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Photoinduced hydrogen atom abstraction in *N*-(adamantyl)phthalimides: structure–reactivity study in the solid state

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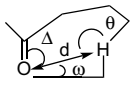
ABSTRACT

Adamantyl-functionalized phthalimides were synthesized and the probability of intramolecular photochemical hydrogen atom abstraction in the solid state analyzed by X-ray crystallographic analyses. These analyses and solid-state photolyses showed that the parameters determining photochemical reactivity for typical carbonyl compounds in the solid state can also be extended to phthalimides. Only *N*-(2-adamantyl)phthalimide underwent a solid-state photochemical reaction, which is the first example in the phthalimide series. This reaction is regio- and stereoselective, resulting in an *endo*-alcohol. On the other hand, the photoreaction of *N*-(2-adamantyl)phthalimide in solution gives an *exo*-alcohol as the main product together with an *endo*-alcohol and a benzazepindione.

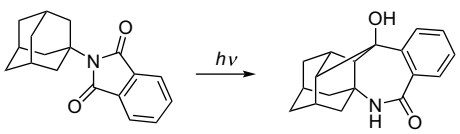
1. Introduction

The Norrish type II reaction is an important deactivation pathway of the triplet excited state of carbonyl compounds. It has been thoroughly examined on experimental[1] and theoretical grounds,[2] as well as in the solid state.[3] Scheffer et al. developed a structure–reactivity relationship for the solid-state intramolecular photochemical γ-H abstractions by carbonyl chromophores followed by Yang cyclization.[3] Four parameters direct the reactivity of the carbonyl group in the excited state. The first of these is the distance (d) between the carbonyl oxygen and the γ-H atom. The optimal value for d is equal to the sum of the van der Waals radii for oxygen and hydrogen, which is 2.72 Å. The second parameter Δ is defined as the C=O···H angle, with an optimal value between 90° and 120°. The third parameter is the C–H···O angle (θ), which is expected to have an optimal value 180°, whereas the fourth parameter ω is the angle by which the γ-H atom lies outside the plane defined by C=O and assumed to adopt an optimal value around 0°.



The phthalimide group is a very useful chromophore and its photochemistry has been intensively studied and reviewed by Griesbeck et al.[4] and others.[5] It shows typical reactivity of the excited-state carbonyl chromophore: homolytic C–H activation, resulting in cycloaddition and photoreduction products. In addition, the phthalimide chromophore is characterized by a high oxidation potential of its first excited singlet state and the first and the second excited triplet states.[4d,6] Therefore, in the presence of electron-rich substrates, homolytic activations are in competition with electron transfer photochemistry. Due to the versatile photochemical reactivity of phthalimides and its applicability in synthesis,[4,5,7] the photochemistry of phthalimides is still a subject of widespread interest. However, to the best of our knowledge, solid-state photochemistry of phthalimides has not been reported.

In the context of our work on the synthesis of polycyclic compounds with different functionality[8] we turned our attention to adamantane derivatives of phthalimides. We discovered that *N*-(1-adamantyl)phthalimide (**1**) does react in a domino photochemical reaction in solution giving rise to a 2,4-methanoadamantane derivative of benzazepine **A** (Eq. 1).[9]



1 **A** (1)

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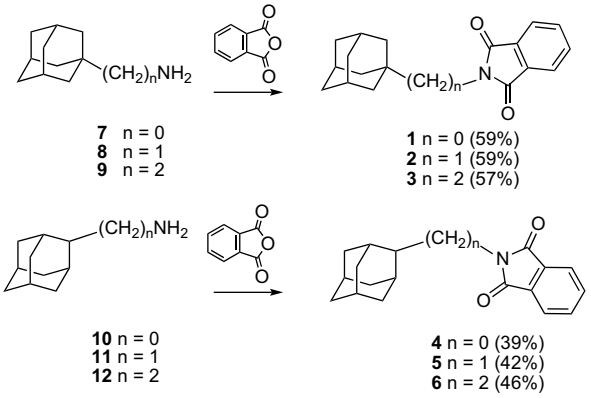
In this paper we report the synthesis of five new adamantane phthalimides (**2**–**6**), and the investigation of their structure by X-ray crystallographic analysis. The investigation of the structure by X-ray provides information on the probability to form photochemical H-abstraction products on irradiation in the solid state. To verify the findings obtained by X-ray analysis we performed photolyses of phthalimides **1**–**6** in the solid state. Phthalimide **4** was also irradiated in solution and the selectivity of the photoreactions was compared.

