2,7,11,16-Tetra-tert-Butyl Tetraindenopyrene Revisited by an “Inverse” Synthetic Approach

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Abstract: A new synthetic route to tetraindenopyrene (TIP)—a bowl-shaped cut-out structure of C_{70}—is reported. The key step in this approach is a fourfold palladium-catalyzed C-H activation that increases the yield more than 50 times in comparison to the approach originally described by Scott and co-workers. Besides examination of its optoelectronic properties and study of its aggregation in solution, TIP was also re-investigated by dispersion-corrected DFT methods, which showed that dispersion interactions significantly increase the bowl-to-bowl inversion barrier. Furthermore, TIP was used as a semiconductor in p-channel thin-film transistors (TFTs).

The discovery of fullerene C_{60} in 1985[1] stimulated chemists to synthesize this molecule,[2] other fullerenes or cut-outs thereof—the so-called buckybowls.[3] Buckybowls have interesting properties themselves, but have also been used for the bottom-up synthesis of fullerenes, for example, by flash vacuum pyrolysis.[4] Besides corannulene,[5] sumanene[6] is the simplest substructure of C_{60} and therefore it is not surprising that these two compounds are the most frequently studied.[7] In contrast to C_{60}-related buckybowls, similar approaches to compounds representing substructures of C_{70} (Figure 1) are much rarer.[8] In this respect, Kuo’s C_{38}H_{14} and C_{40}H_{14} bowls are among the largest realized so far, with bowl depths of up to 2.33 Å.[8] Other substructures of C_{70}, such as rubicenes[9] or dibenzorubicenes show smaller bowl depths of 1.68 Å[10a] or twisted[10a, 11] conformations in the solid state. Some of these molecules have been employed as the semiconductor in p-channel thin-film field-effect transistors, with a maximum reported charge-carrier mobility of 1 cm^{2}/V·s.[11]

Another substructure of C_{70} is tetraindenopyrene (TIP, 2, Figure 1), which had been the subject of theoretical investigations by Havenith et al.[12] and was later synthesized by Scott and co-workers.[13] The key step of Scott’s TIP synthesis was a quadruple Pd-catalyzed direct arylation of pyrene 1, which provides a yield of only about 0.5% of TIP 2. In the same publication, a one-pot procedure from 1,3,6,8-tetrabromopyrene and 2-bromophenyl boronic acid was described, but yields were again in the range of 0.5%.[13] Despite the very low yield of the cyclization step, the photophysics of TIP 2 were thoroughly investigated at that time. Based on these properties, the authors suggested that TIP may be a potential candidate for organic electronics or materials chemistry, such as long wavelength dyes for special high-temperature applications. Very recently,
the synthesis of a structurally related tetra-n-octyl TIP by an alumina-mediated HF elimination was reported. Unfortunately, neither full characterization nor detailed discussion on photophysical or electrochemical properties were included. It is known that the K region of pyrene has a substantial olefin character, and thus the C–H activation may occur by a Heck coupling mechanism, rather than by a C–H activation in which the hydrogen is abstracted from a benzene ring. Therefore, we developed an alternative approach towards TIP 2 based on C–H activation of tetrachloropyrene 3 (Figure 1).

The synthesis of pyrene derivative 3 was described previously, starting from pyrene in six consecutive steps. We developed a different synthetic route for 3, starting from the commercially available hexahydropyrene 4 (Scheme 1) which was selectively fourfold-brominated to 5 and isolated in 84 % yield by simple filtration. Subsequent Suzuki–Miyaura cross-coupling under Fu conditions (Pd2dba3, H2PtBu3BF4, THF, K2CO3aq (1 m), 80 °C, 16 h; c) 3 equiv DDQ, toluene, 130 °C, 4 h; d) NCS, CHCl3, 80 °C, 42 h).

