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Tetra-Aza-Pentacenes *via* a One-Pot Friedländer Synthesis

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Abstract: Tetra-aza-pentacenes are attractive n-type small molecules for optoelectronic device applications, yet their syntheses are often laborious. Disclosed here is a one-pot Friedländer synthesis of 1,7,8,14-tetraazapentacece (tAP) derivatives (linear and/or bent), fully aromatized *in-situ* despite the absence of an exogenous oxidant. The photophysics of linear tAPs resembles that of regular pentacene while their crystal structures differ. A LUMO energy of -3.71 eV for di-*tert*-butylanisole-substituted linear tAP is similar to that of the well-known acceptor, C_{60}.

Pentacene derivatives are promising candidates for the development of high performance organic optoelectronic devices, such as photovoltaics (OPVs) and organic field effect-transistors, due to their strong optical absorptivities and high charge carrier mobilities.[1, 2] In most cases, pentacene and its derivatives have been used as p-type semiconductors in these devices; however, n-type pentacene derivatives have been formed through cyclopentannulation strategies or by the introduction of peripheral electron withdrawing groups such as chlorine, fluorine, trifluoromethyl, and nitrile substituents.[2, 3] Peripheral electron withdrawing groups are effective in lowering HOMO and LUMO energy levels, but increase the molecular volume, perturbing the favorable bulk morphology of pentacene. Aza-substitution is an alternative method of lowering the frontier orbital energy levels that does not impact the molecular volume of pentacene.

Houk and Winkler used DFT calculations to identify a series of aza-pentacenes comprised of pyridine moieties as potentially promising n-type materials.[4] We have also carried out a theoretical study on a combinatorial library of tetra-aza-pentacenes.[5] In our study, we determined that incorporating four nitrogens into the pentacene framework lowers the energy level of the LUMO to approximately that of C_{60}, making these aza-acenes attractive candidates as OPV acceptor materials. Of the 135 possible substitution patterns for tetra-aza-pentacene, only 3 have been reported, all containing pyrazine moieties derived from condensations of orthodiaminoaryls.[6, 7] Moreover, synthetic routes to prepare aza-acenes with pyridine rather than pyrazine moieties remain scarce. Herein we disclose a base-catalyzed Friedländer synthesis that provides access to these promising materials, previously thought to be inaccessible.[7]

This report focuses on 1,7,8,14-tetraazapentacene (tAP), which is predicted to have several properties, *i.e.* LUMO energy (3.37 eV), dipole moment (μ = 0.00 D), and electron reorganization energy (λ = 0.15 eV), that closely resemble values found in C_{60}. Our retrosynthetic analysis (Figure 1, **A**) of the target tAP involves the construction of two naphthyridines by ring fusion at 2,5-positions of cyclohexadione with substituted amino-pyridines. Similar acid-catalyzed Friedländer syntheses of di-aza-pentacenes starting from 1,4-cyclohexanedione and 2-aminobenzaldehyde derivatives have been reported to yield linear dihydro-di-aza-pentacene adducts, which were then oxidized to fully aromatized products.[8] Several reports claim that *o*-amino-aryl-aldehydes and 1,4-cyclohexanedione exclusively give products formed by fusion at the 2,3-positions of the dione under basic conditions, Figure 1 (**B**).[9-12] In our hands, we observe adducts resulting from the cyclohexanedione-ring fusion at the 2,5- and 2,3-positions (Scheme 1), which will be hereafter referred to as "linear" (***l***) and "bent" (***b***) products, respectively.

Figure 1. (**A**) Retrosynthesis of tetra-aza-pentacenes comprised of pyridine residues. (**B**) A reported example of a not-fully aromatized Friedländer product from base-catalyzed conditions with ring fusion at the 2,3-positions of the dione.[12]

Scheme 1. One-pot Friedländer synthesis of tetra-aza-pentacenes. i) EtOH, aq. 2M NaOH (0.5 eq), N_2 atm, 12-hour reflux.

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The reaction between 1,4-cyclohexanedione and 2-amino-nicotinaldehyde (**1a**) in refluxing ethanol, promoted by 2M aqueous NaOH, yielded a dark purple suspension containing both the linear (**2l**) and bent (**2b**) Friedländer products (Scheme 1). Compound **2b** is air-stable and relatively soluble in dichloromethane, which facilitates purification and characterization. However, the air-sensitivity of **2l** – like regular pentacene[13] – made purification challenging, and no acceptable NMR data could be recorded due to its poor solubility. Nevertheless, we were able to obtain crystals of **2l** suitable for X-ray crystallography in low yields (<1%) by sublimation at 290 °C and 10^{-6} torr.