2. Results and discussion

2.1. Synthesis

Adamantane phthalimides **1**–**6** were synthesized by coupling phthalic anhydride with the corresponding amines **7**–**12**, respectively (Scheme 1). The imide condensations were performed in moderate yields using a modification of the solvent-free procedure[10] in a melt of phthalic anhydride. Amine **7** was obtained from commercial sources, amine **8** was prepared from 1-adamantanecarboxylic acid, which was transformed to the cyanide[8f] and reduced with $LiAlH_4$.[11] Amine **9**[12] was obtained from 1-adamantylacetic acid, which was transformed to its amide[13] (treatment with $SOCl_2$ followed by liquid NH_3) and reduced with $LiAlH_4$. For the preparation of amines **10**–**12**, 2-adamantanone was used as a starting material. Amine **10** was obtained from a reaction with formamide and subsequent treatment with HCl,[14] amine **11** was prepared by reduction of the corresponding cyanide,[15] which was prepared from adamantanone in a reaction with TosMIC.[8e] Compound **12** was synthesized from adamantanone, which was transformed to the methylidene nitrile[16] by a modification of a literature procedure[17] and reduced with $LiAlH_4$. All new phthalimides **2**–**6** were characterized by spectroscopic methods (see Section 4).



Scheme 1.

2.2. Crystal structures and probability for photochemical H-abstraction

In order to investigate the probability of adamantane phthalimides **1**–**6** to undergo photochemical H-abstraction, we examined their crystal structures (see Supplementary data). The single crystals of adamantane phthalimides **2**–**6** were obtained by slow evaporation from their solutions; the crystal structure of adamantane phthalimide **1** has been published earlier.[18] The relevant parameters (vide supra) obtained by X-ray analysis, which indicate their probability for intramolecular photochemical H-abstraction in the solid state are compiled in Table 1.

As can be seen from the data in Table 1, most of the investigated compounds have at least one H-atom available for intramolecular H-abstraction by the carbonyl moiety of the phthalimide chromophore ($d \leq 2.72$ Å). The values for the Δ angles are generally in the range 90–120° or slightly below these values. However, most of the values for the ω angle are not close to 0° and there are large deviations of the angle θ from 180°.

Table 1
The relevant geometric parameters d, ω, Δ and θ obtained from the crystal structures of phthalimides **1**–**6**

Compound	d (Å)	ω (°)	Δ (°)	θ (°)
1[a]	2.41 (C8O2···H–C14)[b]	21.98	92.59	122.87
	2.41 (C8O2···H–C14A)	21.98	92.59	122.87
	2.48 (C1O1···H–C10)	57.29	94.72	96.94
2	2.85 (CO1···H–C11A)	104.90	77.36	103.44
	2.87 (CO1···H–C11B)	18.16	101.71	102.50
	2.87 (CO4···H–C30B)	10.94	98.22	106.89
	2.87 (CO3···H–C37B)	95.44	80.82	109.29
3	2.96 (CO2···H21–C10)	35.56	83.82	111.79
	3.40 (CO1···H20–C10)	60.76	73.05	103.21
4	2.29 (CO1···H–C17)	35.37	108.36	134.19
	2.36 (CO2···H–C15)	46.00	100.93	132.65
5	2.59 (CO2···HA–C11)	80.20	84.72	121.58
	2.78 (CO2···H–C18)	56.04	117.70	117.19
	3.33 (CO1···H–C10)	60.76	74.53	104.83
6	2.92 (CO2···HA–C10)	36.90	83.98	113.22
	3.42 (CO1···HB–C10)	57.70	73.67	102.46

[a] Data taken from the Cambridge crystallographic database.
[b] The atom notations correspond to the *ORTEP* drawings presented in Supplementary data.

