Title: Systematically Studying the Effect of Fluoride on the Properties of Cyclophanes Bearing Naphthalene Diimide and Dialkoxyaryl Groups

Authors: Steven J Langford; Alexander Young; Simon Drew; Subashani Maniam

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Systematically Studying the Effect of Fluoride on the Properties of Cyclophanes Bearing Naphthalene Diimide and Dialkoxyaryl Groups

Alexander Young,[a] Simon Drew,[b] Subashani Maniam,[a] and Steven J. Langford*[a]

Dedication ((optional))

Abstract: Anion-π interactions between the Lewis basic anion fluoride and π-acidic naphthalene diimide was systematically studied in a series of cyclophanes in which the properties are modulated through the influence of a second, electron rich aromatic unit. The systems and subsequently generated radical anions, upon addition of fluoride, were studied by absorption spectroscopic and EPR techniques. The results infer a modulation as a result of the nature and strength of the π-π interaction in the macrocyclic structure.

Introduction

The non-covalent interactions between a π-acidic (or electron poor) aromatic system and an anion were until recently thought of as an unimportant phenomenon of academic interest.[1] However, the work of Deyá et al. not only characterised the interaction but highlighted its existence to the scientific community.[1a] Anion-π interactions have now become a new branch of study in supramolecular chemistry, with current investigations primarily using electron poor aromatic (π-acidic) systems with strong reversed quadrupoles, as a means to study their self-assembly, anion transport systems and anion detection.[2]

Naphthalene diimides (NDIs) are highly versatile molecules and have been used extensively in supramolecular chemistry due to their π-electron deficiency and subsequent ability to form charge transfer complexes or act as an n-type material.[3] This electron poor, or π-acidic system, can be tuned, like other NDI properties (such as solubility, absorption and emission), making NDIs a candidate for studying anion-π interactions. Importantly, several groups have reported the facile conversion of NDI to the radical anion through interactions with fluoride.[4] The resultant product is both stable and often brightly coloured indicating a potential use in sensors, molecular logic and catalytic processes. Here, we report the synthesis and subsequent derivation of an NDI-based cyclophane which explores the effect of a pre-existing π-π interaction on the initial anion-π interaction and subsequent generation of the anion radical.

The proposed cyclophane (Fig. 1) consists of three major components: a π-acidic NDI component (blue), an electron rich aromatic component (red), and the linking groups that form the ring structure, whose length dictates the flexibility in the system. The resultant system should have a "closed" structure as a result of the π-π interactions and partial charge transfer interactions between the π–rich and π–deficient aromatic groups, which also leads to the formation of a coloured product – the colour of which is dependent on the nature of the π–rich group (for example yellow to purple).[5] Upon the addition of fluoride, an anion-π interaction ensues, leading to the formation of an NDI• anion species. Ideally, the formation of the radical anion disrupts the π-π interaction, "opening" the cyclophane and forming a highly coloured species. Altering the length of the linking chain, the size of the aromatic unit or the symmetry of the aromatic unit therefore should affect the strength of the π-π interaction and hence effect the response by the addition of fluoride.

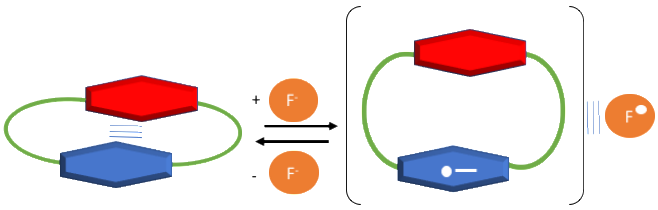

Figure 1. Proposed effect of fluoride on the cyclophane formed using naphthalene diimide (NDI, blue) and dialkoxybenzene units. The nature of the anion interaction is shown as a charge transfer.

Results and Discussion

Synthesis

The focus of interactions is between the NDI, aromatic unit and fluoride, so we wanted to retain as much integrity around the NDI as possible. As a result, the same NDI component **1** was used in the synthesis of all cyclophanes (Scheme 1). 1,4,5,8-naphthalene carboxylic dianhydride was reacted with excess β-alanine in glacial acetic acid yielding **1** in 84% yield. This diacid precursor would then be reacted with a range of dialcohols to form cyclophanes bearing ester and polyether functionality. The dialcohols **2-5** were formed in moderate yield (40-49%) after recrystallization by reacting hydroquinone (1,4HQ) or naphthalene diols (1/5DN, 1/4DN) with a chloroethoxyether in DMF using standard chemistry.[6] Conversion of **1** to the bis(acid chloride) was achieved using thionyl chloride in benzene solvent (caution) before being mixed with a slight excess of **2-5** under high dilution conditions. While the chlorination could be achieved as well in other solvents, we found that the cyclisation reaction occurred best in benzene solvent. This promotion of cyclisation is likely a result of cooperative electronic effects and a limiting of steric effects which might occur through interactions with other solvents like toluene or 1,4-dioxane. Depending on the aromatic unit used a purple (**2** and **3**), orange (**4**) or dark blue (**5**) product precipitates out over time, which was filtered off and purified via column chromatography affording pure **6-9** in 44%, 24%, 10% and 6% yield, respectively. The trending yields and colour difference between **6, 8,** and **9** reflect the nature of the stabilizing π-π and charge transfer interactions as a result of the differing aromatic units and non-optimised interactions in a constrained system. The yield difference between **6** (n=1) and **7**