All compounds were fully characterized (see the Supporting Information). By vapor diffusion of n-pentane into saturated solutions of 5 and 6 in dichloromethane, crystals of sufficient quality for single-crystal X-ray diffraction analyses were obtained (Figure 2). Tetrabromide 5 crystallized in the orthorhombic space group Pnna with Z = 4. The crystal packing is driven by halogen bonding between two bromides with dBr–Br = 3.63 Å and dispersion interactions of the bromides with the aliphatic hydrogen (dC-H-Br = 3.08–3.36 Å, Figure 2a), forming two-dimensional sheets. The distance between adjacent sheets is dominated by Br–π interactions (dp-π = 3.63 Å), and these layers are twisted by 16.0° with respect to each other (Figure 2b, c). Tetraaryl hexahydropyrene 6 crystallized in the triclinic space group P-1 with Z = 2 (Figure 2d). The molecules interact only by weak dispersion interactions of the pe-
Peripheral tert-butyl groups with the central naphthyl subunits (Figure 2e).

For the final cyclization by palladium-catalyzed direct arylation under C–H activation, typical reaction conditions (PdCl₂(PCy₃)₂, DMAP, 200 °C, 48 h) were used to give the targeted TIP 2 in 29% yield, along with the threefold-cyclized product 8 in 20% yield (Scheme 2). We also performed the cyclization using a wide range of conditions (e.g., various concentrations, solvents, temperatures, duration, alternative Pd sources, alternative bases), but did not obtain greater than 29% yields for 2 nor a higher ratio between the yields for 2 and 8.

The two compounds can be distinguished by ¹H NMR spectroscopy. Whereas TIP 2 shows four clearly defined signals between δ = 7.0 and 7.5 ppm (corresponding exactly to the previous report), trindenopyrene 8 shows a more complex signal pattern consisting of 14 signals (two signals overlap at 7.8 and 7.2 ppm) between δ = 6.9 and 8.2 ppm (Figure 3 bottom). Mass spectrometry shows a molecular ion peak for 2 of m/z 722.495 (m/z calc for C₅₆H₅₀+: 722.391), which is two mass units smaller than that of trindenopyrene 8 (m/z calc for C₅₆H₅₂+: 724.407 found: 724.484), consistent with the missing C–C bond.

TIP 2 showed a strong concentration dependence (c = 0.10–3.08 mM) of the chemical shifts in the ¹H NMR spectra in CD₂Cl₂ (Figure 4), which is indicative of strong π–π-stacking.[23] At room temperature, protons H₆ (Δδ = 0.37 ppm) and H₅ (Δδ = 0.19 ppm) are more weakly influenced than H⁴ (Δδ = 0.92 ppm) and H³ (Δδ = 0.63 ppm), because H⁴ and H³ are sterically shielded by the adjacent tert-butyl group against stacking.

Assuming infinite π-stacks, the averaged association constant Kₐ was determined to be 2.45×10³ ± 0.77×10³ M⁻¹ (ΔG = −19.0 kJ mol⁻¹) at 293 K by a least-squares curve fitting of the infinite (isodesmic) association model (for details see the Supporting Information).[22a,24] This association constant is much higher than values reported, for example, for hexabenzocoronene-based thiophene dendrimers (Kₐ up to 710 M⁻¹ in CDCl₃) and within an order of magnitude of values reported for various perylene- and naphthalene bisimides.[24d] From measurements performed at temperatures ranging from 243 to 293 K, we determined ΔH = −15.8 kJ mol⁻¹ and ΔS = −11.9 J mol⁻¹ K⁻¹ from a van’t Hoff plot; this suggested that the aggregation in solution is driven by both enthalpy and entropy.[26] The strong aggregation tendency is also reflected by a moderate solubility of 2 in CH₂Cl₂ of (4.00 ± 0.63) mg mL⁻¹.

![Scheme 2](image)

Scheme 2. Synthesis of tetraindenopyrene 2 by C–H activation.

![Figure 3](image)

Figure 3. ¹H NMR spectra (400 MHz) of a) TIP 2 and b) trindenopyrene 8 in CD₂Cl₂ at room temperature.