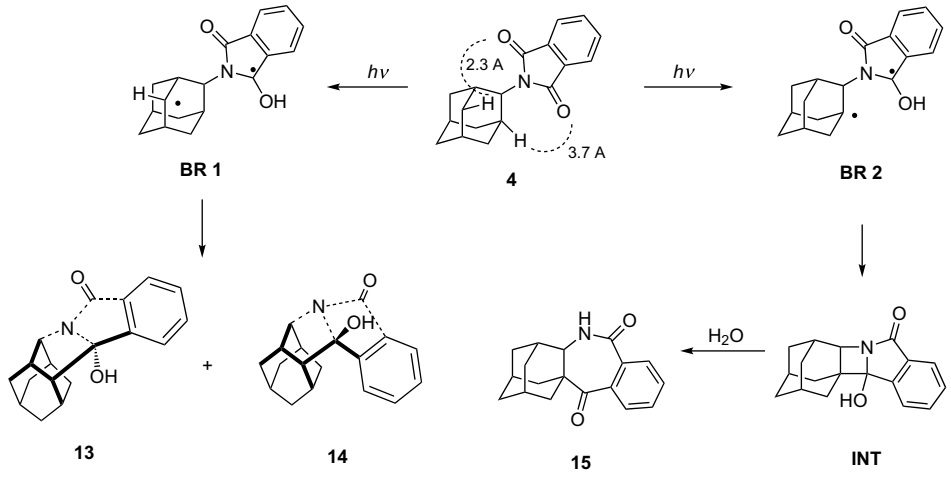
The adamantane H-atoms in **3** and **6** cannot be activated by the excited state of the phthalimide moiety. The only H-atoms in **3** and **6**, which may be available for H-abstraction are in a γ-position to the carbonyl at the ethylene spacer (at C10, see Supplementary data S9 and S18). The distance between the closest γ-H atom in **3** and **6** is, however, slightly larger than the sum of van der Waals radii, what implies that photochemical H-abstraction in the crystalline state is not highly feasible.

In phthalimide **1**, three H-atoms are at the optimal distance available for abstraction. However, the abstraction of the H-atom at C10 (see Supplementary data S3) in the solid state appears to be not possible, due to the unfavorable θ value (96.94°). Additionally, the abstraction of H-atoms at C14 and C14A is also difficult due to the same reason, low θ values (122.87°).

Phthalimide **2** crystallized with two independent molecules in the crystal unit. In each of these two molecules there are two H-atoms of the adamantane skeleton at the δ-position to the carbonyl chromophore, at the distance available for the abstraction. However, the abstraction of only axial δ-H atoms (H–C11B and H–C30B, see Supplementary data S6) is expected to be feasible due to the unfavorable angle ω for the equatorial H-atoms (H–C11A and H–C37B). On the other hand, abstraction of the axial H-atoms is also difficult because of the low θ value.

In phthalimides **4** and **5** there are two H-atoms of the adamantane skeleton, which are at the distance available for the H-abstraction. In **5**, these H-atoms (H–C11 at δ-position, and H–C18, at ε-position, see Supplementary data S15) are, however, at the angle ω (80.20 and 60.76°, respectively), which is probably too high for the reaction to take place in the solid state. In **4**, available H-atoms for the abstraction are at the positions C17 and C15 of the adamantane (δ-position to the carbonyl, see Supplementary data S12). Although all the parameters (d, ω, Δ and θ) assume similar values, ω and d are slightly lower for the H at C17 suggesting the higher reactivity at that position than at the C15.

The crystal structures of phthalimides **1**–**6** were also examined for the intermolecular short contacts between the carbonyl oxygen and hydrogen atoms. Upon excitation of molecules, due to these



Scheme 2.

short contacts, intermolecular hydrogen abstractions may take place. However, in **1**–**6** most of the short contacts with the carbonyl oxygen are formed by aromatic H-atoms, which do not undergo photochemical H-abstractions. The shortest distance between the aliphatic adamantane H-atoms of one molecule and the carbonyl oxygen of the other molecule is 2.69 Å (for **1**, the distance between O3 and H42), which is larger than the intramolecular distance to the potentially reactive hydrogen (Table 1). Consequently, photochemical intermolecular hydrogen abstractions in crystals **1**–**6** are not anticipated.

2.3. Photochemical reactivity

In order to verify the finding obtained by X-ray structural analysis on the probability of phthalimides to undergo photoinduced H-abstraction, we performed irradiation of phthalimides **1**–**6** in the solid state. For that purpose, crystals of the phthalimides were grown from CH_2Cl_2 solution and analyzed by microscopy and X-ray diffractometer. Irradiation was performed for all samples in the form of single crystals and in the form of films obtained by the fast evaporation of CH_2Cl_2 from the Petri dishes. Although single crystals and films of the same phthalimide obtained by the evaporation of the solvent differed in particle size, the samples were isomorphic, as shown by X-ray diffractometry and microscopy.

