed to being markedly slow in 37+\(\pi\) (\(k_r = 4 \times 10^5\) s\(^{-1}\) in MeTHF). Unlike the photophysical properties of 36, which are characteristic of emission from an ICT state, luminescence from 36+\(\pi\) indicates that the excited state transitions are localized on the donor ligand, and hence undergo conventional phosphorescence rather than TADF. This assignment for the luminescence is confirmed by the minimal shift in energy and millisecond emission lifetime found upon cooling to 77 K. The difference in properties for 36+\(\pi\) versus 36 is caused by the lower energy for \(^1\)LE state of the phenanthrocarbazolyl moiety (see ESI) compared to that for the carbazolyl ligand. In contrast, complex 37+\(\pi\) is capable of efficient TADF from the ICT state as borne out by emission spectra (Fig. 8) that are similar, albeit redshifted, to spectra reported for 37. The fast

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**Table 1** Photophysical data for carbene–Au–carbazolyl complexes

<table>
<thead>
<tr>
<th>Complex</th>
<th>Solvent</th>
<th>(\lambda_{abs}^a)</th>
<th>(\lambda_{em,298,K} (\lambda_{77,K}))</th>
<th>(\Phi_{PL/\nu})</th>
<th>(\tau_{298,K} (10^{-6},s))</th>
<th>(k_r (10^{5},s^{-1}))</th>
<th>(k_{nr} (10^{5},s^{-1}))</th>
<th>(\tau_{77,K} (10^{-3},s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>36+(\pi)</td>
<td>1% PS film</td>
<td>385</td>
<td>452 (426)</td>
<td>1.00</td>
<td>3.6 (54%)</td>
<td>4.4(^b)</td>
<td>&lt;0.04(^b)</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>MeCy</td>
<td>405</td>
<td>424 (424)</td>
<td>0.89</td>
<td>1.2</td>
<td>7.8</td>
<td>0.9</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>MeTHF</td>
<td>365</td>
<td>452 (426)</td>
<td>0.79</td>
<td>2.6</td>
<td>3.0</td>
<td>0.8</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>1% PS film</td>
<td>388</td>
<td>506 (502)</td>
<td>0.52</td>
<td>5.1 (70%)</td>
<td>3.1(^b)</td>
<td>11(^b)</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>MeCy</td>
<td>416</td>
<td>502 (504)</td>
<td>0.03</td>
<td>30.0</td>
<td>0.01</td>
<td>0.3</td>
<td>2.9 (90%)</td>
</tr>
<tr>
<td></td>
<td>MeTHF</td>
<td>382</td>
<td>504 (498)</td>
<td>0.02</td>
<td>57</td>
<td>0.004</td>
<td>0.2</td>
<td>14 (8%)</td>
</tr>
<tr>
<td>37+(\pi)</td>
<td>1% PS film</td>
<td>425(^c)</td>
<td>512 (506)</td>
<td>0.85</td>
<td>0.83</td>
<td>10.0</td>
<td>1.8</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>MeCy</td>
<td>450</td>
<td>522 (456)</td>
<td>0.88</td>
<td>1.1</td>
<td>8.0</td>
<td>1.1</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>MeTHF</td>
<td>412</td>
<td>544 (428)</td>
<td>0.50</td>
<td>0.79</td>
<td>6.3</td>
<td>6.3</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>1% PS film</td>
<td>420</td>
<td>529 (500)</td>
<td>0.74</td>
<td>3.3 (47%)</td>
<td>3.4(^b)</td>
<td>1.2(^b)</td>
<td>4.4 (43%)</td>
</tr>
<tr>
<td></td>
<td>MeCy</td>
<td>460</td>
<td>544 (500)</td>
<td>0.81</td>
<td>0.9 (91%)(^d)</td>
<td>9.1</td>
<td>2.1</td>
<td>1.8 (59%)</td>
</tr>
<tr>
<td></td>
<td>MeTHF</td>
<td>417</td>
<td>566 (498)</td>
<td>0.39</td>
<td>0.6 (96%)(^d)</td>
<td>6.9</td>
<td>11</td>
<td>2.4 (72%)</td>
</tr>
</tbody>
</table>

\(^a\) ICT band. \(^b\) Calculated from the weighted averages of both contributions. \(^c\) Obtained from excitation spectrum. \(^d\) An additional minor contribution from a longer lifetime component is needed to fit the observed data and assigned to \(p\)-type delayed fluorescence. See ESI.
radiative rate \(k_r = 9.1 \times 10^5 \text{s}^{-1}\) and high photoluminescence efficiency \(\Phi_{\text{PLQY}} = 0.81\) at room temperature in MeCy, along with luminescence that is redshifted from polar solvent (MeTHF) to non-polar solvent (MeCy and polystyrene film), is also consistent with emission from an ICT state. Emission at 77 K (500 nm) is structured and polarity-independent. In this case, solvent molecules are frozen as a glass around the complex molecules, thus restricting stabilization of the excited ICT state upon going from 298 K to 77 K. The ICT state in MeCy retains ICT character even in frozen matrix. For MeTHF, note that the destabilization of the ICT state upon going from 298 K to 77 K is greater in MeCy and MeTHF than in the PS film. This is likely due to enhanced solute–solute interactions on cooling the fluid solutions to 77 K, whereas the relative orientations of the solutes are fixed in a more random fashion at room temperature in the PS film. In contrast, the emission spectrum of 38+π is structured at 77 K and assigned to a low-lying \(3\)LE transition on the phenanthroindolyl ligand. The short lifetime measured for 38+π in MeTHF (\(r = 1.1 \times 10^{-4} \text{s}\)) compared to that for 38+π (\(r = 1.5 \times 10^{-2} \text{s}\)) is consistent with an ICT transition for the former complex and \(3\)LE phosphorescence for the latter derivative.