![Figure 4](image)

Figure 4. ¹H NMR spectra (400 MHz) of TIP 2 in CD₂Cl₂ at concentrations between 0.10 and 3.08 mM at 293 K.
tempts to grow single crystals from various solvents produced needle-shaped crystals, which unfortunately could not be structurally refined by X-ray diffraction.

TIP 2 was revisited by theoretical calculations. Scott mentioned that the TIP has a bowl-shaped structure.\textsuperscript{12, 13} However, only the bowl-to-bowl inversion barrier calculated by DFT (B3LYP/6-31G*) was discussed, and no further details, such as geometrical parameters or energy levels of frontier molecular orbitals, were provided (see also the Discussion below).\textsuperscript{14} To obtain further insights into the structural details of TIP 2, dispersion-corrected (D3)\textsuperscript{27} DFT methods (B3LYP/6-311G(d,p)) were used to calculate molecular properties. It was found that the input geometry (MM2 optimized models) is crucial to the outcome of the DFT optimization. Starting from a planar input, the DFT optimization using ultra-tight convergence criteria also produced a planar geometry. A frequency analysis of the result shows an imaginary frequency with 15.5i cm$^{-1}$, which is indicative of a transition state. A second optimization, this time performed with an already contorted input, resulted in a bowl-shaped structure that no longer shows an imaginary frequency; this indicates that it is a realistic energy minimum (Figure 5). The bowl depth is 0.69 Å (if measured to the original 2,7-positions of the pyrene) or 1.44 Å (maximum bowl depth) and thus similar to the bowl depth of dibenzorubicene (1.68 Å).\textsuperscript{10b} The dispersion-corrected calculations gave a greater bowl depth than those performed without the D3 correction term (1.18 Å); this result deviates by about 20%, thus indicating that dispersion has a significant effect in stabilizing a contorted structure. The tert-butyl groups do not contribute substantially to the curving by dispersion interactions (see the Supporting Information).

Based on the dispersion-corrected model, the bowl-to-bowl inversion barrier was calculated to be 6.47 kJ mol$^{-1}$ ($\Delta G = 11.9$ kJ mol$^{-1}$, Figure 6). This is substantially higher than without dispersion correction (2.99 kJ mol$^{-1}$) and even higher than the previously published value (1.38 kJ mol$^{-1}$).\textsuperscript{13} Although the estimated inversion barrier is higher, it still means that TIP 2 fluctuates 51 billion times per second between the bowl-shaped minima, much too fast to be determined by variable-temperature NMR measurements. In comparison, corannulene shows an experimentally determined inversion rate of 200 000 per second at room temperature with a corresponding inversion barrier of $\Delta G = 43 \pm 1$ kJ mol$^{-1}$ (10.2 ± 0.2 kcal mol$^{-1}$).\textsuperscript{2}

Additional information on the electronic structure of TIP 2 were obtained by AICD\textsuperscript{28} and NICS calculations (HF/6–31+G(d), Figure 5). The outer benzene rings (A) show typical aromatic character with comparable NICS(−1) and NICS(+1) values of −8.8 and −8.7. NICS(−1) is the concave and NICS(+1) the convex side of the bowl. Aromaticity is also observed for the D-rings (NICS(−1) = −11.7 and NICS(+1) = −7.3,

