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Sensitive and Selective Photoinduced-Electron-Transfer-Based Sensing of Alkylating Agents

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In memory of Bernard Dietrich

Abstract: Photoinduced-electron-transfer (PET)-based chemosensing is a very elegant way of reporting the presence of a guest species in solution. This method was successfully applied for the detection of different ionic species, such as cations, anions, and protons. Herein, we report on the application of the PET chemosensing concept for the efficient and selective detection of different alkylating agents. 2-(2-Dimethylaminoethyl)benzo[*de*]isoquinoline-1,3-dione (**1**) was found to be a highly selective and effective PET chemosensor that turns luminescent upon reacting with different alkylating agents. This PET-based system detected even rather weak alkylating agents, such as dichloromethane. A PET-based sensor that consists of **1** as the active component could detect rather low concentrations of alkylating agents in solution and in the gas phase.

Keywords: alkylation · electron transfer · hydrogen bonds · luminescence · sensors

Introduction

Alkylating agents, such as dimethyl sulfate[1] and alkyl halides,[2,3] are commonly used in organic synthesis[2,4] and are widely used in large-scale industrial synthesis.[5] Similar alkylating agents are also used as soil sterilizers,[6] anticancer drugs,[7] and unfortunately also as warfare agents.[8]

Many of these materials, especially the methylating agents,[9] are toxic and/or mutagenic owing to their ability to react with many nucleophilic species in the body.[10] It has been established that such alkylating materials alkylate nucleobases, introducing defects into the genetic code.[11] This process is associated with mutagenesis and carcinogenesis.[12] Considering the wide use and high toxicity of alkylating agents the need for improved, simple, sensitive, and selective methods for their detection in solution and in the gas phase becomes apparent.

Previous attempts made by different groups to develop efficient sensing tools for alkylating agents have focused mainly on colorimetric systems that change their color either upon reaction with an alkylating agent[13] or in a two-step reaction, in which the sensing molecule reacts with the alkylating agent and the adduct further reacts with a third component.[14] Some of these systems are both specific and rather sensitive, compared to colorimetric detection methods. Nevertheless, owing to the inherent advantages of luminescence-based sensing, it is clear that systems that rely on a switching-on of the luminescence upon reaction with an alkylating agent should display improved sensing properties. Photoinduced electron-transfer (PET) signaling of a recognition process is a very elegant method that was developed for reporting the presence of metal cations and protons.[15,16] This approach was first proposed by Weller[17] and later perfected by De Silva et al.[15] and other groups.[16] PET-based sensing has been successfully applied for the detection of different metal ions,[18] protons,[19] and more recently anions,[20] mostly in solution.

PET-based chemosensors consist of a luminescent species that is attached to a recognition group, Scheme 1. In the un-

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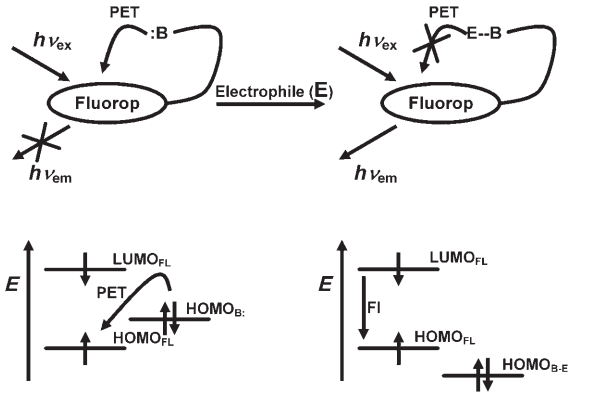
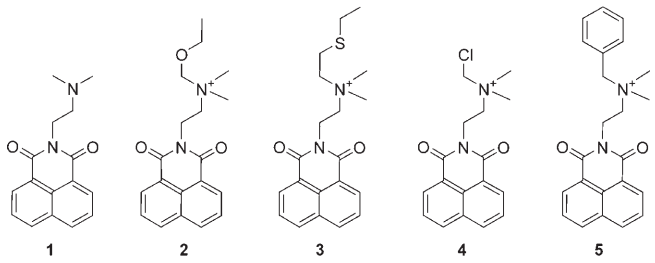


