A “waiting” carbon nitride radical anion: a charge storage material and key intermediate in direct C–H thiolation of methylenes using elemental sulfur as the “S”-source†

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Potassium poly(heptazine imide), a carbon nitride based semiconductor with high structural order and a valence band potential of +2.2 V vs. NHE, in the presence of hole scavengers and under visible light irradiation gives the corresponding polymeric radical anion, in which the specific density of unpaired electrons reaches 112 μmol g⁻¹. The obtained polymeric radical anion is stable under anaerobic conditions for several hours. It was characterized using UV-vis absorption, time resolved and steady state photoluminescence spectra. The electronic structure of the polymeric radical anion was confirmed by DFT cluster modelling. The unique properties of potassium poly(heptazine imide) for storing charges were employed in visible light photocatalysis. A series of substituted dibenzylidisulfanes was synthesized in 41–67% yield from the corresponding methylenes via cleavage of the methyl C–H bond under visible light irradiation and metal-free conditions.

Introduction

C–H functionalization of hydrocarbons mediated by heterogeneous visible light photocatalysts is highly attractive for sustainable chemistry.¹ This strategy can afford high value-added chemicals from inexpensive reagents, minimize the number of steps and hence auxiliary chemicals, reduce the number of by-products and could potentially use only sunlight as the energy source, while the photocatalyst can be easily separated from the solution and used again.² Numerous examples of heterogeneous photocatalysts and photocatalytic reactions have been reported in the literature – the hydrogen evolution reaction³⁴ and overall water splitting,³⁵ and styrene production, just to name a few.⁶ Due to their chemical inertness, arising from very high C–H bond energies and ionization potentials, selective functionalization of hydrocarbons is quite challenging.⁷ The literature, describing C–H functionalization of hydrocarbons mediated by heterogeneous photocatalysts, is mostly represented by synthesis of aldehydes, ketones and carboxylic acids, since O₂ in all these cases is used as an electron scavenger and hydrogen oxidation as the thermodynamic driving force.¹⁰–¹³

In order to transcend the borders of heterogeneous photocatalysis applied to organic synthesis and to broaden the spectrum of products, semiconductors with high oxidation power of photogenerated holes may be envisioned for use. According to this strategy, a potent thermodynamic driving force for substrate oxidation is created, eliminating the need for O₂, while mild electron acceptors can then be used to remove the electron from the conduction band (CB) and close the photocatalytic cycle.

In this regard, potassium poly(heptazine imide), K-PHI hereafter (Fig. 1a),¹⁴ a carbon nitride based material, is a promising candidate to assay this strategy.¹⁵–¹⁷ The band structure of K-PHI is schematically shown in Fig. 1d. Due to the highly positive valence band (VB) potential, +2.22 V vs. NHE, photogenerated holes are effective oxidants for application in organic synthesis. For example, K-PHI was successfully used in the oxidation of alcohols to aldehydes and 1,4-dihydropyridines to pyridines,¹⁸ in the synthesis of 1,3,4-oxadiazoles by oxidative cyclization of N-acylhydrazones,¹⁹ in thioamide synthesis by photocatalytic Kindler reaction,²⁰ and in oxygen and hydrogen evolution reactions.²¹

On the other hand, the CB in K-PHI is located at −0.5 V vs. NHE, which is significantly lower compared, for example, to that of graphitic carbon nitride (g-CN), −1.29 V vs. NHE. Therefore, it is reasonable to assume that the K-PHI radical anion, hereafter denoted as K-PHI⁻, formed from K-PHI upon its single electron...
reduction, would be stable and have a lifetime above the μs–s timescale (Fig. 2). The viability of this idea was recently proved by Lotsch et al. who have reported radical carbon nitride species with a lifetime exceeding hours, while the material was applied in the hydrogen evolution reaction and a sunlight harvesting device.23,24
In view of hydrocarbon C–H bond activation, the long living K-PHI might be a key intermediate permitting employment of reagents different from the abovementioned O₂. The mechanism describing this approach is summarized in Fig. 2.

In the present work, we have shown that K-PHI in the presence of hole scavengers, even those as weak as toluene, when triggered by visible light, acts as a capacious electron buffer and forms a stable radical anion under air-free conditions. This feature was applied in visible light photocatalytic activation of the C–H bond of hydrocarbons – we have developed a simple and convenient method to synthesize dibenzyl disulfanes from inexpensive methylenes and S₂ under visible light irradiation using K-PHI as a heterogeneous photocatalyst under metal-free conditions.

