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Dihydropyrene as an Aromaticity Probe for Partially Quinoid Push–Pull Systems

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Although aromaticity is a key concept in chemistry that is frequently used to explain the structure and reactivity of organic compounds, it remains challenging to actually measure this property. Proper probes allow for an experimental quantification of aromaticity using nuclear magnetic resonance (NMR) spectroscopy and in this study 15,16-dimethyl-15,16-dihydropyrene (DHP) is demonstrated to be particularly well suited for this purpose. DHP has two internal methyl groups, which are positioned within the π cloud of this bridged, planar, and rigid [14]annulene, and are therefore shifted to higher field in proton NMR spectra owing to ring-current effects. A specific DHP derivative bearing strongly electron-donating dimethylamino and strongly electron-accepting nitro groups in a relative pseudo-*para* orientation has been synthesized and characterized with respect to its quinoid character. Solvatochromism as well as a reduced ring current show that the partial quinoid character in this push–pull DHP derivative is about 12%. This study extends the scope of DHP as an aromaticity probe and aids in the better understanding of the phenomenon of aromaticity.

When Kekulé described the cyclic formula of benzene in 1865[1] he marked the starting point for a debate that continues today.[2] This is well reflected by the still-unanswered question "What is aromaticity?", and although many attempts have been made, among which the approaches of Hückel,[3,4] Pauling,[5] and Clar[6] are the most important contributions, a simple definition cannot be given.[7] Nevertheless, by following one of these descriptions, the aromatic character of a molecule could be determined quantitatively by comparison of a fully aromatic system with a non-aromatic analogue. Although benzene is considered to be the most aromatic molecule, finding a non-aromatic reference compound such as 1,3,5-cyclohexatriene is problematic.

In most cases, structural, electronic, or magnetic properties are considered,[2] and either obtained or calculated by experimental and theoretical methods, respectively. On the structural level, aromaticity can be expressed in terms of bond alternation and mean bond lengths, accessible either from X-ray measurements or by applying harmonic oscillator model of aromaticity (HOMA) calculations.[8] The electronic criterion can be calculated as resonance energy or aromatic stabilization energy or it can be deduced from measured heats of reaction (for example, by comparing hydrogenation reactions) or equilibrium constants.[9,10] Last but not least, the magnetic properties of a molecule can be obtained experimentally from magnetic susceptibility and NMR spectroscopy experiments or theoretically from nuclear-independent chemical shifts (NICS).[11–15] In particular, NMR spectroscopy has become a widely applied technique since ring-current effects can readily be observed. For example, it has been shown in numerous examples that in annulenes the external proton signals are shifted to lower field, whereas the internal proton signals are shifted to higher field due to the opposing magnetic field inside and outside of the aromatic ring, which makes them suitable as aromaticity probes.[16] Nevertheless, as in all experimental cases, the choice and availability of appropriate reference compounds is critical for the outcome of the study.

Boekelheide and Phillips first described 15,16-dimethyl-15,16-dihydropyrene (DHP) (**1**), which can be regarded as a bridged, rigid, and planar [14]annulene (Figure 1, in which numbers refer to atom numbers). They observed the ^{1}H NMR spectroscopy signal of the internal methyl protons $\delta(Me_{int})$ at −4.25 ppm, whereas the reduced analogue **2** shows the corresponding signals at 0.97 ppm, that is, $\Delta\delta(Me_{int}) = 5.22$ ppm, thus indicating that **1** is aromatic, whereas **2** is not (Figure 1).[17,18] Since **2** has roughly the same geometry as **1** and almost no anisotropy effects are apparent, this system displays one of the very few candidates where a good reference compound is available, hence aromaticity can be evaluated by assuming that aromaticity (or rather resonance energy) is proportional to the ring current (or rather chemical shift).[15,19–21] Comparing the shielding of the internal methyl

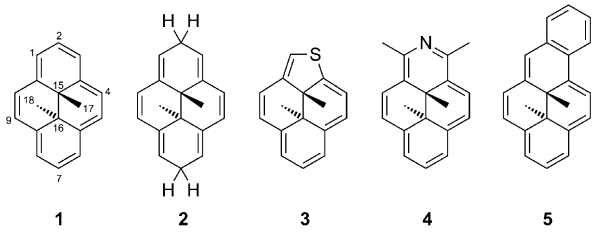

Figure 1. Parent DHP **1** (numbers refer to atom numbers), reduced DHP **2**, thia-analogue **3**, aza-analogue **4**, and 1,2-benzo-DHP **5**.