[a] Mr A. Young, Dr S. Maniam, Prof. S.J. Langford
School of Chemistry
Monash University
Wellington Rd, Clayton, Victoria, Australia 3800
E-mail: steven.langford@monash.edu
[b] Dr S. Drew
Department of Medicine
Royal Melbourne Hospital
The University of Melbourne
Victoria, Australia, 3010

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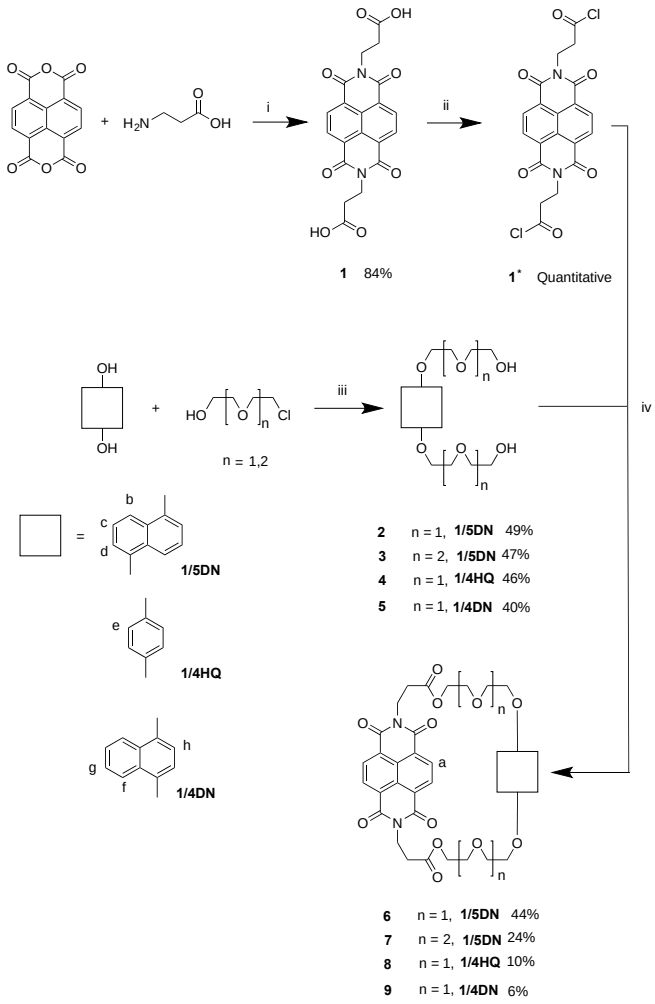
(n=2) is a result of the preorganization differences between the two cyclophanes.



Scheme 1. General synthesis of the cyclophanes **6-9** used in this study.

Clear evidence for the formation of the cyclophanes **6-9** can be gained through ^{1}H NMR spectroscopy in comparison to the starting aromatic materials. Figure 2 provides an example based on cyclophane **7** in $CDCl_3$. Most notably across all naphthalene based examples is the upfield shift for all aromatic protons as a result of the anisotropy associated with the NDI and dialkoxynaphthalene units (Table 1). The shift of $\Delta\delta$ 0.2-0.4 is consistent with other examples of interactions between two aromatic species such as those observed by Fallon et al. between a [2]catenane species bearing interacting NDI and 1/5HQ units.[5a] An interesting and different trend is seen for **8** though, bearing the C_6H_4 group. While the trend of shift is similar for the effect of the NDI on the 1/4HQ signals, leading to a smaller but upfield shift of 0.3 ppm, the effect for 1/4HQ on the NDI leads to a less significant and downfield shift of 0.1 ppm. This likely indicates a free rotation of the HQ unit exposing the NDI to a more edge-to-face interaction in solution. For other patterns, see the supplementary information.

Compound	H[b]	$\sigma_{components}$	$\sigma_{cyclophane}$	$\Delta\sigma$
6	H_a	8.67 (**1**)	8.55	0.11
	H_b	7.74 (**2**)	7.33	0.40
	H_c	7.39 (**2**)	7.13	0.26
	H_d	7.00 (**2**)	6.49	0.51
7	H_a	8.67 (**1**)	8.55	0.12
	H_b	7.74 (**3**)	7.33	0.41
	H_c	7.39 (**3**)	7.13	0.26
	H_d	7.00 (**3**)	6.49	0.51
8	H_a	8.67 (**1**)	8.68	-0.01[a]
	H_e	6.86 (**4**)	6.43	0.43
9	H_a	8.67 (**1**)	8.55	0.12
	H_f	8.13 (**5**)	7.63	0.50
	H_g	7.54 (**5**)	7.32	0.22
	H_h	6.86 (**5**)	6.40	0.46

[a] a negative shift indicates a downfield movement relative to the starting material. [b] Refer labels to Scheme 1.

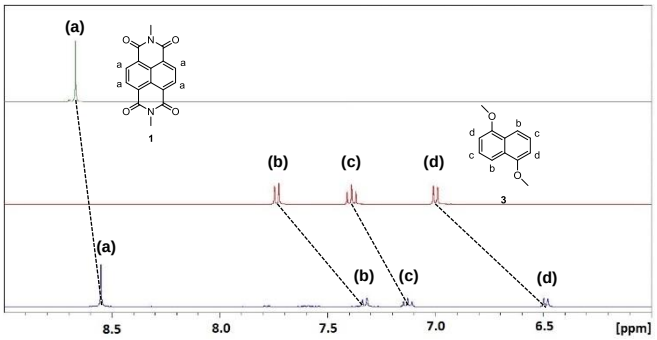
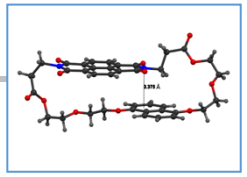


Figure 2. ^{1}H-NMR spectra of **1**, **3** and **7** in DMSO-d_6 solvent at 300K denoting the chemical shift changes between the cyclophane and its precursors.