Results and discussion

K-PHI was prepared according to a procedure reported by us earlier. The powder X-ray (PXRD) pattern shows diffraction peaks typical of this material. Among them, the intense peak at ~27° is due to stacking of layers similar to g-CN, and the peaks at 8.1°, 14.2°, 21.8°, 36.0° and 43.9° are related to an ordered in-layer arrangement (Fig. 1b). The high resolution TEM image reveals the crystalline structure of the synthesized K-PHI with interlayer distances of 0.33 nm and an in-plane periodicity of 1.1 nm (Fig. 1c). The X-ray photoelectron, ultraviolet photoelectron, diffuse reflectance UV-vis absorption, photoluminescence, and Fourier-transform infrared (FT-IR) spectra, N₂ absorption isotherm and SEM image of K-PHI are given in the ESI (Fig. S1) and they are consistent with those reported previously.

In order to check the possibility of using K-PHI as an electron buffer and subsequently applying it in photocatalytic hydrocarbon functionalization, we performed the following experiment. A mixture of K-PHI and p-methylanisole (holes scavenger) in acetonitrile was mixed, degassed and kept under a N₂ atmosphere throughout the course of the experiment (Fig. 1e). The suspension was irradiated with a 461 nm LED. After irradiation was stopped, we noticed that the suspended particles of K-PHI had changed colour from orange to “avocado green” (Fig. 1f). The colour change was taken as the first piece of evidence of K-PHI radical anion formation, hereafter denoted as K-PHI⁻. Upon addition of excess dimethylviologen dichloride dihydrate (MV²⁺), yellow K-PHI immediately precipitated, while the solution changed its colour to intense blue, which is due to MV²⁺ single electron reduction to its radical cation (MV³⁺) (Fig. 1g). Measuring the absorbance of the solution at λ = 606 nm (Fig. 1j) and taking into account the extinction coefficient of MV³⁺ in acetonitrile of ε = 13 900, the specific number of electrons stored by the polymeric K-PHI was calculated to be 112 μmol per gram of the material. In the control experiment, when MV²⁺ and K-PHI were mixed together prior to irradiation, no MV³⁺ was formed. However, MV²⁺ was converted into MV³⁺ upon subsequent light irradiation. This implies that energy input is essential to enabling electron flux. Note that the capacity of the covalent g-CN in the same experiment was orders of magnitude lower.

The optical properties of the suspended K-PHI⁻ (Fig. 1f) were investigated. The UV-vis absorption spectrum (Fig. 1h) shows a broad absorption band in the 600–750 nm range, which is in agreement with the observed green colour. The photoluminescence (PL) lifetime of K-PHI⁻ is 0.35 ns versus 0.66 ns for K-PHI (Fig. 1i). The room temperature steady-state PL spectrum of the K-PHI⁻ suspension is significantly lower compared to that of K-PHI in the ground state, while the maximum is shifted to a shorter wavelength (555 nm). This observation supports that p-methylanisole indeed acts as a hole scavenger – it depopulates the number of holes and hence reduces PL.

We observed a colour change of the suspension from green back to yellow when the suspension was exposed to S₈ or O₂ implying that these molecules can be used in combination with K-PHI in the subsequent functionalization of hydrocarbons (shown below).

In order to characterize theoretically the electronic structure of K-PHI, we conducted a density functional theory (DFT) study on a model K-PHI cluster containing 6 heptazine units and 2 potassium ions. Its geometry was optimized using several pure (PBE and BLYP) and hybrid (PBE0, B3LYP, and BHHLYP) generalized gradient approximation (GGA) functionals (see the Experimental section and ESI† for details).