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groups of **1** and an analogue, such as the thia derivative **3** ($\delta(Me_{int}) = -1.16$ ppm; -1.32 ppm) or the aza derivative **4** ($\delta(Me_{int}) = -3.75$ ppm; -3.80 ppm), to the same reference compound **2** reveals their aromaticity to be 42 and 95% of that of DHP **1**, respectively (**3**: 2.21/5.22 = 0.42 and **4**: 4.75/5.22 = 0.91).[22] Mitchell expanded the scope of DHP as an aromaticity probe by taking advantage of the bond-localizing effect of aromatic systems fused to the DHP core. Comparing $\delta(Me_{int})$ of benzo-fused DHP **5** and other annelated aromatic compounds allowed their aromaticity to be quantified by simple NMR spectroscopy measurements. This was used to evaluate the homoaromaticity of cycloheptatriene[23] and the aromaticity of polycyclic conjugated hydrocarbons,[21,24] annulenes,[25,26] charged aromatics,[27,28,23] antiaromatics,[29,30] and metal-coordinated aromatics,[31] although the latter led to rather controversial results.[32,33]

However, to the best of our knowledge, the rather versatile DHP aromaticity probe has never been used to determine the quinoid character in push–pull systems, which would widen the applicability of this method considerably. Therefore, we used the dimethylamino group as a strong donor in combination with a nitro group as a strong acceptor on the 2,7-di-*tert*-butyl-DHP core bearing the internal methyl protons, which serve as our aromaticity probes (Figure 2). For this push–pull DHP **6** there are three Kekulé structures, of which the two $\mathbf{6}_{arom}$ display aromatic character while $\mathbf{6}_{quin}$ represents the quinoid structure. For a strong donor–acceptor system the quinoid structure is more pronounced and therefore reduces the ring current and aromaticity as a result of the apparent bond localization.

DHP **6** was synthesized by starting from the well-known 2,7-di-*tert*-butyl-DHP **7**[34] in 14% yield over five steps. After nitration with $Cu(NO_3)_2$ in the 4-position[35] and subsequent reduction with Zn in the presence of acetic anhydride,[36] a second nitration step[37] provided 4-amido-9-nitro-DHP **10**. Deprotection using 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU)[38] gave the free amine **11**, which can be methylated with MeI and K_3PO_4 (Scheme 1).

The push–pull DHP **6** is an almost black compound, and comparison with the UV/Vis spectra of 4-nitro-DHP **8** reveals that the electron-donating moiety in **6** causes a large bathochromic shift (Figure 3). This can be assigned to the contribution of the zwitterionic, quinoid form and easier accessibility of a charge-transfer state. Such a finding is well known for the observed bathochromic shift when going from colorless nitrobenzene to the deeply yellow *para-N,N*-dimethylnitroaniline.[39]

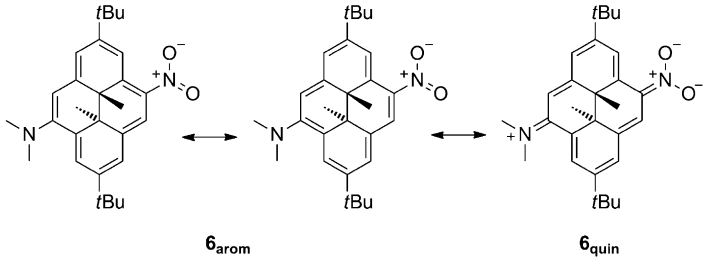
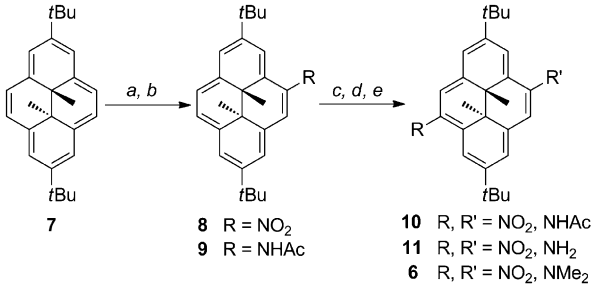


Figure 2. Push–pull DHP **6** with aromatic and quinoid resonance structures.



Scheme 1. Synthesis of **6**: (a) $Cu(NO_3)_2$, 5 h, (Ac_2O), 92%; (b) Zn, Na(CH_3COO), 2 h, Ac_2O, 95%; (c) HNO_3, cetyltrimethylammonium bromide (CTAB), 12 h, CH_3CN, 29%; (d) DBU, 80 °C, 3 h, CH_3OH, quant.; (e) K_3PO_4, MeI, 2 d, 56%.