Crystals of **6-9** suitable for x-ray crystallography were obtained by diffusion of methanol into DMSO solutions of the four cyclophanes. Upon cooling, the small purple crystals formed were subject to crystallographic analysis. The crystal structures of compounds **6,7** and **9** (Figs. 3-5), bearing naphthalene units, have a distinct "closed" form at a distance of 3.4 Å between the two off-set aromatic units consistent with π-π stabilisation. This phenomenon is also *inter*-cyclophane, leading to a canted and alternating donor-acceptor–donor-acceptor stacking arrangement in the crystals as expected, also set at an intermolecular distance of 3.4-3.5 Å. Cyclophanes **6** and **7** differ by CH_2CH_2O, which is easily accommodated within the crystal structure to yield the same organizational motif.

Table 1. Comparison of ^{1}H-NMR Shifts of compounds 1-5 (components) to 6-9 (cyclophanes)



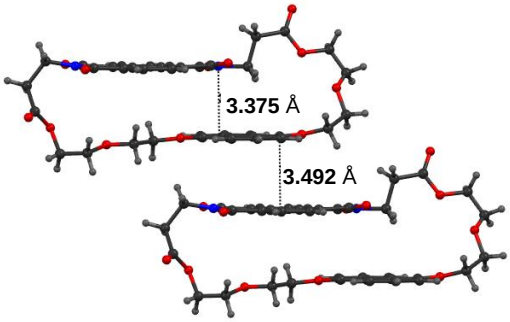


Figure 3. X-ray crystal structure of **6** showing the inter-plane separation between aromatic units.

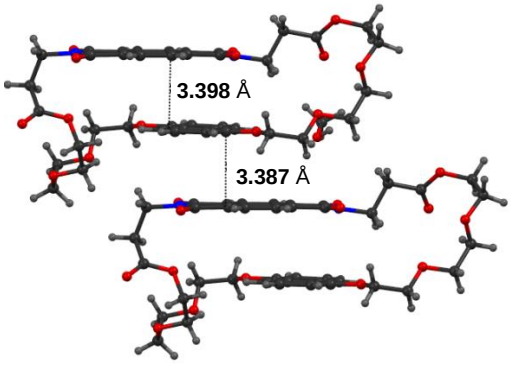


Figure 4. X-ray crystal structure of **7**, showing the inter-plane separation between aromatic units. Note: A molecule of methanol is incorporated in the lattice and has been omitted for clarity,

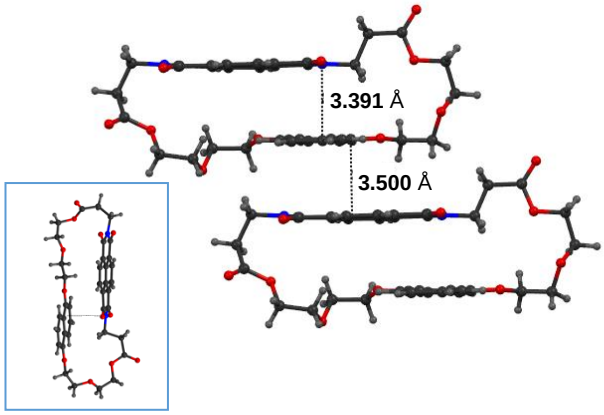


Figure 5. X-ray crystal structure of **9**, indicating π-stabilisation.

Interestingly the macromolecular crystal structure of **8** (Fig. 6), differs dramatically to the other three examples. While the closed form exists with internal plane separations of 3.425 Å, consistent with π-π stabilization, there appears to be no significant inter-cyclophane interaction. The more disordered crystal packing observed can be attributed in part to the role of the phenyl unit.

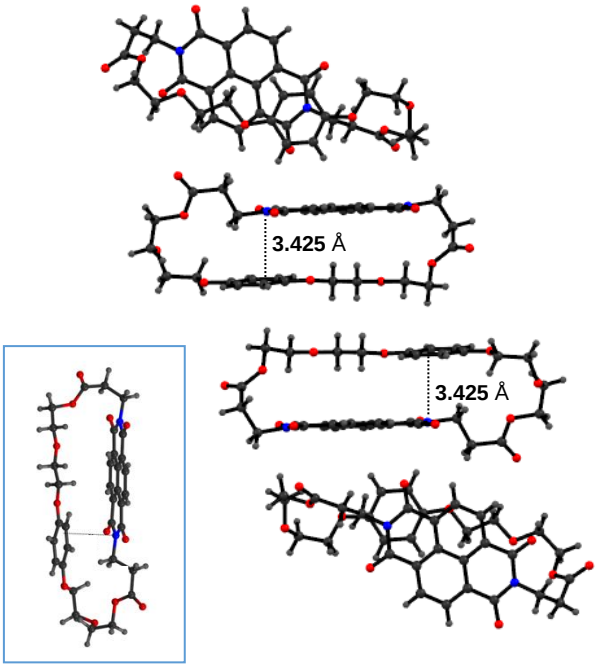


Figure 6. X-ray crystal structure of **8**, indicating π-π interactions in individual molecules but not in the overall crystal structure.