From the investigated phthalimides, only **4** underwent a solid-state photochemical reaction, as was predicted from the X-ray structural analysis. However, the conversion of the reaction was very much dependant on the size of the particles. Therefore, we also performed irradiation experiments of phthalimides **1**–**6** in the form of microcrystals. To prepare these microcrystals, we applied the procedure of Garcia-Garibay et al.[19] Phthalimides were ground and suspended in H_2O. The (micro)suspension was maintained by addition of sodium dodecyl sulfate (SDS). Similarly, only **4** underwent photochemical transformation but the photolysis of the microsuspension was 2–3 times faster than photolysis of the film.

In order to characterize the photoproducts of **4**, we have performed preparative solid state and microsuspension irradiations. After extended irradiation of films (3 days), or microsuspensions (1 day), the photoproducts were separated by column chromatography. Although the photochemical reaction of **4** was slow, it was selective giving one main product, *endo*-alcohol **13**, which was isolated in 10% yield. Only traces (less than 1%) of *exo*-alcohol **14** and benzazepindione **15** were detected by HPLC.

The irradiation of phthalimide **4** was also performed in solution phase, using solvents of different polarity (cyclohexane, acetone, CH_3CN and CH_3CN/H_2O (3:1)). The photochemical reaction gave three products (**13**–**15**, Scheme 2), which were isolated and fully characterized. The photolysis of **4** was clearly the most efficient in acetone ($\Phi \sim 0.004$),[20] suggesting that it occurs via a triplet excited state. On the other hand, in nonpolar solvents almost no conversion took place. After 16 h photolysis in cyclohexane, the conversion of **4** was <3%. On addition of water to the CH_3CN solution of **4**, its photochemical reactivity was enhanced. Thus, after 16 h photolysis (100 mg in 200 mL, 16 lamps 8 W, 300 nm), the conversion of **4** in CH_3CN was 35%, whereas in CH_3CN/H_2O (3:1) (under same conditions), complete conversion was achieved. However, the same ratio of the photoproducts was obtained on irradiation in CH_3CN and CH_3CN/H_2O. The structures of the photoproducts were determined by spectroscopic methods and additionally proven by X-ray analysis (see Supplementary data).

2.4. Mechanism of the photochemical reaction

According to the isolated products **13**–**15**, we propose the mechanism of the photochemical transformation of **4** in solution (Scheme 2). After population of the triplet excited state, hydrogen abstraction of the adamantane-H by the phthalimide moiety takes place. Due to the molecular motions, several hydrogen atoms of the adamantane skeleton are available for the abstraction by the phthalimide carbonyl. Although it is generally known that γ-H abstraction is faster by an order of magnitude than δ-H abstraction, in case of **4**, two biradicals are formed (BR-1 and BR-2 Scheme 2). However, the δ-H atoms are closer to the phthalimide carbonyl than the corresponding γ-H atoms. According to AM1 calculation,[21] in the most stable ground-state conformer in the gas phase, the distance between the carbonyl of the phthalimide moiety and the adamantane-H at position 4 (δ-H atoms, at C15 or C17, Supplementary data S12) is 2.3 Å, which coincides with the distance found in the crystal structure of **4**. Moreover, BR-1 is more stable than BR-2 (~5 kcal/mol). Therefore, formation of BR-1 is favored, as in the case of solid-state reaction (vide infra). Combination of biradical BR-2 gives the azetidinol (INT), which is unstable and easily opens to more stable azepindione **15**, which was isolated. On the other hand, combination of BR-1 gives two products, *exo*-alcohol **14** and *endo*-alcohol **13** in a ratio 3:1.

In the case of solid-state reactions where molecular motions are restricted, only the closest H-atoms can be abstracted, which are at the appropriate angle to the phthalimide carbonyl group. The X-ray structural analysis for phthalimide **4** indicated that reactive H-atoms are at the positions C15 and C17 of the adamantane

moiety. Therefore, irradiation of **4** in the solid state gives only BR-1. Due to restricted molecular motions, cyclization of BR-1 is selective giving mainly *endo*-alcohol **13**. This result is not surprising since the geometry of *exo*-alcohol **14** differs largely from the geometry of *endo*-alcohol **13** in comparison with the starting material **4**.