Complex 38+π exhibits higher photoluminescence quantum yields in all media compared to 38. The yields increase from MeTHF (\(\Phi_{\text{PLQY}} = 1.4\%\)) to MeCy (\(\Phi_{\text{PLQY}} = 24.2\%\)) to the PS film (\(\Phi_{\text{PLQY}} = 49\%\)). The lower emission efficiency in polar solvents is attributed to the greater reorganization of the excited state structure in polar solvents. Generally, complex 38 displays comparable, although slower radiative rates \(k_r\) and faster non-radiative rates \(k_{\text{nr}}\) in all solvents relative to 38+π. The slower \(k_{\text{nr}}\) of 38+π is likely due to a slower rate of rotation or exchange caused by the larger free volume of the 38+π ligand.

Comparing the carbazolyl and indolyl MAC complexes, it is noted that both appear to undergo TADF emission; however, the former (carbazolyl) family exhibits higher photoluminescence efficiencies due to lower rates of non-radiative decay. In comparing 38 to 38+π, the low steric profile about the indolyl ligand appears to have a greater influence on the photophysical performance than any energetic differences. In contrast, the discrepancy in performance between 36 and 36+π is attributed primarily to the energetics induced by π-conjugation. In other words, the photophysical properties of indolyl-based complexes are primarily influenced by decreased steric hindrance of the indolyl ligand, whereas the performance of the carbazolyl-based
complexes is primarily dictated by the π-conjugation thermodynamics.

Conclusions

In summary, we have developed a modular platform to access N-heterocycles with extended π-conjugation by leveraging heterarynes and Pd-catalysis. Of note, these represent rare examples of metal-mediated transformations of N-heterocyclic arenes. Through the construction of two C–C bonds in a single operation, this methodology allows for the direct π-extension of heterocyclic scaffolds through the appendage of three or more aromatic rings. The methodology offers a convergent platform for accessing important heterocycles with structural and electronic diversity. Notably, a new carbazolyl precursor, whose synthesis relies on a key retro-Brook rearrangement, can also be leveraged in this reaction to access carbazole derivatives. Heterocycles accessed in our methodology were ligated to Au–NHC complexes to give new two-coordinate metal complexes.

We find that extending the π-conjugation of the donor ligand influences the photophysical properties of the two-coordinate Au(II)–NHC complexes. The principal effect of π-extension in these compounds is stabilization of the triplet energy as opposed to only a minor perturbation of the donor strength. Therefore, depending on the nature of the carbene paired with the donor ligand, luminescence can be tuned to achieve emission from either the 3LE or ICT state. Thus, a relatively weak electron accepting carbene such as BZI in 36 and 36+π gives only inefficient 3LE emission, whereas the stronger electron accepting MAC carbene in 37 and 37+π leads to efficient emission from the ICT state. The carbazolyl (37 and 37+π) and indolyl (38 and 38+π) complexes allow for the direct comparison of two systems that undergo TADF emission from the ICT state. The π-extension of the carbazolyl ligand in 37+π leads to a red-shift in emission. However, π-extending the indolyl-based ligand in 38+π results in an unexpected blue-shift in emission energy that may owe to the different position of substitution.42

These studies should prompt further structure–photophysical property studies of donor ligands in these metal complexes to enhance OLED stability and efficiency. Furthermore, these studies demonstrate that heterarynes can be strategically leveraged as central building blocks for accessing π-extended scaffolds with notable properties.

Data availability

Full details on the synthesis and characterization of compounds, photophysical data, and computational methods are accessible in the ESI†

Author contributions

K. A. S., J. V. C., and R. B. S. designed and performed experiments and analyzed experimental data pertaining to the heterocyclic PAHs. M. D. and N. U. synthesized, characterized, and studied the photophysical properties of the metal complexes. P. I. D., M. E. T., and N. K. G. directed the investigations and prepared the manuscript with contributions from all authors; all authors contributed to discussions.

Conflicts of interest

One of the authors (Mark E. Thompson) has a financial interest in the Universal Display Corporation.

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Notes and references


35 When the N–H variant of the 4,5-indolyne precursor was utilized in our general annulation conditions, only minimal amounts of the desired product were observed.


50 See ESI† for preparation of 1 wt% polystyrene film.