Effect of Fluoride Addition

The UV-Vis spectrum of NDI **1** in DMSO shows two distinct π-π* absorption bands at 350 and 380 nm, consistent with other core unsubstituted NDIs.[7] Upon addition of fluoride, new bands formed at 475, 610, 675 and 760 nm are consistent with the fluoride-π interaction forming an NDI radical, suggesting that the NDI unit by itself is π-acidic.[4a] There appears to be little effect from the imide carboxylic acid groups in **1** on the formation of the radical. The spectra of **2** and **3** bearing alkoxynaphthalene groups showed three distinct π-π* absorption bands at 290, 300 and 320 nm, **4** has a band at 290 nm and **5** shows a band at 340 nm. There is no effect of fluoride addition to these bands, hence we infer that any change in spectra is a result of the combined influences of the alkoxyaromatic unit and fluoride on the spectrum of the NDI chromophore. The spectra for cyclophanes **6-9** in DMSO are for the most part a representation of overlay of the two chromophoric components with the addition of a very weak and broad charge transfer band as a result of the interaction of π-electron rich and π-electron deficient components. There is no appreciable fluorescence from **6-9** as a result of quenching effects. The addition of fluoride to each cyclophane leads to clear and distinct visual colour changes as shown in Fig. 7.

Figure 7. Distinct colour changes occur upon addition of fluoride to the cyclophanes. This example shows the change with 0.5mM of **6** in DMSO in the absence of F^- (left) and with the addition of F^- (right).

Table 2. X-ray crystallographic data of compounds **6-9**

Compound	6	7[a]	8	9
chemical formula	$C_{38}H_{34}N_2O_{12}$	$C_{43}H_{46}N_2O_{15}$	$C_{34}H_{32}N_2O_{12}$	$C_{38}H_{34}N_2O_{12}$
M_w	710.67	830.82	660.62	710.67
crystal system	Triclinic	Ortho-rhombic	Ortho-rhombic	Triclinic
space group	P -1	A b a 2	P b c a	P -1
Z	2	8	8	2
a [Å]	9.5940(19)	58.603(3)	9.1232(5)	8.2193(5)
b [Å]	12.443(3)	14.3935(5)	25.6813(13)	8.8854(6)
c [Å]	15.482(3)	9.1727(4)	25.8360(18)	21.9895(14)
α [°]	67.51(3)	90	90	88.793(5)
β [°]	76.43(3)	90	90	80.805(5)
γ [°]	73.86(3)	90	90	85.265(5)
V[A^3]	1623.1(6)	7737.2(5)	6053.3(6)	1579.84(18)
$D_{calculated}$	1.454	1.426	1.450	1.494
μ [cm^{-1}]	1.09	9.10	9.35	1.12
2 θ_{max} [°]	57.4	132.26	134.24	55
T[K]	100(2)	123(2)	123(2)	123(2)
total reflns	8115	26733	27202	13718
unique reflns	8115	3677	5398	7266
R_{int}	0.0000	0.0504	0.0481	0.0329
parameters	554	643	433	469
final R1 (I>2θ(I))	0.0849	0.0541	0.0423	0.0530
wR2(all data)	0.2439	0.1459	0.1143	0.1300
GOF	1.040	1.069	1.041	1.031

[a] Compound **7** contains one molecule of methanol in the lattice

Spectroscopically, this change in colour is observed as a dramatic change in the absorption spectra of **6-9** (Fig. 8). All spectra show new bands at 465, 610, 675 and 760 nm with fine structure changes to the bands at 350 and 380 nm attributable to the formation of an NDI radical. Interestingly the intensity of the absorption change due to radical formation relative to the size of the π-π* bands at 350 and 380 nm in the order **8** ≈ **9** > **7** ≈ **6**. This same pattern can be attributed to the reduction potential of the NDI units in **6-9** by electrochemical means (see SI). No significant fluorescence was detected upon reduction.