3. Conclusion

A series of new adamantane phthalimides **2**–**6** have been synthesized and characterized by spectroscopic methods and X-ray crystallographic analysis. The probability of photochemical H-abstraction on phthalimides **1**–**6** in crystalline state was examined by X-ray analysis. The analysis indicated that parameters determining the photochemical reactivity of typical carbonyl compounds in the solid state can be extended to phthalimides. From the investigated phthalimides, only **4** underwent solid-state photochemical reaction. Photoreaction of **4** is regio- and stereoselective, giving *endo*-alcohol **13** as the main product. On the other hand, the photoreaction in the solution gave a mixture of *endo*-**13** and *exo*-**14**, together with the benzazepindione product **15**.

4. Experimental part

4.1. General

^{1}H and ^{13}C NMR spectra were recorded on a Bruker AV-300 or 600 Spectrometer at 300 or 600 MHz, respectively. All NMR spectra were measured in $CDCl_3$ using tetramethylsilane as a reference. Melting points were obtained using an Original Köfler Mikroheitztisch apparatus (Reichert, Wien). IR spectra were recorded on a FT-IR ABB Bomem MB 102 spectrophotometer and elemental analyses were performed at the Central Analytical Laboratory, at the Ruđer Bošković Institute. The samples were analyzed on a Shimadzu HPLC equipped with a diode array detector on a Phenomenex Luna 3u C18(2) column using CH_3OH/H_2O (20%) as a solvent. Silica gel (Merck 0.05–0.2 mm) was used for chromatographic purifications. Solvents were purified by distillation. 1-Aminoadamantane, 1-adamantanecarboxylic acid, 1-adamantylacetic acid and 2-adamantanone are commercially available. Irradiations were performed in a Rayonet reactor equipped with 16 lamps with the 300 nm output or in a Luzchem reactor.

4.2. Preparation of adamantane phthalimides, general procedure

In a round bottom flask (50 mL) equipped with a stopper, phthalic anhydride (1.5 equiv) was melted. To the melt, 1 equiv of adamantaneamine was added in several portions (sometimes added as a CH_2Cl_2 solution). After the addition was complete, the reaction mixture was stirred over 10 min with the stopper, after which stopper was removed and stirring continued for another 10 min to remove water. To the cooled reaction mixture, CH_2Cl_2 (100 mL) was added, and the solution washed with 10% acetic acid (3×30 mL) and 10% solution of $NaHCO_3$ (3×30 mL). Washed organic layer was dried over anhydrous $MgSO_4$, filtered and the solvent was removed on a rotary evaporator. The crude reaction mixture was purified by column chromatography on SiO_2 using CH_2Cl_2 as an eluent.

N-(1-Adamantyl)phthalimide (**1**) was obtained in 59% yield (1.65 g) from 1-aminoadamantane (1.5 g, 9.92 mmol).

Colourles crystals; mp 137–139 °C (lit.[22] 138–139 °C); ^{1}H NMR ($CDCl_3$, 600 MHz) δ/ppm: 7.75–7.74 (m, 2H), 7.66–7.65 (m, 2H), 2.52 (br s, 3H), 2.16 (br s, 6H), 1.80–1.70 (m, 6H); ^{13}C NMR (150 MHz, $CDCl_3$) δ/ppm: 169.6, 133.5, 131.9, 122.4, 60.3, 40.1, 36.1, 29.7.

N-(1-Adamantylmethyl)phthalimide (**2**) was obtained in 59% yield (2.11 g) from 1-aminomethyladamantane (2.0 g, 12.10 mmol).

Colourless crystals; mp 139–140 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm: 7.85–7.82 (m, 2H), 7.72–7.69 (m, 2H), 3.37 (s, 2H), 1.95 (br s, 3H), 1.67 (d, 3H, J=12.2 Hz), 1.61 (d, 3H, J=12.2 Hz), 1.60–1.55 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm: 169.0, 133.7, 132.0, 123.0, 49.6, 40.7, 36.6, 35.4, 28.1; IR (KBr) ν_{max}/cm^{-1}: 2902, 2847, 1767, 1713. Anal. Calcd for $C_{19}H_{21}O_2N$: C 77.26, H 7.17, N 4.74. Found: C 77.19, H 7.24, N 4.83%.

N-[2-(1-Adamantyl)ethyl]phthalimide (**3**) was obtained in 57% yield (845 mg) from 1-(2-aminoethyl)adamantane (0.86 g, 4.80 mmol).

