Anion-π Catalysis on Carbon Nanotubes

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Abstract: *Induced π acidity from polarizability is currently emerging as most effective to stabilize anionic transition states on aromatic π surfaces, that is anion-π catalysis. To access extreme polarizability, we here propose a shift of attention from homogeneous toward heterogeneous anion-π catalysis on higher carbon allotropes. According to benchmark enolate addition chemistry, multi-walled carbon nanotubes equipped with tertiary amine bases outperform single-walled carbon nanotubes clearly. This difference is consistent with polarizability of the former not only along but also between the tubes. Inactivation by π-basic aromatics and saturation with increasing catalyst concentration support that catalysis occurs on the π surface of the tubes. Increasing rate and selectivity of existing anion-π catalysts (naphthalenediimides > fullerenes) on the surface of unmodified nanotubes is consistent with transition-state stabilization by electron sharing into the tubes, i.e., induced anion-π interactions. On pristine tubes, anion-π catalysis is realized by non-covalent interfacing with π-basic pyrenes.*

The term anion-π interaction refers to the binding of anions on the surface of extended π-conjugated systems, usually aromatic planes.[1-3] Anion-π interactions have received little attention, presumably because they are counterintuitive and comparably rare in nature. Catalysis with anion-π interactions has been introduced explicitly six years ago.[3] Since then, anion-π catalysis has been realized for asymmetric enolate, enamine and iminium chemistry, cascade reactions, cycloadditions and autocatalytic epoxide opening ether cyclizations.[3,4]

In light of its importance in chemistry and biology, the addition of malonic half thioester **1** to enolate acceptor **2** has emerged as reaction of choice to assess the activity of new anion-π catalysts. The formation of addition product **3** (or A) occurs in competition with the decarboxylation product **4** (or D, Figure 1a).[3,5] Recently confirmed by theory,[6] the selective acceleration of enolate addition by anion-π catalysis has been attributed to the discrimination of flat and bent enol and keto tautomers **5** and **6**, respectively, on π-acidic surfaces (Figure 1, red arrow).
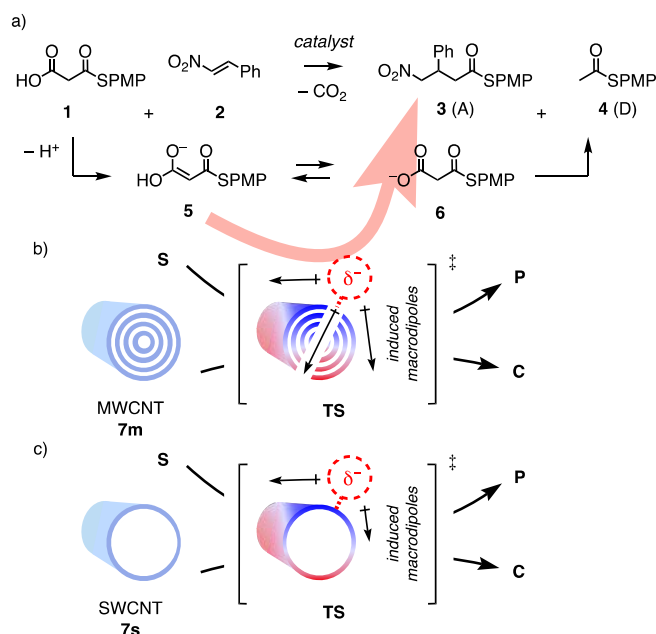
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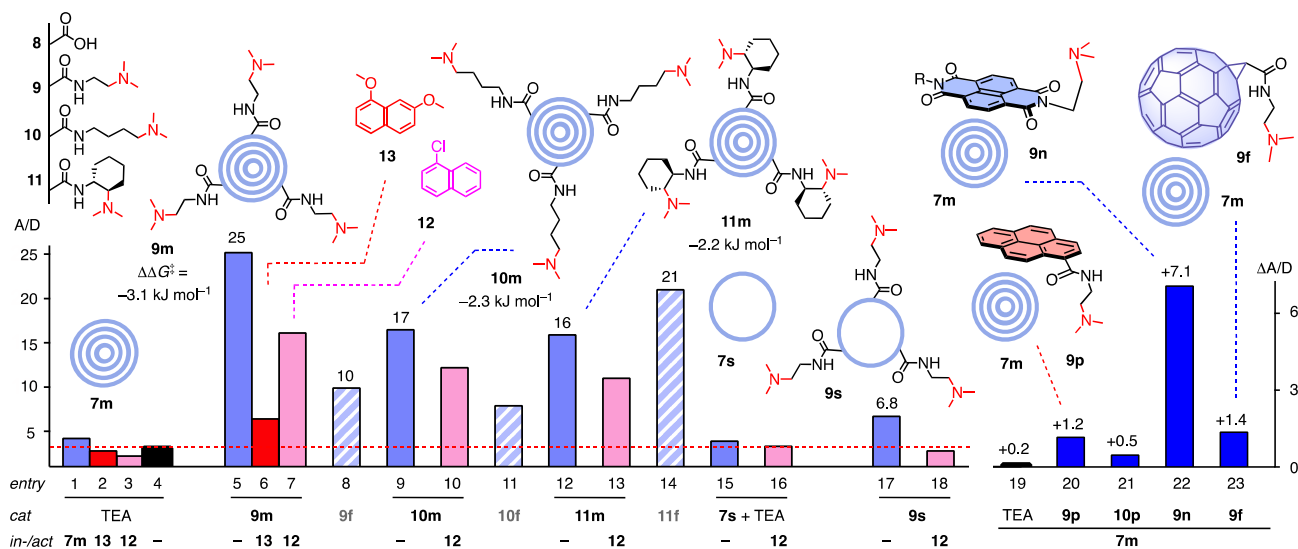[#] These authors contributed equally