To a first approximation the energies of the highest occupied (HOMO) and lowest unoccupied (LUMO) molecular orbitals of the model cluster can be compared with the edge energies of K-PHI valence and conduction bands respectively. These orbitals are of π-type and are located mainly on the nitrogen atoms of the poly(heptazine imide) matrix (Fig. 3). Among the functionals used, B3LYP gave the best agreement with the optical band gap determined experimentally, 3.02 eV vs. 2.72 eV (Table 1). On the other hand, PBE0 revealed that the HOMO of the K-PHI cluster is located at +2.08 eV, which is comparable with the valence band position, +2.22 eV, determined by adding the optical band gap value, 2.72 eV (Fig. S1ef), to the conduction band value, −0.5 eV. Moreover, this valence band position agrees well with the VBM, +2.40 eV, determined directly using ultraviolet photoelectron spectroscopy (UPS) (Fig. S1d). Since the HOMO position is slightly more positive than the oxidation potential of toluene (or even more positive than that of p-
methylarenes was converted into the corresponding disulfanes (Fig. 4). Dibenzyl disulfane 1a was obtained in 56% isolated yield, while p-methoxysubstituted disulfane 1b was obtained with even higher, 67%, yield. Interestingly, that steric effect is negligible and 1,2-bis(2-methoxybenzyl)disulfane 1c was isolated with 63% yield. Ethylbenzene was exclusively oxidized at the α-position of the alkyl chain furnishing disulfane 1d. This result again supports the idea that upon oxidation of alkylarene by K-PHI, first reactive species of benzyl-type is formed, which subsequently reacts with sulfur. Disulfane 1d was isolated as a 1 : 1 mixture of its diastereomers as proven by $^{13}$C NMR, FT-IR and mass spectra were identical to those of the reference (Fig. S2†).

The developed photocatalytic system is indeed versatile and tolerant to different functional groups. A series of substituted methylarenes was converted into the corresponding disulfanes (Fig. 4). Dibenzyl disulfane 1a was obtained in 56% isolated yield, while p-methoxysubstituted disulfane 1b was obtained with even higher, 67%, yield. Interestingly, that steric effect is negligible and 1,2-bis(2-methoxybenzyl)disulfane 1c was isolated with 63% yield. Ethylbenzene was exclusively oxidized at the α-position of the alkyl chain furnishing disulfane 1d. This result again supports the idea that upon oxidation of alkylarene by K-PHI, first reactive species of benzyl-type is formed, which subsequently reacts with sulfur. Disulfane 1d was isolated as a 1 : 1 mixture of its diastereomers as proven by $^{13}$C NMR, FT-IR and mass spectra were identical to those of the reference (Fig. S2†).

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light (Fig. 5a), as this wavelength matches the K-PHI optical band gap, 2.72 eV. UV light (350 nm) gave disulfane with a slightly lower yield, which could be rationalized by consecutive S–S bond cleavage under the highly energetic UV radiation. On the other hand, under green light (522 nm) almost no disulfane was generated. The apparent quantum yield (AQY) of \( p \)-methylanisole photooxidation at 461 nm was calculated to be 0.23 ± 0.02% [Fig. 5a]. Our calculations are based on the photon flux measured using an optical power meter equipped with an integrating sphere, taking into account that every polysulfane molecule requires oxidation of two \( p \)-methylanisole molecules. It indicates that C–H bond oxidation at close to room temperature is a difficult process especially in the absence of any metal co-catalysts, but still possible due to K-PHI.

All this behavior indicates that, in contrast to photochemical water splitting with g-CN, this time the reduction process is the slow, rate determining step, as there is obviously no straight chemical reaction channel for the sulfur to quickly take up the photogenerated electron to restore the ground state of the photocatalyst.

The Hammett plot (Fig. 5b) supports that the reaction is sensitive to electronic effects. The \( \rho \)-constant is −0.75, suggesting that the rate limiting step involves positively charged species – the radical cation of benzyl type.

In the reaction mixture we detected intermediate polysulfanes, namely 1,4-bis(4-methoxybenzyl)tetrasulfane and 1,3-bis(4-methoxybenzyl)trisulfane, when oxidation of \( p \)-methylanisole was studied. Given that the chemical shift of the methylene groups depends on the number of sulfur atoms between the benzyl fragments, the peak at 4.13 ppm was assigned to the \( \text{CH}_2 \) group of 1,3-bis(4-methoxybenzyl)trisulfane while the one at 4.01 ppm to the \( \text{CH}_2 \) group of 1,2-bis(4-methoxybenzyl)disulfane (Fig. 5c). The designed photocatalytic system can also produce polysulfides with up to 5 sulfur atoms when excess sulfur was used (Fig. S3†).

The time dependent composition of the reaction mixture is shown in Fig. 5d. Already after 86 min, 50% of sulfur was consumed. However, the yield of disulfane was only 30% of the theoretical value, suggesting that at the beginning of the reaction sulfur is rapidly converted into polysulfides and stored in the form of bis(4-methoxybenzyl)polysulfanes. Nevertheless, the intermediate tetra- and trisulfides were completely converted into 1,2-bis(4-methoxybenzyl)disulfane after ca. 27 h of irradiation, implying that disulfane is the most stable under the given photocatalytic conditions. The amount of target disulfane asymptotically approaches the theoretical value, expected for the given amount of sulfur, and after 44 h 93% of the maximum possible quantity was obtained, proving that the stoichiometric ratios between reagents and products are indeed as described in Fig. 4.