The formation of linear Friedländer aza-pentacenes from the same starting materials (1,4-cyclohexanedione and **1a**) was hinted at by Majewicz and Caluwe. They reported the formation of unidentified "intractable and multi-colored products" when KOH was used as a catalyst. [10] When piperidine was used in similar syntheses, bent Friedländer products were exclusively isolated, illustrating the importance of the catalyst choice.[11, 12, 14]The presumptive intermediate after the first Friedländer event is a naphthyridocyclohexanone, which has inequivalent alpha positions with respect to the ketone. Deprotonation of the more acidic alpha proton leads to the bent isomer, while deprotonation at the less acidic site leads to the linear isomer, meaning that the bent isomer is the product of the more favored thermodynamic intermediate enolate. In the previously reported conditions using weak base (piperidine), a rapid acid-base equilibrium quickly tautomerizes all of the intermediate to the thermodynamic enolate, leading to exclusive formation of the bent isomer. Our conditions employing strong base (NaOH) trap some of the less favored kinetic enolate, leading to formation of the linear isomer, although the bent isomer is still the major product.

The *in-situ* aromatization of the synthesized tAPs was somewhat surprising due to the lack of an added oxidizing agent in the reaction. Reactions were carried out in rigorously oxygen-free environments, which eliminates the possibility of O_2 as an oxidant. One plausible mechanism for the aromatization of tAPs is deprotonation-hydride elimination. Reetz and Eibach demonstrated a similar method to aromatize dihydro-acenes into their corresponding acenes in good yields, with potassium fencholate or n-butyl lithium as the catalyzing base.[15]

The poor solubility of the unsubstituted tAP (**2l**) hinders purification, therefore we used a substituted nicotinaldehyde precursor (**1b**) bearing 2,6-di-*tert*-butylanisole (DTBA) as a solubilizing group. Subjecting **1b** to 1,4-cyclohexadione in the same Friedländer conditions leads to new linear (**3l**) and bent (**3b**) tetra-aza-pentacene derivatives which are substantially more soluble than **2l**/**2b**. The DTBA groups did not show improvement in the air-sensitivity of **3l** (see Figure S2 for photo-oxidation monitoring of **3l**). Given molar absorption spectra of individual pure components, as well as the UV-vis absorption spectrum of the crude product mixture (see SI), we used a mixture analysis technique described by Harris[16] to determine the **3l**:**3b** product ratio of 1:7. The reaction yields both the linear and bent tetra-aza-pentacenes because 1,4-cyclohexanedione has only hydrogen substituents on the alpha carbons. Therefore, to promote formation of the linear tAP, 2,5-dibenzylcyclohexane-1,4-dione (**4**) was used in place of the unsubstituted cyclohexanedione, and as expected, only the linear 6,13-dibenzylated tAP (**5l**) was isolated. The presence of two atropisomers (*syn* and *anti*) of **5l** was indicated by NMR spectroscopy. A NOESY ^{1}H NMR spectrum confirmed that the singlets of the benzylic methylene (δ = 4.87 and 5.10 ppm) are not geminal, and hence must belong to two atropisomers (See SI, spectrum S11).

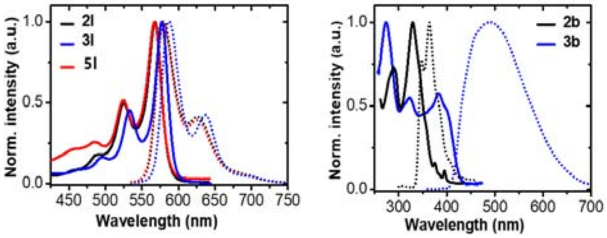

Figure 2. Absorption (solid lines) and emission (dotted lines) spectra of linear tAPs **2l**, **3l**, and **5l** (left), and bent tAPs **2b** and **3b** (right) in DMSO.