Colourless crystals; mp 158–160 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm: 7.83–7.80 (m, 2H), 7.69–7.67 (m, 2H), 3.71–3.65 (m, 2H), 1.96 (br s, 3H), 1.71 (d, 3H, J=12.0 Hz), 1.66 (d, 3H, J=12.0 Hz), 1.61–1.57 (m, 6H), 1.44–1.39 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm: 168.2, 133.6, 132.2, 122.9, 42.1, 41.9, 36.9, 33.1, 31.8, 28.4; IR (KBr) ν_{max}/cm^{-1}: 2910, 2849, 1766, 1717. Anal. Calcd for $C_{20}H_{23}O_2N$: C 77.64, H 7.49, N 4.53. Found: C 77.94, H 7.66, N 4.53%.

N-(2-Adamantyl)phthalimide (**4**) was obtained in 39% yield (2.52 g) from 2-aminoadamantane (3.46 g, 22.88 mmol).

Colourless crystals; mp 103–104 °C (lit.[23] 103 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm: 7.80–7.77 (m, 2H), 7.69–7.66 (m, 2H), 4.32 (br s, 1H), 2.57 (br s, 2H), 2.33 (br s, 1H), 2.29 (br s, 1H), 1.96–1.92 (m, 6H), 1.79 (br s, 2H), 1.71–1.66 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm: 169.4, 133.6, 132.0, 122.6, 61.2, 38.4, 37.6, 32.7, 31.9, 27.5, 26.8.

N-(2-Adamantylmethyl)phthalimide (**5**) was obtained in 42% yield (912 mg) from 2-aminomethyladamantane (1.20 g, 2.40 mmol).

Colourless crystals; mp 123–125 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm: 7.85–7.82 (m, 2H), 7.72–7.69 (m, 2H), 3.82 (d, 2H, J=7.8 Hz), 2.17–2.09 (m, 3H), 1.89–1.56 (m, 12H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm: 168.6, 133.7, 132.0, 123.0, 42.9, 40.9, 38.6, 38.0, 31.4, 29.9, 27.9, 27.8; IR (KBr) ν_{max}/cm^{-1}: 2915, 2889, 1764, 1708. Anal. Calcd for $C_{19}H_{21}O_2N$: C 77.26, H 7.17, N 4.74. Found: C 76.85, H 6.77, N 4.96%.

N-[2-(2-Adamantyl)ethyl]phthalimide (**6**) was obtained in 46% yield (1.37 g) from 2-(2-aminoethyl)adamantane (1.73 g, 9.64 mmol).

Colourless crystals; mp 128–130 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm: 7.85–7.81 (m, 2H), 7.47–7.68 (m, 2H), 3.68 (t, 2H, J=15,1 Hz), 1.91–1.51 (m, 17H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm: 167.4, 132.8, 131.2, 122.1, 40.9, 38.0, 37.3, 35.6, 30.6, 30.5, 30.4, 27.1, 26.9; IR (KBr) ν_{max}/cm^{-1}: 2906, 2889, 2872, 2852, 1767, 1703. Anal. Calcd for $C_{20}H_{23}O_2N$: C 77.64, H 7.49, N 4.53. Found: C 77.71, H 7.10, N 4.68%.

4.3. Photochemistry of adamantane phthalimides in the solid state

(A) Adamantane phthalimides **1**–**6** (10 mg) were dissolved in CH_2Cl_2 (10 mL) and solutions were poured into the Petri dishes. After evaporation of the solvent, the samples were irradiated in a Luzchem reactor at 300 nm over 3 days. After irradiation, samples were analyzed by ^{1}H NMR.

(B) Adamantane phthalimides **1**–**6** (100 mg) were dissolved in CH_2Cl_2 (10 mL). The solutions were spread on the walls of quartz cuvettes (20 mL) to form thin films upon evaporation of the solvent. The quartz cuvettes with the film of the phthalimides were filled with N_2 and irradiated in a Rayonet reactor over 3 days. After irradiation, the samples were analyzed by HPLC and ^{1}H NMR.

(C) Adamantane phthalimides **1**–**6** (100 mg, crystals grown from CH_2Cl_2) were ground with a mortar and pestle and suspended in 150 mL H_2O to which sodium dodecyl sulfate (100 mg) was added. The suspension was irradiated over 24 h. The irradiated mixture was continuously stirred and purged with N_2 to maintain the suspension. After the irradiation, the precipitate was separated from the solution by centrifugation, dissolved in CH_2Cl_2 and dried over anhydrous $MgSO_4$. After filtration, solvent was evaporated on a rotary evaporator to afford crude mixture, which was analyzed by ^{1}H NMR and HPLC.