Figure 1. a) Benchmark reaction for anion-π catalysis, increasing with increasing A/D values, that is the yield of enolate addition product A (**3**, red arrow) divided by the yield of decarboxylation product D (**4**). b) For anion-π catalysis on MWCNTs **7m**, anionic transition states **TS** are expected to stabilize themselves by repelling electron density (red) along as well as between the stacked tubes. c) **TS** stabilization on SWCNTs **7s** occurs only along this single tube. PMP: *para*-methoxyphenyl, **S**: substrates, **P**: products, **C**: catalysts.

For catalyst development, the strength of anion-π interactions is of central importance. Removal of electron density from aromatic systems for this purpose is limited because of the onset of catalyst degradation, electron transfer and nucleophilic aromatic substitution.[2,3] Induced rather than intrinsic anion-π interactions could ultimately be more promising.[3] Induced anion-π interactions originate from the polarization of the aromatic system in response to the presence of negative charges, repelling the nearby π electrons toward the other end of the π system, thus inducing oriented macrodipoles or rather multipoles that have their focal point on the inducer, enabling and strengthening anion binding on the π surface (Figure 1b, c). Anionic transition states emerging on π surfaces thus induce their own stabilization, create their own catalyst. This idea has been supported by anion-π catalysis on π-stacked foldamers[6] and on [60]fullerene monomers[7] and dimers.[3] From there, a shift of attention toward heterogeneous anion-π catalysis on higher carbon allotropes was the obvious next step.

Since their discovery, carbon nanotubes have been explored extensively to understand their unique structures and properties.[8] For their use in materials science, much emphasis

Figure 2. A/D values for product **3** divided by **4** obtained with substrates **1** (200 mM) and **2** (10 eq) in THF-d_8/CDCl$_3$ 1:1 (blue, black), **12** (pink) or **13** (red) for covalent MWCNT anion-π catalysts **9m–11m** compared to SWCNT **9s** and controls TEA (black), fullerenes **9f-11f** (striped)[7] with 20 mol% of catalyst (tertiary amine), with indication of differential transition-state stabilization $\Delta\Delta G_{TS}^{\ddagger}$ for A vs D for **9m–11m** vs TEA (left), and ΔA/D values with or without the addition of **7m** (9 w/w% of the reaction mixture) to **9p**, **10p**, **9n**, **9f** and TEA (5 mol%, blue) (right). The error levels of A/D values are estimated to be within ±10%. **m**: multi-walled, **s**: single-walled, **n**: naphthalenediimide, **f**: fullerene, **p**: pyrene, R: leucylhexyl, *cat*: catalyst, *in-/act*: in-/activator.