Scheme 1. A schematic presentation of the PET-based sensing approach and its respective generalized energy diagram.

bound dark state, the binding moiety of the recognition group serves as a quencher for the excited state of the luminescent part. This process relies on the fact that binding of protons and metal ions is usually achieved by using Lewis bases that possess lone-pair electrons. These lone-pair electrons serve as efficient quenchers for the excited state.[15a] Upon binding of a metal ion or a proton, the lone-pair electrons of the binding moiety become engaged in the newly formed bond and are dramatically stabilized. Consequently, these electrons can no longer serve as quenchers for the luminescent part of the molecule. Therefore, in the complex form, the luminescence is regained, thus signaling the capture of a guest. The use of such an approach to signal the capture of an alkylating agent should also be possible, provided that the atom that bears the lone-pair electrons of the recognition group also acts as an efficient nucleophile.

Herein, we report on the application of the PET chemosensing method for the efficient and selective detection of alkylating agents both in solution and in the gas phase. 2-(2-Dimethylaminoethyl)benzo[*de*]isoquinoline-1,3-dione (**1**) is



found to be a highly selective and effective PET chemosensor that turns fluorescent upon reaction with different alkylating agents. PET-based sensing of alkylating agents may be performed either in solution or in the solid state and is capable of detecting even rather weak alkylating agents such as dichloromethane. A combined experimental–computational approach has been applied to rationalize the results.

Experimental Section

Materials: Compound **1** was prepared according to a previously reported literature procedure.[21]

*General procedure for the preparation of alkyl derivatives of **1***: Compound **1** (100 mg, 0.37 mmol) was dissolved in dichloromethane (10 mL) that contained one drop of triethylamine. Upon addition of the alkylating agent, the product precipitated as a white powder. The white powder was filtered and recrystallized to obtain high-quality crystals for X-ray diffraction measurements.

[2-(1,3-Dioxo-*1H*,*3H*-benzo[*de*]isoquinolin-2-yl)ethyl]ethoxymethyldimethylammonium chloride (**2**): ^{1}H NMR (200 MHz, [D$_6$]DMSO, 25 °C, TMS): δ = 8.52 (d, J = 7.3 Hz, 2H), 8.50 (d, J = 8.1 Hz, 2H), 7.90 (t, J = 7.7 Hz, 2H), 4.79 (s, 2H), 4.46 (t, J = 6.8 Hz, 2H), 3.86 (q, J = 7.0 Hz, 2H), 3.54 (t, J = 6.8 Hz, 2H), 3.12 (s, 6H), 1.19 ppm (t, J = 7.0 Hz, 3H); MS (TOF LD+): m/z: 327.2 [M^+].

[2-(1,3-Dioxo-*1H*,*3H*-benzo[*de*]isoquinolin-2-yl)ethyl]-(2-ethylsulfanylethyl)dimethylammonium chloride (**3**): ^{1}H NMR (200 MHz, [D$_6$]DMSO, 25 °C, TMS): δ = 8.53 (d, J = 7.3 Hz, 2H), 8.51 (d, J = 8.1 Hz, 2H), 7.90 (t, J = 7.8 Hz, 2H), 4.44 (t, J = 7.4 Hz, 2H), 3.73–3.54 (m, 4H), 3.21 (s, 6H), 2.96 (m, 2H), 2.63 (q, J = 7.3 Hz, 2H), 1.22 ppm (t, J = 7.4 Hz, 3H); MS (TOF LD+): m/z: 357.1 [M^+].

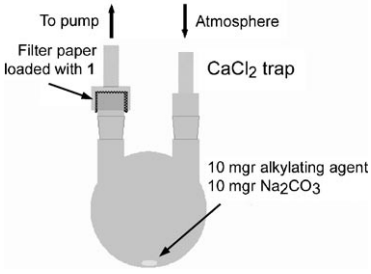
Chloromethyl[2-(1,3-dioxo-*1H*,*3H*-benzo[*de*]isoquinolin-2-yl)ethyl]dimethylammonium chloride (**4**): ^{1}H NMR (300 MHz, [D$_6$]DMSO, 25 °C, TMS): δ = 8.53 (d, J = 6.1 Hz, 2H), 8.51 (d, J = 6.4 Hz, 2H), 7.90 (t, J = 7.5 Hz, 2H), 5.53 (s, 2H), 4.49 (t, J = 7.5 Hz, 2H), 3.73 (t, J = 7.5 Hz, 2H), 3.31 ppm (s, 6H); MS (TOF LD+): m/z: 317.1 [M^+].