2-*endo*-Hydroxy-10-aza-hexacyclo[9.5.1.1^{12,14}.1^{16,18}.0^{2,10}.0^{3,8}]-nonadeca-3,5,7-triene-9-one (**13**). Yield 10 mg (10%). Colourless crystals; mp 156–168 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ/ppm: 7.74 (dd, 1H, J=7.6, 0.8 Hz, H-a), 7.62 (ddd, 1H, J=7.4, 7.6, 1.0 Hz, H-c), 7.55 (d, 1H, J=7.6 Hz, H-d), 7.47 (ddd, 1H, J=7.4, 7.6, 0.9 Hz, H-b), 4.20 (t, 1H, J=4.9 Hz, H-2), 2.80 (m, 1H, H-9), 2.69 (br s, 1H, OH), 2.60 (t, 1H, J=3.9 Hz, H-4), 2.32 (br s, 1H, H-5), 2.26 (br s, 1H, H-1), 1.99 (ddd, 1H, J=12.7, 5.7, 3.3 Hz, H-6), 1.93 (ddd, 1H, J=12.9, 6.2, 3.3 Hz, H-8), 1.89 (br s, 1H, H-7), 1.80 (d, J=12.7 Hz, H-6), 1.75–1.68 (m, 3H, H-8/10), 1.61–1.59 (m, 2H, H-9/3); ^{13}C NMR ($CDCl_3$, 150 MHz) δ/ppm: 179.2 (C-2′), 151.2 (C-3′), 133.7 (C-a), 132.7 (C-4′), 129.6 (C-a), 123.9 (C-c), 122.4 (C-b), 98.6 (C-5′), 67.3 (C-2), 46.5 (C-4), 38.9 (C-3), 36.1 (C-6), 35.3 (C-8), 34.6 (C-9), 32.7 (C-10), 32.1 (C-1), 28.5 (C-5), 25.3 (d, C-7); IR (KBr) ν_{max}/cm^{-1}: 3408, 2911, 1697.

4.4. Photochemistry of *N*-(2-adamantyl)phthalimide (4) in solution

N-(2-Adamantyl)phthalimide (**5**, 610 mg, 2.17 mmol) in 1 L of CH_3CN (c=2.17×10^{-3} M) was irradiated over 16 h at 300 nm. During irradiation, solution was continuously purged with N_2 and cooled by H_2O. After photolysis, solvent was removed on a rotary evaporator, and the residue chromatographed on a column filled with silica gel using CH_2Cl_2/CH_3OH (up to 10%) as eluent. In the first fraction 496 mg (81%) of the starting phthalimide **5** was isolated, followed by a mixture (114 mg) of the photochemical products, which were separated by repeated chromatography on a thin layer of silica gel using CH_2Cl_2/CH_3OH (2%) and CH_2Cl_2/Et_2O (20%) as eluent.

2-*endo*-Hydroxy-10-aza-hexacyclo[9.5.1.1^{12,14}.1^{16,18}.0^{2,10}.0^{3,8}]-nonadeca-3,5,7-triene-9-one (**13**). Yield 27 mg (4.4%).

2-*exo*-Hydroxy-10-aza-hexacyclo[9.5.1.1^{12,14}.1^{16,18}.0^{2,10}.0^{3,8}]nonadeca-3,5,7-triene-9-one (**14**). Yield 63 mg (10.5%). Colourless crystals; mp 202–205 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ/ppm: 7.69 (d, 1H, J=7.5 Hz, H-a), 7.56 (ddd, 1H, J=7.5, 7.3, 0.9 Hz, H-c), 7.49 (d, 1H, J=7.5 Hz, H-d), 7.45 (ddd, 1H, J=7.5, 7.3, 0.9 Hz, H-b), 4.04 (t, 1H, J=4.8 Hz, H-2), 3.41 (br s, 1H, OH), 3.14 (br s, 1H, H-3), 1.99 (ddd, 1H, J=13.2, 5.7, 2.7 Hz, H-10), 1.95 (ddd, 1H, J=13.2, 5.7, 2.7 Hz, H-10), 1.90 (br s, 1H, H-7), 1.78 (ddd, 1H, J=9.3, 6.2, 3.1 Hz, H-9), 1.72 (m, 1H, H-6), 1.63–1.67 (m, 2H, H-5, H-9), 1.04 (ddd, J=14.0, 3.8, 2.0 Hz, H-8), 1.00 (d, 1H, J=14.0 Hz, H-8); ^{13}C NMR ($CDCl_3$, 150 MHz) δ/ppm: 171.4 (C-2′), 146.1 (C-3′), 134.7 (C-4′), 132.7 (C-a), 129.4 (C-d), 124.1 (C-c), 123.0 (C-b), 98.4 (C-5′), 59.7 (C-2), 47.2 (C-4), 38.9 (C-3), 36.6 (C-6), 34.0 (C-9), 32.8 (C-10), 31.5 (C-8), 29.1 (C-1), 27.3 (C-5), 25.6 (C-7); IR (KBr) ν_{max}/cm^{-1}: 3287, 2915, 1661; MS (EI) m/z 282 (20, M$^+$), 281 (100, M$^+$), 148 (15), 134 (15), 105 (15), 92 (15); HRMS calculated for $C_{18}H_{19}NO_2$ 281.1416; observed 281.142.