The UV-visible absorption and emission spectra of the three linear tAPs (**2l**, **3l,** and **5l**) in DMSO are shown in Figure 2 (left). The compounds exhibit well-defined vibronic progressions observed in other known tetra-aza-pentacenes[17] and acene molecules in general.[18] The unsubstituted tAP (**2l)** and the dibenzylated tAP (**5l)** show identical absorption and emission maxima, (λ_{abs} = 567 nm and λ_{em} = 580 nm), whereas spectra for **3l** are red-shifted (λ_{abs} = 577 nm and λ_{em} = 588 nm). The difference indicates the absence of conjugation between the benzyl groups and the aza-acene core as opposed to weak conjugation between the DTBA groups and the parent tAP core. Compared to the TIPS-bearing tetra-aza-pentacenes (pyrazine-based) reported by Bunz, et al.[17] the absorption spectra of our pyridine-based linear tAPs are hypsochromically shifted, implying a wider band-gap in the present tAPs. Thus, changing the substitution patterns of four nitrogens in the pentacene core can significantly affect the absorption/emission properties of the compounds. On the other hand, absorption and emission spectra of the bent derivatives, **2b** and **3b**, are considerably blue-shifted relative to the linear counterparts (Figure 2, right). According to Clar's rule,[19] the bent isomers have more aromatic π-sextets (*i.e.* two versus one) which results in a wider HOMO – LUMO gap, hence the observed hypsochromic shift. A greater red-shifting observed from **2b** to **3b** is indicative of more pronounced conjugation of the **3b** tAP core with DTBA groups.

Cyclic voltammetry measurements of soluble tAPs (**3b** and **3l**) were carried out under anaerobic conditions (see SI). The linear isomer, **3l**, exhibits an irreversible reduction wave with a reduction peak at -0.95 V *versus* Fc/Fc$^+$. This value is similar to the first reduction potential for fullerene C_{60} (E^{red} = -0.97 V *vs.* Fc/Fc$^+$).[20] The 6,13-ethynylated tetraazapentacene reported by Miao et. al., showed the first reduction at a half-wave potential of -0.79 V *vs.* Fc/Fc$^+$.[21] Using the conversion equation by Sworakowski and co-workers,[22] the reduction potential of **3l** corresponds to E_{LUMO} of -3.71 eV. Hence, from purely hydrocarbon pentacene (E^{red} = -1.76 V, *i.e.* LUMO = -2.75 eV)[23] to **3l**, the LUMO was lowered by *ca.* 1 eV, emphasizing the effect of incorporating inductively electron-withdrawing atoms in the framework. The cyclic voltammogram of bent DTBA-tAP (**3b**) exhibits two reversible reduction peaks at -1.65 V and -1.99 V

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(see SI). The more negative reduction potentials in the bent isomer are consistent with Clar's argument referred to above. Oxidation waves were not observed for either **3b** or **3l**.

Single crystal structures for **2l**, **3b** and **5l** are shown in Figure 3 (Cambridge Crystallographic Data Center numbers (CCDC) are 1866946, 1866947, and 1866945, respectively). Structures **3b** and **5l** belong to the triclinic space group $P\bar{1}$, and **2l** belongs to the monoclinic C2/c. Carbon–carbon bond lengths in all three tAP cores fall in the range of 1.349(4) Å – 1.454(2) Å, and follow a pattern of bond length alternation observed in pentacene (short perimeter versus long internal C-C bonds).[24] The carbon-nitrogen bonds are short, reminiscent of the bond length pattern observed in acridine.[25] The structure core of **2l** and **5l** are planar, whereas that of **3b** is twisted with an offset angle of 17.4° between planes of the two terminal naphthyridines.