Summarizing all the abovementioned observations, the tentative mechanism of methylarene photocatalytic oxidative thiolation is shown in Fig. 6. Visible light excites K-PHI giving rise to K-PHI* species with a bound electron–hole exciton pair. At this point two pathways, oxidative and reductive quenching of K-PHI*, are in principle possible.39 However, the reaction proceeds predominantly via the oxidation of methylarene (ArMe) to the corresponding radical cation (ArMe.*) which occurs relatively fast. The leftover K-PHI − is oxidized by \( S_8 \) back to the initial K-PHI, closing the photocatalytic cycle, while sulfur is then converted into \( S_{6}^{-} \) (structure a on Fig. 6). We are aware that in solution sulfur can form polysulfides of different lengths as well as cyclic molecules,38,39 but for clarity of presentation we assume that linear \( S_n^{-} \) is the only product of sulfur reduction. Due to the positive charge, ArMe* is a much stronger acid (\( pK_a = -13 \)) than K-PHI (\( pK_a = 40 \)) compared to the neutral ArMe (\( pK_a = 54 \)).

On the other hand, \( S_n^{-} \), similar to the well-studied trisulfur radical anion \( S_3^{-} \),41 is basic and therefore abstracts a proton
from ArMe⁺. This transfer produces HS₆⁻ and ArCH₂⁺ respectively. The formation of ArCH₂⁺ was proven indirectly – we observed 1,2-diphenylethane as a major product when toluene was used both as a reagent and a solvent (Table S1,† entries 2 and 9). In this case, the concentration of ArCH₂⁺ radicals becomes high enough to favour their recombination. In acetonitrile, in the next step a C–S bond is created by recombination between the HS₆⁻ and ArCH₂⁺ radicals. A transition of hydro polysulfides to disulfides requires evolution of H₂S and extrusion of extra sulfur atoms, which in turn participate in subsequent reactions with ArMe. Apparently, K-PHI is also involved in all these steps, i.e. the polysulfides obviously react similarly to the original sulfur reactant. H₂S was detected as Ag₂S, when the reaction mixture headspace was allowed to react with AgNO₃ (Fig. S4†). Also traces of intermediate RCH₂SH were detected by GC-MS of the reaction mixture additionally supporting the mechanism (mass spectra, Fig. S5†). Finally, the structure of K-PHI remains unaffected as proved by the identical nature of its PXRD patterns and FT-IR spectra before and after the photocatalytic experiment (Fig. S6†).

Conclusions

Potassium poly(heptazine imide) enables the photoredox thiolation of methylenes with elemental sulfur. This reaction takes place under very mild conditions and blue light irradiation. The reaction proceeds via formation of polysulfides as intermediates, which potentially could also be isolated, if reaction is terminated at the appropriate time. The discovered photocatalytic conversion of methylenes into disulfides clearly reflects the high oxidation power of K-PHI that activates the methyl C–H bond toward subsequent reaction with sulfur species. Mechanistic studies suggest that the reaction proceeds first via methylene oxidation by the photogenerated hole of K-PHI*, leaving a K-PHI⁻ radical anion. We isolated this long living K-PHI⁻ radical anion and characterized it spectroscopically. The exceptionally long lifetime of the K-PHI⁻ radical anion arises from its high stability under air-free conditions, as plausibilized by model calculations revealing a narrow band of delocalized states for the extra electron. All of this makes K-PHI a promising photo-responsive material for energy storage applications. The newly disclosed reaction is convenient for the generation of a number of technically very useful disulfanes, as they, for instance, are used for rubber processing, surface modifications, or click chemical modifications of (bio)polymers. We expect the reaction to be more general and applicable to the oxidative modification of all C–H positions where the cation radical is resonance stabilized.

Experimental section

³H and ¹³C NMR spectra were recorded on an Agilent 400 MHz spectrometer using the signal of TMS (0 ppm) as a reference. ¹³C APT experiments were conducted to distinguish between C, CH₂ and CH, CH₃ carbon atoms. An Agilent 6890 Network GC System coupled with an Agilent 5975 Inert Mass Selective detector (electron ionization) was used for reaction mixture composition analysis and to obtain mass spectra of the products. Irradiance of the LED module was measured using a PM400 Optical Power and Energy Meter equipped with integrating sphere S142C.