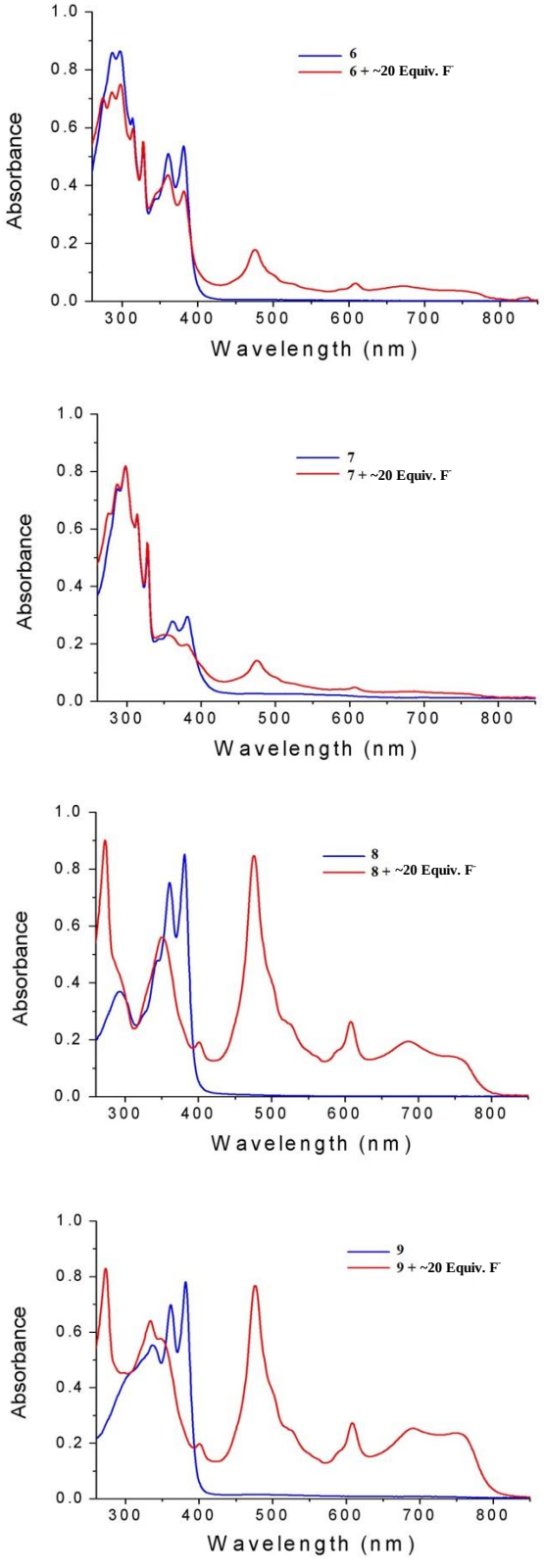


Figure 8. Absorption spectra of cyclophanes **6-9** in the absence (blue) and presence of fluoride (red, ~ 20 equiv.)). [**6-9**] = 1 mM in DMSO. Signals at λ > 450 nm are a result of $NDI^{\cdot-}$ formation.

EPR Spectroscopy

Continuous-wave EPR spectra were acquired for each of the cyclophanes **6-9** in the presence of an excess of fluoride ions (Figure 9). Consistent with previous investigations of model NDI compounds **10-12** reduced electrochemically,[7] the 13-line signal is commensurate with the formation of a radical with spin density delocalized across all atoms of the NDI, leading to magnetic hyperfine coupling with coupling with the two ^{14}N nuclei, four naphthalene ^{1}H nuclei and small coupling with the four *N*-CH_2 exocyclic protons (Table 3). No EPR signal was detected in the absence of fluoride.

Table 3. Spin Hamiltonian parameters obtained from simulation of the experimental spectra. Estimated uncertainty in g factor is ±0.0001. Estimated uncertainty in hyperfine couplings is ±0.05 MHz.

Compound Spectrum	$\langle g \rangle$[a]	$\langle A(^{14}N) \rangle$[b]	$\langle A(^{1}H) \rangle$[c]	$\langle A(^{1}H) \rangle$[d]	Linewidth[e]	ref.
6	2.0039	2.69	5.33	0.64	0.43	[g]
7	2.0036	2.53	5.39	0.67	0.43	[g]
8	2.0035	2.71	5.34	0.63	0.35	[g]
9	2.0036	2.65	5.40	0.49	0.48	[g]
1	2.0037	2.68	5.36	0.56	0.49	[g]
10[f]	2.0040	2.70	5.40	0.60		[7]
11[f]	2.0040	2.70	5.40	–		[7]
12[f]	2.0040	2.70	5.40	0.60		[7]

[a] $\langle g \rangle = (g_x + g_y + g_z)/3$. [b] $\langle A \rangle = (A_x + A_y + A_z)/3$. Coupling to two equivalent ^{14}N nuclei (MHz). [c] Coupling to four equivalent ^{1}H nuclei (MHz). [d] Unresolved coupling to four equivalent nuclei (MHz). [e] Lorentzian peak-to-peak linewidth in gauss (G). [f] **10**, **11** and **12** = *N,N*-dipentyl, diisopropyl, and dipropargyl naphthalene diimides, respectively. [g] This work.

Since the g and A parameters reflect the delocalisation of the LUMO and are principally determined by the local structure of the NDI, it is not surprising that all compounds share similar EPR parameters.

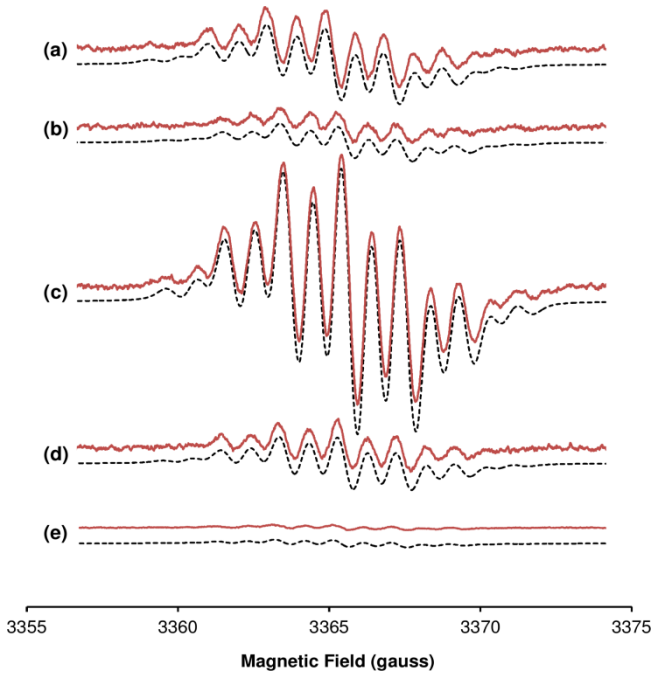


Figure 9. X-band solution EPR spectra of (a) **6**, (b) **7**, (c) **8**, (d) **9**, and (e) **1** in DMSO solvent [0.5mM] after the addition of excess fluoride. Dashed line: simulation using the parameters in Table 3.