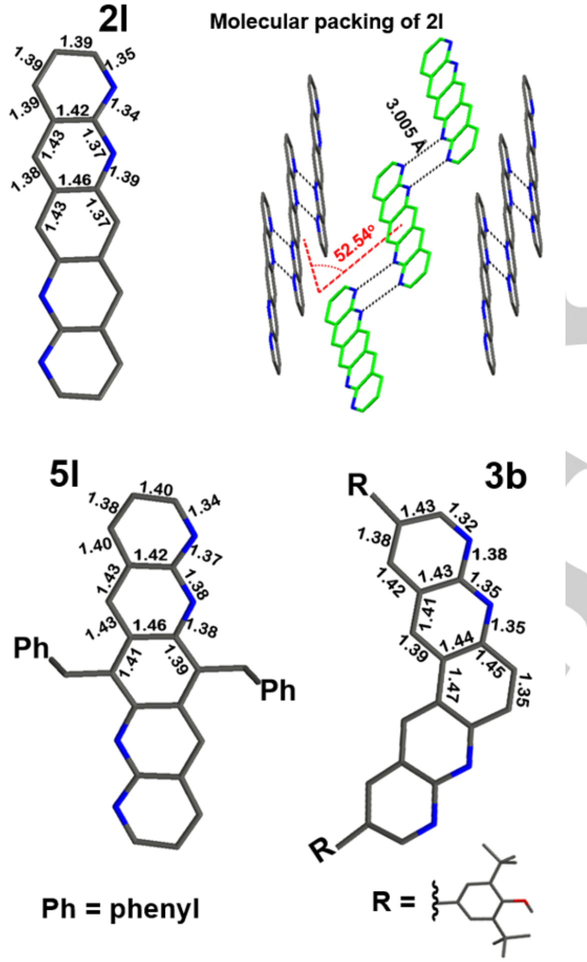

Figure 3. X-ray single crystal structures of **2l** (with its molecular packing), **5l**, and **3b**. Nitrogen atoms are in blue; grey and green colors are used in crystal packing of **2l** for clearer view. Hydrogen atoms are omitted for clarity. Crystal packing and discussion for **5l** and **3b** can be found in SI.

The arrangement of pentacene in the crystal lattice is well studied and known for its edge-to-face herringbone packing motif.[24, 26] The tetra-aza-pentacenes adopt substantially different crystal packing structures (see SI for **3b** and **5l** packing discussion). Neighboring molecules in **2l** are organized into ribbons with adjacent nitrogen atoms aligned opposite each other at a distance close to the sum of van der Waals radii (N···N spacing = 3.005(2) Å, Figure 3). The molecules in these ribbons are arranged in a shallow staircase with a step height of 0.8 Å. The series of slip-stacked ribbons form a sheet propagating in the crystallographic *ab* plane. The molecules in these sheets are not cofacially stacked alongside adjacent sheets, but rather are disposed edge-to-face at an angle of ~53°. The unit cell contains two sheets, related by a glide plane, that alternate along the crystallographic *c* axis in a fashion reminiscent of herringbone packing. Thus, **2l** has cofacial *pi*-stacking in two dimensions, and herringbone-like packing in the third. In contrast, the herringbone arrangement in the crystal packing of pentacene (edge-to-face angle = 52°) propagates in two dimensions, with collinear end-to-end packing in the third.

Isoda and co-workers reported different packing behaviors in the crystal of 5,6,13,14-tetraazapentacene due to induced CH···N hydrogen bonds between molecules from neighboring columns.[27] Similarly, Campbell *et.al*. proposed that packing in multi-nitrogen-substituted pentacene structures should be dominated by flattened herringbone or sheet-like arrangements due to intermolecular CH···N interactions.[28] For the case of **2l**, however, CH···N hydrogen bonds are overshadowed by N···N interactions.

In conclusion, a Friedländer reaction has been used to form fully aromatized tetra-aza-pentacene products in the absence of an exogenous oxidant. Peripheral substitution yields more soluble materials and allows for the isolation and characterization of pure tetra-aza-pentacene molecules. Unsubstituted 1,4-cyclohexanedione permits the formation of both linear and bent Friedländer products, whereas blocking its 2,5-positions enforces exclusive formation of the linear isomer. The photophysical properties of the linear tAPs are similar to pentacene, whereas their crystal structures differ. The electrochemistry of dibenzylated tAP agrees well with computational results, with reduction potentials comparable to that of fullerene acceptors. Therefore, this class of tAPs are promising as potential n-type semiconductors to contribute to the fast-growing research on optoelectronic devices, such as OPVs and/or OFETs, and the adopted synthetic strategy opens up avenues to access other aza-substituted acenes of the same family.

Experimental Section, Supporting Information

Synthetic procedures and characterization data (elemental analysis, MALDI, NMR, electrochemistry, X-ray crystallography, and theoretical calculations) as well as supplementary discussions can be found in the supporting information.

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Keywords: tetra-aza-pentacene • acenes • Friedländer reaction • one-pot synthesis • n-type molecules

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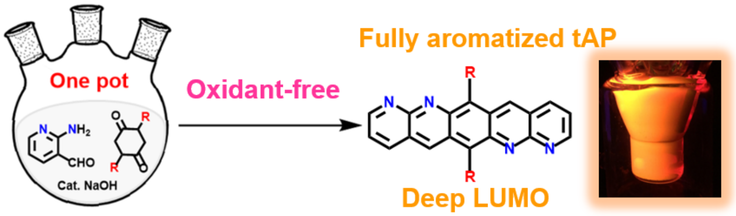

A one-pot Friedländer synthesis catalyzed by strong base (NaOH) yields 1,7,8,14-tetraazapentacenes (tAPs), fully-aromatized *in-situ*, despite the absence of an exogenous oxidizing agent. The LUMO level of linear tAPs is comparable to C_{60}.

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