10-Azapentacyclo[10.3.3.1^{14,16}.0^{1,11}.0^{3,8}]nonadeca-3,5,7-triene-2,9-dione (**15**). Yield 16 mg (2.7%). Colourless crystals; mp 260–262 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ/ppm: 7.91 (dd, 1H, J=7.6, 1.2 Hz, H-a), 7.63 (dt, 1H, J=7.5, 1.4 Hz, H-c), 7.58 (dt, 1H, J=7.5, 1.4 Hz, H-b), 7.48 (dd, 1H, J=7.6, 1.3 Hz, H-d), 6.55 (br s, 1H, NH), 3.88 (br s, 1H, H-2), 2.21 (ddd, 1H, J=13.2, 4.5, 2.4 Hz, H-8), 2.12–2.09 (m, 2H, H-3, H-5), 2.06 (ddd, 1H, J=13.3, 4.7, 2.5 Hz, H-8), 2.00 (br s, 1H, H-7), 1.90–1.82 (m, 4H, H-4, H-6, H-9, H-10), 1.80–1.76 (m, 1H, H-9), 1.73 (ddd, 1H J=13.3, 4.8, 2,3 Hz, H-10), 1.70–1.67 (m, 2H, H-4, H-6); ^{13}C NMR ($CDCl_3$, 150 MHz) δ/ppm: 208.4 (C-5′), 170.0 (C-2′), 137.0 (C-3′, C-4′), 131.8 (C-a, C-d), 129.2 (C-c), 128.2 (C-b), 56.6 (C-2), 53.2 (C-1), 39.3 (C-6), 36.4 (C-4/9), 36.2 (C-4/9), 31.2 (C-3), 31.1 (C-8/10), 30.6 (C-8/10), 26.85 (C-5/7), 26.72 (C-5/7); IR (KBr) ν_{max}/cm^{-1}: 3181, 3069, 2913, 1687, 1659; MS (EI) m/z 282 (10, M$^+$), 281 (70, M$^+$), 253 (30), 134 (100), 92 (45); HRMS calculated for $C_{18}H_{19}NO_2$ 281.1416; observed 281.142.

4.5. Crystallography

The single crystals of phthalimides **2**–**6** and **13**–**15** were obtained by slow evaporation of the solvent. Data collections were performed on a Nonius Kappa-CCD-diffractometer, using a graphite monochromated Mo Kα (0.71073 Å) radiation and the Software COLLECT.[24] Datareduction was preformed with Denzo.[25] The structures were solved with SHELXS97 and refined with SHELXL97.[26] The models were refined using the full matrix least squares refinement. Hydrogen atoms were located from difference Fourier maps and refined as free entities for **2**, **4**, **5**, **6**, **14**, **15** or riding entities for **3** and **13**. The atomic scattering factors were those included in SHELXL97. Molecular geometry calculations were performed with PLATON,[27] and molecular graphics were prepared using PLATON, SCHAKAL99[28] and CCDC-Mercury.[29] Crystallographic and refinement data for structures are shown in Supplementary data.

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Supplementary data

^{1}H NMR and ^{13}C NMR spectra and *ORTEP* drawings for **2**–**6** and **13**–**15**, as well as crystallographic and refinement data for structures. Supplementary crystallographic data for this paper can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033; or deposit@ccdc.cam.ac.uk). CCDC: 699053, 699054, 699055, 699056, 699057, 699058, 699059, and 699060 contain the supplementary crystallographic data for this paper. Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.12.010.

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