has conferred to their conducting properties, including many examples for photoinduced electron transfer processes.[9] Consistent with extreme polarizability,[10,11] carbon **nanotubes** can accept, donate, and conduct both electrons (e, n) and holes (h, p).[12] Molecular recognition has attracted attention not only for sensing applications but also for controlled dispersion, purification, and functionalization.[13] Most approaches focus on π-π stacking and dispersion forces, while anion-π and also cation-π interactions with higher carbon allotropes have received little attention,[14] although they are predicted to be strong.[10,15] Contrary to fullerenes,[3,4,16] carbon nanotubes have been explored quite extensively in catalysis, mostly as a scaffold to maximize effective concentrations, occasionally also to modulate redox processes, including the activation of metal catalysts.[12,17] The stabilization of neither anionic nor cationic transitions states by induced π-system polarization, i.e., neither anion-π nor cation-π catalysis, have been explored explicitly on carbon nanotubes.

For this purpose, carbon nanotubes **7** were firstly shortened and endowed with carboxylic acids by oxidative treatment (**8**), and afterwards covalently reacted with tertiary amine bases bearing different linkers to yield **9–11** (Figure 2, Schemes S2-S5). The multi-walled carbon nanotubes (MWCNTs) **7m** used were characterized by *ca.* 11 tubes and a diameter between 6 nm and 13 nm and were functionalized with 0.64 μmol base/mg material in **9m**.[18] Single-walled carbon nanotubes (SWCNTs) **7s** were narrower (diameter between 0.8 and 1.4 nm) and conjugated to 1.19 μmol base/mg material in **9s** (Table S1).

Tested in the above mentioned enolate addition reaction (Figure 1a), suspensions of MWCNTs **7m** in THF-d_8/CDCl$_3$ 1:1 activated triethylamine (TEA) to A/D = 4.3, a selectivity only slightly above the intrinsic A/D = 3.4 for TEA under these conditions (Figure 2, entries 1, 4). With A/D = 25, the highest activity was found for

MWCNTs **9m** (blue, entry 5). With longer and turned spacers in **10m** and **11m**, activities dropped until A/D = 16 (blue, entries 9, 12). A decreasing activity with longer spacers was as with the soluble fullerene models **9f** and **10f** (striped, entries 8, 11),[7] and well explained with increasing entropic losses for transition-state recognition. Lower activity with rigid turns on mismatched **11m** was, however, contrary to fullerene models **11f** (striped, entries 8, 14). This contrast was meaningful because without the cyclopropyl turns, the amine base in **11m** ends up fixed far from the π surface, and the according to computational models[7] unique topological matching in **11f** is ruined. Activities with the best MWCNT catalyst **9m**, also exceeding the best fullerene catalyst **11f**, were quite remarkable considering the shift from homogeneous to heterogeneous catalysis (entries 5, 14). Indeed, the reactions stopped as soon as MWCNT **9m** were centrifuged away, and restarted as soon as they were redispersed (Figure S3). Previous studies on heterogeneous anion-π catalysis on ITO electrodes gave, without applied voltage, extremely favorable decarboxylation (A/D = 0.08).[19]

Kinetics analysis for MWCNT catalyst **9m** confirmed that addition clearly exceeds decarboxylation (Figures 3a, S1). The differences in activation energy of addition and decarboxylation reactions ($\Delta G_{TS}^{\ddagger}$) were compared to that with TEA to give differential transition-state stabilization[3] $\Delta\Delta G_{TS}^{\ddagger}$ = –3.1 kJ mol^{-1} (Figure 2). Decreasing $\Delta\Delta G_{TS}^{\ddagger}$ = –2.3 kJ mol^{-1} for **10m** and $\Delta\Delta G_{TS}^{\ddagger}$ = –2.2 kJ mol^{-1} for **11m** reproduced trends from A/D values very well (blue, entries 5, 9, 12).