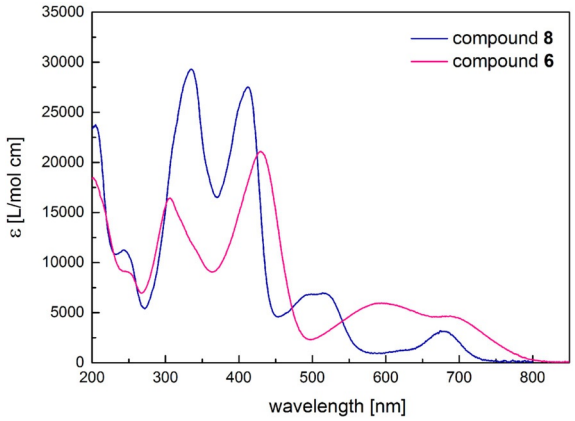


Figure 3. Comparison of UV/Vis spectra of **6** and **8** in CH_3CN at 25 °C. A typical charge-transfer band is observed for the donor–acceptor-substituted **6**.

To prove that the origin of this bathochromic shift is due to the contribution of $\mathbf{6}_{quin}$ we examined the UV/Vis spectra of **6** in various solvents. Not unexpectedly, $\mathbf{6}_{quin}$ is stabilized and hence more influential in more polar solvents, such as dimethylsulfoxide (DMSO) and chloroform, whereas it contributes less in nonpolar solvents, such as toluene or *n*-hexane (Figure 4). This is reflected in the increasing extinction coefficient of the charge-transfer band between 500 and 800 nm in more polar solvents, giving rise to an overall bathochromic and hyperchromic effect. The opposite is observed for the band around 400 nm, which is typical for the aromatic 4-substituted derivatives and the parent unsubstituted DHP. The hypochromic shift of this band in polar solvents shows the smaller contribution of $\mathbf{6}_{arom}$.

Similar effects are observed when comparing the NMR spectra of DHP compounds **6** and **8**. Introduction of the dimethylamino group shifts the signals for the internal methyl protons to lower field, while the signals for the aromatic protons are shifted to higher field. This unambiguously shows the reduced ring current in push–pull system **6** relative to **8** (Figure 5 as well as Figures S1 and S2 in the Supporting Information).

Although these qualitative experiments indicate that a partial quinoid character is present, NMR spectroscopy is the method of choice to quantify the residual aromaticity (RA). A simple comparison[15] of

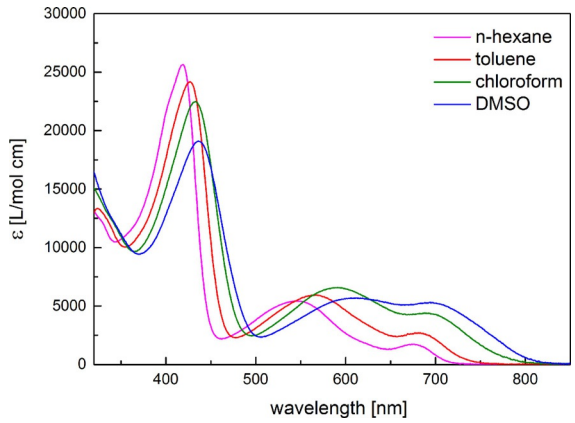


Figure 4. UV/Vis spectra of **6** in various solvents at 25 °C. With increasing solvent polarity the optical transitions are bathochromically shifted. The lowest-energy charge-transfer band becomes more intense, whereas the higher-energy absorption band, reminiscent of the DHP core, decreases.

reference compound **2** with **6** and the parent DHP **7**, respectively, results in a residual ring current (RRC) of 79% and hence a ring-current reduction (RCR) of 21% as shown in Equations (1) and (2).

$$\mathrm{RRC}(\mathbf{6}) = \frac{\delta(Me_{int'}2) - \delta(Me_{int'}6)}{\delta(Me_{int'}2) - \delta(Me_{int'}7)} * 100\% = \frac{0.97 - (-3.02)}{0.97 - (-4.04.)} * 100\% = 79\% \quad (1)$$

$$\mathrm{RCR}(\mathbf{6}) = 100\% - \mathrm{RRC}(\mathbf{6}) \quad (2)$$

At this point, it is necessary to differentiate between substituent effects and bond localization due to a partial quinoid character and therefore reduced aromaticity.[40,41] The ring-current reduction RCR(**6**) can be expressed as the sum of the RCR for each substituent and the RCR due to the partial quinoid character (100%−RA(**6**)). This leads to a simple equation in which the residual aromaticity RA(**6**) can be calculated by correction of RCR(**6**) for the substituent effects in the respective mono-substituted derivatives 4-dimethylamino-DHP **12** and 4-nitro-DHP **8** [Eqs. (3) and (4)].