Synthetic procedures

tert-Butyl p-tolylcarbamate was prepared according to a literature procedure. Mesoporous graphitic carbon nitride (mpg-CN) was prepared according to a literature procedure.

K-PHI was prepared according to a literature procedure. A mixture of 5-aminozotrazole (0.99 g) and LiCl/KCl eutectics (4.97 g) was introduced into a steel ball mill cup. The steel ball was placed and the cup was closed. The mixture of precursors was ground for 5 min at a shaking rate of 25 s⁻¹. The resultant flour-like white powder was transferred into a porcelain crucible, covered with a porcelain lid and placed into an oven. The temperature inside the oven was increased from 20 °C to 600 °C within 4 hours under a flow of nitrogen (15 L min⁻¹) after which it was maintained at 600 °C for another 4 hours. The oven was allowed to cool to room temperature. The melt from the crucible was transferred into a beaker; deionized water (50 mL) and a stir bar were placed into the beaker. The suspension was kept stirring at room temperature for 4 hours until the suspension became fully homogeneous and no agglomerated particles were seen. The solid was separated by centrifugation (6500 min⁻¹, 12 min), washed with water (3 × 2 mL) using a centrifuge to separate particles of the material (13 500 min⁻¹, 1 min) and dried in a vacuum giving 256 mg of the dark-yellow material.

A general procedure of methylarene oxidative thiolation. A screw-capped tube was charged with K-PHI (10 mg), methylarene (0.3 mL), elemental sulfur (0.96 mg, 30 μmol of S atoms) and acetonitrile (2.7 mL). A Teflon coated stir bar was added as well. The suspension was frozen in liquid nitrogen to the solid state and evacuated until a residual pressure of 0.1 mbar was reached. The solid was warmed using a heating gun until the solid melted. The procedure was repeated 3 times and the tube was finally refilled with argon. The suspension was vigorously stirred at +50 °C under blue LED (461 nm, 0.0517 ± 3 × 10⁻⁵ W cm⁻²) irradiation for 24 hours. The reaction mixture was allowed to cool to room temperature and the tube was opened in a fume hood. Attention! Evolution of H₂S! The catalyst was separated by centrifugation (13 000 min⁻¹) and washed with acetonitrile (3 × 1.5 mL). The washings were combined and acetonitrile was evaporated under reduced pressure (+50 °C, 80 mbar). The residue was washed with chloroform (3 × 2 mL) and undissolved particles were separated by centrifugation (13 000 min⁻¹). The evaporation of chloroform under reduced pressure furnished the corresponding disulfane.

1,2-Dibenzyldisulfane. Yield: 56%. The ¹H and ¹³C NMR, and FT-IR spectra were identical to those of the authentic sample purchased from Acros Organics (Fig. S2†). ¹H NMR (400 MHz, CDCl₃): δ = 3.60 (s, 4H, CH₂), 7.23–7.34 (m, 10H, CH). ¹³C NMR (400 MHz, CDCl₃): δ = 43.2 (s, CH₂), 127.4 (s, CH), 129.4 (s, CH), 137.3 (s, CH). MS (EI): 246.1 (M⁺).

1,2-Bis[4-methoxybenzyl]disulfane. Yield: 67%. ¹H NMR (400 MHz, CDCl₃): δ = 3.59 (s, 4H, CH₂), 3.80 (s, 6H, OCH₃), 6.85 (d, JHH = 8.8 Hz, CH, 4H), 7.17 (JHH = 8.8 Hz, CH, 4H). ¹³C NMR (400 MHz, CDCl₃): δ = 43.2 (s, CH₂), 127.4 (s, CH), 129.4 (s, CH), 137.3 (s, CH). MS (EI): 340 (M⁺).
MHz, CDCl₃): δ = 42.7 (s, CH₃), 55.3 (s, OCH₃), 113.9 (s, CH), 129.4 (s, C), 130.0 (s, C), 130.5 (s, CH). MS (EI): 306.1 (M⁺).