Comparing bi- against unimolecular transformations, A/D values increased with substrate concentration (Figure 3c). They also increased with the concentration of catalyst **9m** but not with TEA (Figure 3d). Saturation behavior characterized by a formal EC$_{50}$ = 11 mM supported the presence of active sites on MWCNTs, although the complex heterogeneous system complicates

interpretations, a call for caution that naturally applies for all that follows.

In 1-chloronaphthalene **12**, activities of **9m**–**11m** decreased (Figure 2, pink, entry 7, 10, 13). Hill analysis of the dose-response curve gave an IC_{50} = 5.9 M for the inactivation of catalyst **9m** by **12** (Figure 2, entry 7; Figure 3b, ▽; Table S2). Stronger inactivation was found for the more π-basic 1,7-dialkoxynaphthalene (DAN)[20] **13**, also a liquid at room temperature (IC_{50} = 2.6 M, Figure 2, entry 6; Figure 3b, ▼). These results indicated that the π-basic **12** and **13** inactivate the catalysts by covering the π surfaces of the tubes with a layer repulsive to the anions, and thus provided corroborative support for operational anion-π interactions, i.e., the existence of anion-π catalysis on MWCNTs (entries 5-7, 9-10, 12-13).
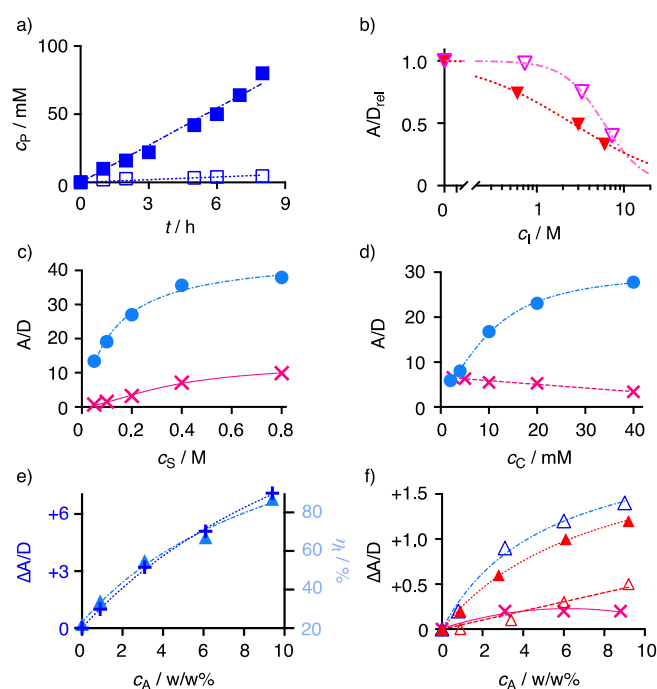

Figure 3. a) Product formation (A, **3**, ■; D, **4**, □) with **9m** as a function of time (10 mol%, 200 mM **1**, 10 eq **2**, THF-d_8/CDCl$_3$ 1:1). b) Normalized A/D values with **9m** as a function of the concentration of inactivators **12** (▽) and **13** (▼). For calibration, A/D of TEA in **12** or **13** were used as A/D$_{rel}$ = 0. c) A/D with **9m** (●) and TEA (✗) (40 mM of tertiary amine) as a function of the concentration of substrate **1**. Equivalents of **2** were kept constant. d) A/D with **9m** (●) and TEA (✗) as a function of their concentration (200 mM **1**, 10 eq **2**). e) ΔA/D (A/D – A/D$_0$, ✚) and conversion after 4 days (▲) with **9n** (5 mol%) as a function of the concentration of activator **7m** (wt% of the reaction mixture). f) ΔA/D with **9f** (△), **9p** (▲), **10p** (△) and TEA (✗) (5 mol%) as a function of the concentration of activator **7m** (wt% of the reaction mixture).