\begin{figure}
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\includegraphics[width=\textwidth]{figure5.png}
\caption{Geometry-optimized model (B3LYP/6–311G(d,p)) of the bowl-shaped TIP 2. a) Top view. b) Side view. AICD plots (HF/6–31+G(d)) of 2 from c) the top/concave side with the magnetic field pointing out of the paper plane and red arrows indicating the direction of the ring current. d) Side view. Canonical MOs of 2 (B3LYP/6–311G(d,p)) with the corresponding orbital energy. e) LUMO; f) HOMO. All calculations were corrected for dispersion (D3).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{Inversion process of 2 via a planar transition state with the calculated difference in energy (black) and free enthalpy (red) derived from DFT calculations (B3LYP/6–311G(d,p)).}
\end{figure}
due to the higher electron density on the bowl’s concave side. As known from unsubstituted pyrene,\textsuperscript{1-3} the C-ring shows smaller aromaticity, with NICS(−1) = −5.3, and here the curvature has by far the greatest influence on the virtual chemical shift, with NICS(+1) = −0.6. The five-membered B-rings are nearly nonaromatic, with NICS(−1) = 1.3 and NICS(+1) = 3.7, and with a tendency toward antiaromatic character, similar to PAHs with fused five-membered rings such as corannulene\textsuperscript{29} or others.\textsuperscript{30} The ring currents derived by AICD calculations (see red arrows in Figure 5c) are in accordance with the trends observed by the NICS calculations. The DFT-calculated energies of the FMOs are $E_{\text{HOMO, DFT}} = −5.5$ eV and $E_{\text{LUMO, DFT}} = −3.0$ eV (Figure 5e and f). Although no oxidation was recorded within the redox window of the solvents employed (CH$_2$Cl$_2$ and o-DCB) at anodic potentials, two quasi reversible reduction potentials were found in both these solvents (Figure 7). In CH$_2$Cl$_2$, the reduction potentials are $E_{\text{red, 1}}^{1/2} = −1.41$ V and $E_{\text{red, 2}}^{1/2} = −1.74$ V. In o-DCB the two reduction peaks were found at slightly lower potentials ($E_{\text{red, 1}}^{1/2} = −1.48$ V and $E_{\text{red, 2}}^{1/2} = −1.84$ V). The first reduction potentials are higher by about 0.3–0.4 V compared to [60]PCBM ($E_{\text{red, 1}}^{1/2} = −1.08$ V) and [70]PCBM ($E_{\text{red, 1}}^{1/2} = −1.09$ V).\textsuperscript{31} Making a commonly used assumption, the electron affinity can be estimated as $E_A = E_{\text{red, 1}}^{1/2} + 4.8$ eV,\textsuperscript{32} corresponding to $E_A = −3.46$ eV in CH$_2$Cl$_2$ and $E_A = −3.42$ eV in o-DCB.

The calculated and experimentally determined FMOs suggest that TIP 2 is potentially interesting for organic electronics applications, both as an electron- and as a hole-conducting semiconductor. Initial experiments using 2 in thin-film transistors (TFTs) indicate hole mobilities of $4 \times 10^{-3}$ cm$^2$V$^{-1}$s$^{-1}$ in TFTs fabricated on silicon substrates and $1 \times 10^{-4}$ cm$^2$V$^{-1}$s$^{-1}$ in TFTs on flexible polyethylene naphthalate (PEN) substrates and on/off current ratios up to $10^3$ measured under ambient conditions (for details, see the Supporting Information).

In summary, we have introduced an alternative synthetic approach to achieve TIP 2 in five consecutive steps and with a 50-fold higher yield both for the final cyclization step (29 vs. 0.5%\textsuperscript{19}) and for the overall synthesis (13 vs. 0.25%). TIP 2 was revisited by dispersion-corrected DFT calculations, revealing that the bowl-to-bowl inversion barrier is substantially higher than previously estimated. Furthermore, TIP 2 was used to fabricate p-channel TFTs, indicating charge-carrier mobilities up to $4 \times 10^{-3}$ cm$^2$V$^{-1}$s$^{-1}$ and on/off current ratios of up to $10^3$. To the best of our knowledge, this is the first example of a transistor based on a nonfunctionalized hydrocarbon buckybowls.\textsuperscript{33–35} The possibility of easily scaling up the synthesis of precursor 3 without the necessity for purification by column chromatography will allow us to provide TIP 2 in sufficiently high amounts to explore its chemistry and physics; this is ongoing in our laboratory.

**Experimental Section**

For experimental details, see the Supporting Information.

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**Conflict of interest**

The authors declare no conflict of interest.

**Keywords:** C–H activation · organic thin film transistors · polycyclic aromatic hydrocarbons · pyrene · tetraidenopyrene

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