$$\mathrm{RCR}(\mathbf{6}) = \mathrm{RCR}(\mathbf{12}) + \mathrm{RCR}(\mathbf{8}) + (100\% - \mathrm{RA}(\mathbf{6})) \quad (3)$$

$$\mathrm{RA}(\mathbf{6}) = 100\% - \mathrm{RCR}(\mathbf{6}) + \mathrm{RCR}(\mathbf{12}) + \mathrm{RCR}(\mathbf{8}) \quad (4)$$

According to Krygowski and Stępień, these substituent effects should originate from a measurement or, if not possible, from a Hammett plot, and in cases in which neither is available, from a statistical average.[41] For 4-nitro-DHP, RCR(**8**) is 6%, which can be measured by NMR spectroscopy and calculated as outlined above. (Dialkyl)amino-substituted DHPs are not stable[36] and it turned out that the $\delta(\mathrm{Me_{int}})$ values of literature-known 4-substituted DHPs do not follow the Hammett equation. On the one hand, there are steric effects from the adjacent hydrogen atom in the 3-position that simply cannot be reflected by the classical Hammett constants. On the other hand, the internal methyl groups are not in conjugation with the π system, but are still affected by it through the ring current, which seems to render inductive effects slightly more important than resonance effects. By taking these considerations into account, the substituent effect of the dimethylamino

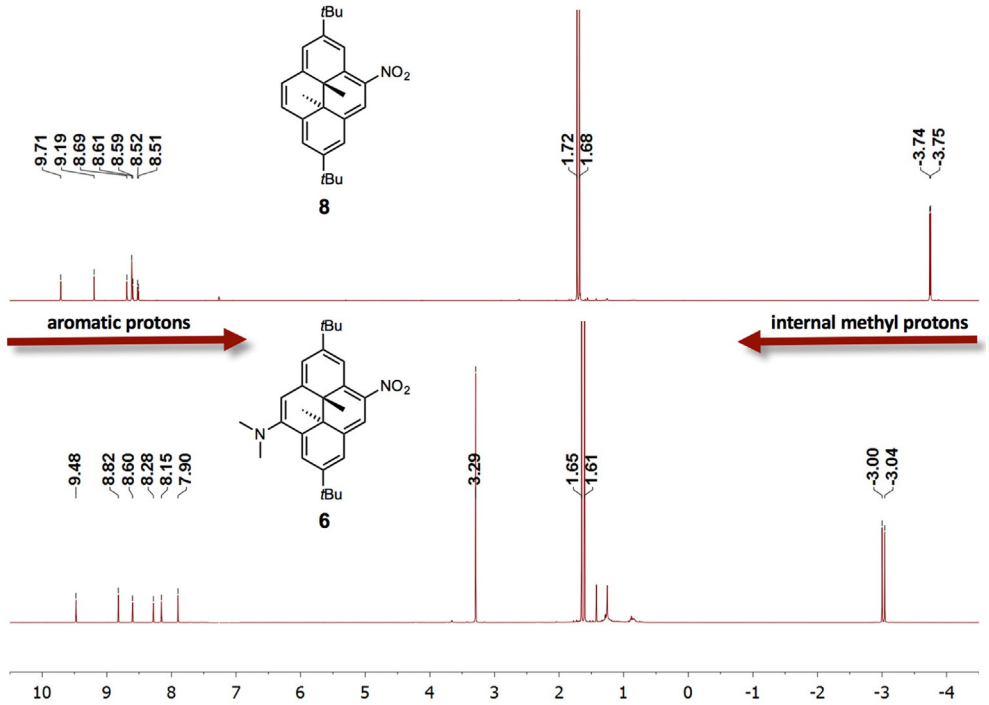


Figure 5. ^{1}H NMR spectra of **6** and **8** in $CDCl_3$ at 25 °C (solvent signal omitted for clarity). The reduced ring current in **6** shifts the internal methyl signals to lower field and the external aromatic proton signals to higher field. x-axis: δ [ppm].

group is estimated to be in the order of other substituents with the very electronegative nitrogen atom adjacent to the DHP core. The only known compounds bearing such substituents are **8** and **9** with RCR(**8**) = 6% and RCR(**9**) = 3%, both of which are in agreement with the observation that substituent effects on the DHP usually do not exceed a shift of 0.3 ppm downfield.[15] Since the dimethylamino group is electron donating and therefore has a shielding effect, the protected amine is regarded as a better model for the dimethylamino group than the nitro group. Following the equations outlined above with RCR(**8**) = 6% and an assumed RCR(**12**) ≈ RCR(**9**) = 3% an approximately 88% RA(**6**) can be estimated, which implies a quinoid character of about 12%. In principle, the higher contribution of $\mathbf{6}_{quin}$ in the polar solvents outlined above should be reflected in NMR spectroscopy measurements as well. Indeed, we see that the ring-current reduction RCR(**6**) correlates with the polarity of the solvent (see Table S1 in the Supporting Information), but a quantification of the quinoid character requires NMR spectroscopy data of **7**, **8**, and **9** to determine the substituent effects and unfortunately **9** was quite insoluble.