SWCNTs **9s** were with A/D = 6.8 less active than MWCNTs **9m** with A/D = 25 (Figure 2, blue, entries 5, 17) but could be further inactivated by π-basic competitor **12** (Figure 2, pink, entries 17, 18). This significant difference is interesting because it supports that transition states on the surface of MWCNTs could be stabilized by polarizability along tubes but also between the layers, somehow combining previously explored through-bond contributions from very large π surfaces beyond fullerenes on the one hand and from through-space synergistic anion-(π)$_n$-π

interactions on π-stacked foldamers on the other hand (Figure 1b).[3]

The binding of anion-π catalyst **9n** (Scheme S1)[3] on the surface of unmodified MWCNTs **7m** increased their activity by maximal ΔA/D = +7.1 (Figure 2, entry 22; Figure 3e, ✚). The coinciding increase in rate and selectivity with MWCNT concentrations supported that the central principles of catalysis also apply for these more complex systems, here increasing transition-state recognition on the naphthalenediimide (NDI) surface in **9n** by electron sharing with the carbon nanotubes **7m** (Figure 3e, ▲). Activation of fullerene anion-π catalysts **9f** was with up to ΔA/D = +1.4 much weaker, perhaps because the convex fullerenes prefer to hide in the concave interior of carbon nanotubes[21] (Figure 2, entry 23; Figure 3f, △).

The binding of the newly synthesized π-basic pyrene[16] **9p** (Scheme S1) by face-to-face π stacking on MWCNTs **7m** slightly increased activity (up to ΔA/D = +1.2, Figure 2, entry 20; Figure 3f, ▲). Contrary to **9n**, however, catalysis with **9p** on **7m** is unlikely to take place on the more repulsive pyrene surface. This system thus documented the possibility of non-covalent interfacing for anion-π catalysis on unmodified nanotubes **7m**, although the obtained activities were rather weak compared to covalent interfacing in **9m** (Figure 2, entry 20). As with covalent interfacing in **10m**, activities decreased with spacer elongation in the complementary non-covalent pyrene interfacer **10p** on **7m** (Figure 2, entry 21; Figure 3f, △). TEA, without π-π interfacer, was the least sensitive to the presence of MWCNTs **7m** (Figure 2, entry 19; Figure 3f, ✗).

In summary, we provide experimental support that anion-π catalysis on carbon nanotubes exists and matters. Highlights include MWCNTs outperforming SWCNTs due to electron sharing within and between the tubes, thus driving induced anion-π interactions from polarizability to the extreme, or the activation of existing anion-π catalysts on the surface of pristine MWCNTs. The amphoteric nature of MWCNTs[12] suggests that, contrary to results from π-stacked foldamers,[6] above insights should hold also for the more conventional stabilization of cationic intermediates on most polarizable π surfaces, i.e., induced cation-π rather than anion-π catalysis.[22] Additional contributions from the reduced dimensionality in 1D sliding kinetics to anion-π catalysis, obviously most inviting on carbon nanotubes, could deserve future attention.[23] The heterogeneous nature of MWCNT anion-π catalysts is particularly appealing for applications toward films on conductive surfaces.[19,24]

Acknowledgements

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Polarizability, driven to the extreme, harnessed for anion-π catalysis: Multi-walled carbon nanotubes i) outperform single-walled ones (polarizable beyond one tube), ii) are inactivated by π-basic competitors (active sites are on tube surface), iii) prefer covalent, linker-sensitive interfacing over non-covalent strategies (pyrene), and iv) activate existing anion-π catalysts by electron sharing (NDIs > fullerenes).
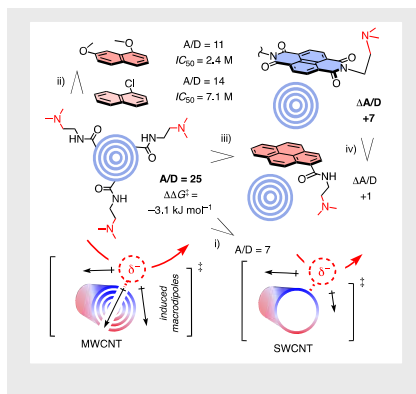
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