Clearly evident from the spectra obtained is a signal commensurate with the formation of the NDI radical upon the addition of fluoride. The splitting pattern in each case is consistent with that generated electrochemically from **10-12** and represents the delocalization of the electron across all atoms of the NDI as well as some contribution of the *N*-CH_2 exocyclic protons. Assuming (i) the timing of sample preparation was consistent, (ii) radical formation is rapid enough to plateau before measurement began, and (iii) once formed, the radicals were stable on the time scale of the data acquisition, then variation in intensity (propensity to radicalise NDI) could be correlated with the degree of pi-pi interaction prior to addition of fluoride. Under the similar conditions of each experiment, we can infer the strength of EPR signal generated, and hence the ease of radical generation is in the order **8 >> 6** > **9** ≈ **7** > **1**. Within the family of cyclophanes, this infers that the interactions between the NDI and alkoxybenzene unit facilitates the generation of the radical anion over alkoxynaphthalenes, consistent with the results obtained from the absorption spectroscopy.

Conclusion

We have synthesised a family of NDI cyclophanes with a pre-existing π-π interaction between π-electron rich and π-electron deficient chromophores, and subjected them to the presence of fluoride. Dramatic colour changes that manifest strong changes in the EPR and absorption spectra of each cyclophane indicates their ability to act as a crude sensor for fluoride. More importantly from a design perspective, the electronic effects of a non-covalent neighbor are significant on the chemistry and physical properties associated with the reduction of the naphthalene diimide unit.

Experimental Section

General Experimental Methods

^{1}H and ^{13}C nuclear magnetic resonance (NMR) spectra were recorded using a Bruker DRX400 NMR Spectrometer (^{1}H at 400 MHz, unless otherwise specified, and ^{13}C at 100 MHz). All samples were prepared in the stated deuterated solvent. The chemical shifts (δ) were calibrated against the residual solvent peak in the spectrum. Each resonance was assigned according to the following convention: chemical shift (δ) measured in parts per million (ppm), multiplicity, coupling constant (J) measured in Hz, number of protons and assignment. Multiplicities are denoted as (s) singlet, (d) doublet, (t) triplet, (q) quartet, broad (b) or (m) multiplet. The ^{13}C NMR spectra were assigned a chemical shift (δ) measured in parts per million.

Low Resolution-Electrospray Ionisation Mass Spectrometry (LR-EIMS) was completed on a Micromass Platform API QMS-quadrapole electrospray mass spectrometer. Spectra were taken in positive ion mode (ESI+) mode unless otherwise stated. [M]* denotes the molecular ion. Matrix-Assisted Laser Desorption Ionization Time of Flight Mass Spectroscopy (MALDI-TOF-MS) was performed on an Ultraflex III instrument (Bruker Daltonics, Germany) with α-cyano-4-hydroxy cinnamic acid as the matrix.

Melting points were performed on a Stanford Research Systems MPA160 melting point apparatus and specified in degrees Celsius (°C).

UV-visible spectra were recorded on the Varian model Cary 60 UV-visible spectrophotometer with solvent and concentration of sample stipulated for each individual experiment. Fluorescent spectra were performed on the Varian model Cary Eclipse fluorescence spectrophotometer, with the solvent, concentration of samples and excitation wavelength recorded for experiment.

Infrared spectra were recorded on a Bruker model IFS Equinox 55 FTIR system paired with a golden gate single bounce diamond micro ATR and a MCT detector.

Analytical thin layer chromatography was performed on silica gel (Silica 60 F254) coated aluminium plates. Column chromatography was performed using silica gel (pore size 0.063-0.2 mm) purchased from Merck as the column stationary phase. The eluting solvents stated in this synthesis section are quoted as volume to volume (v/v) ratios.

X-ray crystal diffraction patterns were determined using an Enraf Nonius FR590 KappaCCD diffractometer, a Bruker Kappa Apex II diffractometer or at the Australian Synchrotron using the PX1 or PX2 beamline, with graphite monochromated MoKα radiation (0.71073 Å) at 123(2)K unless otherwise stated. The crystal data was solved and refined using SHELXS-97 and SHELXL-97 suite of programs with the graphical interface X-Seed v2.0.

Continuous-wave EPR spectra were acquired using a CMS8400 X-band (9.4 GHz) spectrometer (Adani, Belarus) fitted with a TE102 cavity and operating at a fixed time constant of 100 ms and 100 kHz magnetic field modulation. Solution-phase measurements were made at room temperature using a quartz flat cell (Wilmad, WG-808-Q) and the following settings: microwave frequency, 9.44 GHz; microwave attenuation, 16 dB; magnetic field sweep rate, 0.6 gauss s^{-1}; magnetic field modulation amplitude, 0.2 gauss; magnetic field modulation frequency, 100 kHz; receiver gain, 500; time constant, 100 ms. Due to the relatively low signal from compound **1**, the modulation amplitude and number of averages were both increased by a factor of 2. The EPR spectrum presented in Figure 9e was scaled by a factor of ¼ to allow direct comparison with compounds **6**–**9**. The spin Hamiltonian (SH) parameters were determined from numerical simulations of the experimental spectra using Easyspin[8] v.4.5.5 and the Hamiltonian

$$H = \langle g \rangle \beta \, \mathrm{B.S} + \Sigma_k \langle A^k \rangle \, \mathrm{S.I}^k - g_n^k \beta_n \mathrm{B.I} \qquad (1)$$

where S and I are the electron and nuclear vector spin operators, $\langle g \rangle$ and $\langle A \rangle$ are the isotropic electron Zeeman and nuclear hyperfine coupling matrices, β is the Bohr magneton, β_n is the nuclear magneton and B is the applied magnetic field. The summation over k incorporates the superhyperfine and nuclear Zeeman interactions with nucleus k of spin I^k and nuclear g factor g_n^k. The "garlic" function in Easyspin was used to solve equation (1) via a fifth order perturbation approximation and the SH parameters were varied iteratively using the "esfit" module to achieve a least squares minimisation of the difference between the experimental and simulated spectrum. Coupling to two equivalent ^{14}N nuclei and two sets of four equivalent ^{1}H nuclei was assumed for the simulation, using the SH parameters previously reported[7] as a starting point. Although the coupling to the four ^{1}H nuclei adjacent to the imide nitrogens could not be resolved, their inclusion enabled the correct reproduction of the inhomogeneous linewidth without the need for convoluting the spectrum with a Gaussian line broadening parameter. Simulated g factors were corrected by acquiring the spectrum of DPPH (g = 2.0036) in DMSO as a field calibration standard.