It still has to be considered that the push–pull effect is smaller than that in benzene, owing to the naphthalene-like substitution pattern and the twisted, hence, less-conjugated substituents. However, the aromaticity of DHP is smaller than the aromaticity of benzene and therefore the buildup of $\mathbf{6}_{quin}$ should be more feasible. By assuming that these effects roughly cancel each other out, **6** can be regarded as a model compound for *p*-nitroaniline. The reduction of aromaticity is in agreement with calculated literature values for *p*-nitroaniline that amount to 6–16%, depending on the aromaticity index used.[42]

To solidify such findings there is an agreement in the literature to evaluate at least two parameters that correlate with the aromaticity.[15] In most cases, ^3J coupling constants or the shift of the most distant proton are analyzed for this purpose.[21] Both methods will not work for **6**, since there are no vicinal protons and the substituent effect of the dimethylamino group on a most distant proton of **12** cannot be estimated reliably in this case owing to inductive and resonance effects. Although the ^{13}C NMR spectroscopy signals for the internal methyl groups are known to be less reliable than the proton signals for measuring aromaticity,[15,22,30,44] in some cases they give similar results[43] and here they corroborate our findings. For parent DHP **7**, δ(C17,C18) = 14.33 ppm is observed,[34] the reduced reference **2** gives a signal at 23.6 ppm,[45] which would result in RRC(**6**) ≈ 73% and RCR(**6**) ≈ 27% (following the same analysis as for the internal methyl proton signals). On considering the substituent effects, RCR(**8**) ≈ 10% can be obtained from experimental NMR spectra. Gratifyingly, a linear correlation ($R^2 = 0.89$) between δ(C17,C18)[26,46–48] and the inductive effect (σ_F)[49] of a substituent in the 4-position can be found (Figure 6). Following the regression shown in Equation (5), with $\sigma_F(NMe_2) = 0.17$, the carbon atoms of the internal methyl groups should give an average signal at $\delta = 14.7$ ppm.

$$\delta(C_{17,19}) = 1.2793 * \sigma_F + 14.479 \quad (5)$$

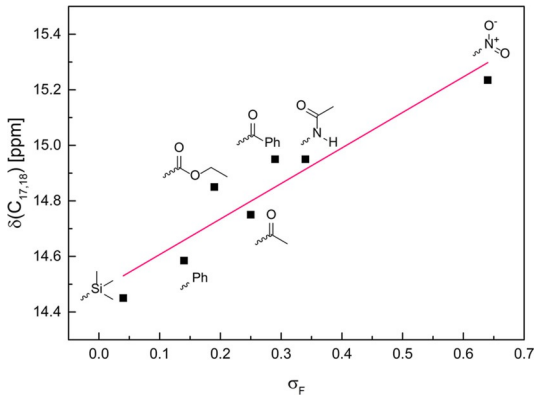


Figure 6. Correlation of δ(C17,C18) in the ^{13}C NMR spectra and the inductive field parameter σ_F.

The ring-current reduction of 4-dimethylamino-DHP **12** can now be estimated to RCR(**12**) ≈ 4%, which leads to RA(**6**) ≈ 87% and approximately 13% quinoid character, which is also within the range of 6–16%.

Although the substituent effect of the dimethylamino group cannot be measured, we have shown how the DHP aromaticity probe can be used to estimate the loss of aromaticity due to push–pull effects. The finding of approximately 12% quinoid character for the strongly polarized DHP carrying dimethylamino and nitro groups in opposing pseudo-*para* orientation is in agreement with calculated literature values for the parent benzenoid 4-nitroaniline. We hope that this study helps in the understanding of the nature of other aromatic push–pull systems such as donor–acceptor porphyrins or annulenes, for which a suitable reference for measuring aromaticity is seldom available. Further investigations will focus on the photochromic properties of this fascinating molecule, which has great potential as an near-infrared (NIR) photoswitch.[50]

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Conflict of interest

The authors declare no conflict of interest.

Keywords: aromaticity · donor–acceptor systems · fused-ring systems · quinoids · solvatochromism

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