1,2-Bis(2-methoxybenzyl)disulfane. Yield: 63%. ¹H NMR (400 MHz, CDCl₃): δ = 3.76 (s, 4H, CH₂), 3.86 (s, 6H, OCH₃), 5.85–6.92 (m, 4H, CH), 7.16 (ddd, JHH = 7.2 Hz, JHH = 1.6 Hz, 2H, CH), 7.25 (dd, JHH = 1.6 Hz, JHH = 8.0 Hz, 4H, CH). ¹³C NMR (400 MHz, CDCl₃): δ = 20.4 (s, CH₃), 55.5 (s, OCH₃), 110.6 (s, CH), 120.2 (s, CH), 125.8 (s, C), 128.8 (s, CH), 131.0 (s, CH), 157.4 (s, C). MS (EI): 306.1 (M⁺).

1,2-Bis(1-phenylethyl)disulfane. Yield: 47%. A mixture of diastereomers. ¹H NMR (400 MHz, CDCl₃): δ = 1.54 (d, JHH = 7.0 Hz, 3H, CH₃), 1.55 (d, JHH = 7.0 Hz, 3H, CH₃), 3.52 (q, JHH = 7.0 Hz, 1H, CH), 7.21–7.34 (m, 10H, CH). ¹³C NMR (400 MHz, CDCl₃): δ = 20.5 (s, CH₃), 49.4 (s, CH), 49.5 (s, CH), 127.4 (s, CH), 127.5 (s, CH), 127.7 (s, CH), 127.8 (s, CH), 128.3 (s, CH), 128.4 (s, CH), 142.4 (s, C), 142.4 (s, C), 157.4 (s, C). MS (EI): 274.1 (M⁺).

1,2-Bis(4-fluorobenzyl)disulfane. Yield: 41%. ¹H NMR (400 MHz, CDCl₃): δ = 3.58 (s, 4H, CH₂), 7.01 (ddd, JHH = 8.6 Hz, JHH = 8.6 Hz, 4H, CH). ¹³C NMR (400 MHz, CDCl₃): δ = 42.4 (s, CH₂), 115.4 (d, JCF = 21.5 Hz, CH), 130.9 (d, JCF = 8.1 Hz, CH), 133.1 (s, CH), 162.2 (d, JCF = 246.4 Hz, CF).

Di-tert-butyl(disulfanediylbis(methylene))bis(4,1-phenylene)dicarbamate. Yield: 51%. ¹H NMR (400 MHz, CDCl₃): δ = 1.51 (s, 18H, CH₂), 3.58 (s, 4H, CH₂), 6.46 (br. s., 2H, NH), 7.15 (d, JHH = 8.0 Hz, 4H, CH), 7.31 (d, JHH = 8.0 Hz, 4H, CH). ¹³C NMR (400 MHz, CDCl₃): δ = 28.3 (s, CH₂), 42.8 (s, CH₂), 118.4 (s, CH), 130.0 (s, CH), 131.8 (s, C), 137.6 (s, C), 152.6 (s, C).

DFT calculations

The calculations were carried out using the GAMESS (US) program package,⁴⁴ their results were visualized with the MacMolPlt graphical interface.⁴⁵ The poly(heptazine imide) matrix was modelled by a cluster comprising 6 heptazine units linked by 4 =NH groups and 2 N atoms. Two K⁺ cations were added to neutralize the negative charge of the matrix, which originated from the deprotonated imide nitrogen atoms. To reduce computational cost, the symmetry of the model cluster was set from the deprotonated imide nitrogen atoms. To reduce computational cost, the symmetry of the model cluster was set to the C₂ᵥ group. The basis was a Dunning–Hay double zeta set with one p-type polarization function on hydrogen atoms and one d-type function on other atoms. For the nitrogen atoms the basis set was additionally extended by a diffuse spher-shell. The geometry of K-PHI was optimized using 2 pure GGA functionals (PBE and BLYP) and 3 hybrids with different amounts of Hartree–Fock exchange (25% for PBE0, 20% for B3LYP and 50% for BHHLYP). The spatial distribution of the frontier orbitals in the cluster was found to be independent of the functional. On the other hand, the increase of the Hartree–Fock exchange percentage in the GGA < B3LYP < PBE0 < BHHLYP series increases the HOMO–LUMO gap by lowering the HOMO and raising the LUMO energies (see Table 1).

Conflicts of interest

There are no conflicts to declare.

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Notes and references

† Due to the M⁺ effect of the methoxy group, the oxidation potential of p-methylanisole is expected to be lower than that of toluene, 2.26 ± 0.02 V vs. SCE.⁴⁸ Alcohols, commonly used holes scavengers, cannot be applied in this case as they were reported to react with MV⁴⁹.