Synthetic Methods

Bis-*N,N'*-(2-carboxyethyl)-1,4,5,8-naphthalenetetracarboxylic Diimide (1)[9]

β-alanine (1.28 g, 14.30 mmol) was added to a stirred solution of NDA (1.55 g, 5.78 mmol) in glacial acetic acid (40 mL). The reaction was heated at 110 °C and left to stir overnight. The reaction was allowed to cool to room temperature before pouring into ice-water (60 mL). The resulting white precipitate was filtered off and dried yielding a powdery white solid (1.94 g, 84%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.66 (s, 4H, ArH), 4.27 (dd, J = 8.0, 7.6 Hz, CH_2), 2.62 (dd, J = 7.6 Hz, CH_2). Mass Spec: (ESI, +ve) calculated m/z = 410.08 observed 433.25 $[M+Na]^+$. Melting Point: >260°C.

General Synthesis of Polyethers 2-5

The dihydroxyaromatic (~20 mmol) was added to a suspension of K_2CO_3 (10 equiv.) in dry MeCN (~100 mL). The suspension was stirred vigorously as the 2-chloroethoxyether (2.5 equiv.) was added over 30 minutes. The reaction was heated under reflux for 4 days and then left to cool to room temperature. The suspension formed was filtered and the filtrate was washed with DCM (3 × 30 mL). The combined organic solutions were concentrated under vacuum and the residue was redissolved in DCM (50 mL) and washed with water (3 × 20 mL). The organic phase was then dried over magnesium sulfate, filtered and the solvent removed *in vacuo*.

2: Using 1,5-dihydroxynaphthalene and 2-(2-chloroethoxy)-ethanol, the residue was recrystallized from EtOAc to afford **2** as a flaky light brown crystalline solid in 48% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 7.87 (d, J = 8.56 Hz, 2H, ArH), 7.36 (t, J = 8.12, 7.88 Hz, 2H, ArH), 6.85 (d, J = 7.64 Hz, 4H, O-CH_2), 4.30 (dd, J = 4.62, 4.86 Hz, 4H, O-CH_2), 4.00 (dd, J = 4.62, 4.86 Hz, 2H, O-CH_2), 3.76 (m, 8H, O-CH_2). Mass Spec: (ESI, +ve) calculated m/z = 336.16 observed 359.1 $[M+Na]^+$. Melting Point: 95.7-96.8°C.[10]

3: Using 1,5-dihydroxynaphthalene and 2-(2-(2-chloroethoxy)-ethoxy)ethanol, the residue was purified by crystallization from AcOEt to afford **3** as a flaky light brown crystalline solid in 44% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 7.87 (d, J = 8.56 Hz, 2H, ArH), 7.34 (dd, J = 8.28,7.76 Hz, 2H, ArH), 6.85 (d, J = 7.64 Hz, 4H, O-CH_2), 4.29 (m, 4H, O-CH_2), 3.99 (m, 4H, O-CH_2), 3.79 (m, 4H, O-CH_2), 3.70 (m, 8H, O-CH_2), 3.60 (m, 4H, O-CH_2). Mass Spec: (ESI, +ve) calculated m/z = 424.21 observed 447.2 $[M+Na]^+$. Melting Point: 69.2-70.9°C.[11]

4: Using 1,4-dihydroquinone and 2-(2-chloroethoxy)ethanol, the crude reside was purified by recrystallization from EtOAc to afford **4** as a flaky light brown crystalline solid in 46% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 6.85 (s, 4H, ArH), 4.08 (m, 4H, O-CH_2), 3.83 (m, 4H, O-CH_2), 3.74 (m, 4H, O-CH_2), 3.65 (m, 4H, O-CH_2). Mass Spec: (ESI, +ve) calculated m/z = 286.14 observed 309.01 $[M+Na]^+$. Melting Point: 94.6-96.1°C.[12]

5: Using 1,4-dihydroxynaphthalene and 2-(2-chloroethoxy)-ethanol, the crude reside was purified by further washing with water (3 x 20 mL) The organic phase was then dried over magnesium sulfate, filtered and the solvent removed *in vacuo* to afford **5** as a dark brown oil 43% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 8.22 (dd, J = 3.28 Hz, 2H, ArH), 7.51 (dd, J = 3.28 Hz, 2H, ArH), 6.71 (s, 2H, ArH), 4.26 (m, 4H, O-CH_2), 3.98 (m, 4H, O-CH_2), 3.78 (m, 8H, O-CH_2), 2.11 (bs, 2H, OH). ^{13}C NMR: (100 MHz, $CDCl_3$): δ 149.0, 126.7, 126.1, 121.9, 105.0, 72.8, 70.0, 68.5, 61.95. Mass Spec: (ESI, +ve) calculated m/z = 336.1573 observed 359.1465 $[M+Na]^+$.

General Synthesis of Cyclophanes 6-9

The diacid **1** (~0.5 mmol) was suspended in dry benzene (CAUTION, 30 mL) and 4 drops of DMF added. Oxalyl chloride (4 equiv.) was added to the suspension and the temperature raised to 50 °C with stirring for 21 h. The solution was then cooled and concentrated to remove excess oxalyl chloride. The diacid chloride generated was redissolved in dry benzene (CAUTION, 30 mL) and was added dropwise with stirring to the diol **2-5** (1.1 equiv.) in benzene (200 mL). The mixture was maintained at 50 °C and left to stir for a further 4 days. The

solvent was removed under reduced pressure and the mixture purified by column chromatography (SiO2, 1:10 acetone/DCM).

6: Using **2** as the diol, cyclophane **6** was prepared as a bright purple solid in 44% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 8.71 (s, 4H, ArH),), 7.52 (d, *J* = 8.4 Hz, 2H, ArH), 7.17 (t, *J* = Hz, 2H, ArH), 6.38 (d, J = 7.8 Hz, 2H, ArH), 4.32 (m, 4H, O-CH_2), 4.27 (m, 4H, O-CH_2), 3.75-3.68 (m, 12H, O-CH_2), 2.67 (t, J= 6.88 Hz, 4H, O-CH2). ^{13}C NMR: (100 MHz, $CDCl_3$): δ171.0, 162.3, 153.9, 130.8, 126.5, 126.4, 126.3, 125.3, 114.5, 105.1, 66.7, 63.4, 37.0, 33.6. Mass Spec: (ESI, +ve) calculated *m/z* = 710.2112 observed m/z= 733.1999 $[M+Na]^+$. Melting Point: 132.0-136.3°C.

7: Using **3** as the diol, cyclophane **7** was prepared as a dark purple solid in 24% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 8.32 (s, 4H, ArH), 7.23 (d, *J* = 8.4 Hz, 2H, ArH), 6.87 (t, *J* = 8.4, 7.8 Hz, 2H, ArH), 6.39 (d, J = 7.8 Hz, 2H, ArH), 4.49 (m, 4H, O-CH_2), 4.32 (m, 4H, O-CH_2), 4.05 (m, 4H, O-CH_2), 3.93 (m, 4H, O-CH_2), 3.75 (m, 12H, O-CH_2), 2.82 (t, J= 7.32 Hz , 4H, O-CH2). ^{13}C NMR: (100 MHz, $CDCl_3$): δ 171.0,, 162.6, 153.8, 130.4, 126.1, 125.9, 125.8, 124.9, 114.0, 71.1, 71.0, 69.8, 68.8, 67.7, 64.0, 36.7, 33.2. Mass Spec: (MALDI, +ve) calculated *m/z* = 798.26 observed 821.58 [M+Na]+. Melting Point: 196.4-198.5°C.

8: Using **4** as the diol, cyclophane **8** was prepared as a bright orange solid in 10% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 8.71 (s, 4H, ArH), 6.48 (s, 4H, ArH), 4.38 (m, 4H, O-CH_2), 4.23 (m, 4H, O-CH_2), 3.66 (m, 4H, O-CH_2), 3.50-3.44 (m, 8H, O-CH_2), 2.70 (t, J= 6.88 Hz 4H, O-CH2). ^{13}C NMR: (100 MHz, $CDCl_3$): δ 171.0, 162.6, 153.8, 130.4, 126.1, 125.9, 125.8, 124.92, 114.0, 105.4, 77.5, 77.2, 76.8, 71.1, 71.0, 69.8, 68.8, 67.7, 64.0, 36.7, 33.2 Mass Spec: (ESI, +ve) calculated *m/z* = 660.1955 observed 661.2019 $[M+H]^+$. Melting Point: 240.3-243.3°C

9: Using **5** as the diol, cyclophane **9** was prepared as a dark blue solid in 6% yield. ^{1}H NMR: (400 MHz, $CDCl_3$): δ 8.56 (s, 4H, ArH), 7.8 (dd, *J* = 3.28 Hz, 2H, ArH), 7.35 (dd, *J* = 3.28 Hz, 2H, ArH), 6.25 (s, 4H, O-CH_2), 4.28 (m, 4H, O-CH_2), 4.22 (m, 4H, O-CH_2), 3.77 (m, 4H, O-CH_2), 3.69 (m, 8H, O-CH_2), 2.62 (m, 4H, O-CH_2). δ 171.0, 162.4, 148.4, 130.8, 126.7, 126.5, 126.2, 126.1, 121.7, 104.0, 69.6, 69.5, 67.7, 63.9, 37.0, 33.5. Mass Spec: (ESI, +ve) calculated *m/z* = 710.2112 observed 711.2174 $[M+H]^+$. Melting Point: 238.1-240.2°C

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Keywords: naphthalene diimide • anion-π interactions • π-π interactions • radical • EPR • fluoride • sensor

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Entry for the Table of Contents (Please choose one layout)

Layout 1:

FULL PAPER

The interaction and reaction of fluoride with a family of cyclophanes bearing naphthalene diimides is explored against the influence of a spatially neighbouring aromatic unit. The systems are explored spectroscopically, by x-ray crystallography and EPR techniques.

*Alexander Young, Simon Drew, Steven J. Langford**

Page No. – Page No.

Systematically Studying the Effect of Fluoride on the Properties of Cyclophanes Bearing Naphthalene Diimide and Dialkoxyaryl groups