Benzyl-[2-(1,3-dioxo-*1H*,*3H*-benzo[*de*]isoquinolin-2-yl)ethyl]dimethylammonium chloride (**5**): ^{1}H NMR (200 MHz, [D$_6$]DMSO, 25 °C, TMS): δ = 8.54 (d, J = 8.2 Hz, 2H), 8.50 (d, J = 7.8 Hz, 2H), 7.90 (t, J = 7.7 Hz, 2H), 7.63–7.51 (m, 5H), 4.68 (s, 2H), 4.57 (t, J = 7.7 Hz, 2H), 3.58 (t, J = 7.7 Hz, 2H), 3.13 ppm (s, 6H); MS (TOF LD+): m/z: 359.2 [M^+].

High-quality crystals of **1** for single-crystal X-ray diffraction were obtained by crystallization from dichloromethane. Crystals of the alkylated derivatives **2**, **3**, and **5** were obtained by slow evaporation of their respective solutions in acetonitrile. Crystals of **4** were obtained by slow evaporation of its solution in dichloromethane. All reagents and solvents were used as received unless otherwise stated.

Apparatus: NMR spectra were recorded on Bruker AC-200F and Bruker AM-300 spectrometers. Mass spectra were recorded by using MALDI micro MX (MICROMASS). Absorption spectra were recorded on a Shimadzu UV-1601 spectrometer and fluorescence spectra were recorded on a Perkin–Elmer LS 50 luminescence spectrometer. All the optical measurements were performed in analytical grade solvents. The effect of residual water in the solvents and materials was tested and found to be negligible.

Solid-state reactions were performed by using a homemade system, Scheme 2. Filter paper (Whatman, Cat. No. 1001070) was dipped into a solution of **1** (20 mg mL^{-1}) in acetonitrile for 1 min. The filter paper was left to dry in the dark, then placed in a Teflon holder. The Teflon holder was fitted into one of two ground joints of a round-bottomed flask. The second joint was fitted with a tube that contained calcium chloride beads.



Scheme 2. Schematic presentation of the gas-phase detection system.

The Teflon holder was connected to a vacuum pump that aspirated the atmosphere of the flask through the filter paper. The experiment was performed by placing the relevant alkylating agent (10 mg) and Na_2CO_3 (10 mg) at the bottom of the two-necked round-bottomed flask, then allowing the system to equilibrate for about 30 min and then aspirating the atmosphere of the flask for different periods of time.

Crystallography: Single crystals of **1**, **3**, **4**, and **5**[22] were mounted on a Nonius KappaCCD diffractometer and the data was collected by using $Mo_{K\alpha}$ ($\lambda = 0.7107$ Å) radiation. The diffraction intensities were collected at room temperature by ω and ϕ scans by using the "Collect" software. Data reduction was carried out with the help of the DENZO-SMN program;[23] the structures were solved by direct methods with SHELXS97[24] and refined against F^2 with SHELXL97.[24] ORTEP and TEXRAY programs were used for structure analysis and material publication.

All the non-hydrogen atoms of **1**, **3**, and **4** were refined anisotropically. The hydrogen atoms were then placed at their calculated positions and refined isotropically by applying a riding model. Crystals of **5** included unspecified amounts of chloride and bromide ions in the unit cell and were therefore only refined isotropically.[22]

Crystal data for **1**: $C_{16}H_{16}N_2O_2$; $M_r = 268.31$, crystal size $0.45 \times 0.25 \times 0.10$ mm; triclinic space group $P\bar{1}$, $a = 7.253(1)$, $b = 9.627(2)$, $c = 10.867(2)$ Å, $\alpha = 99.45(3)$, $\beta = 91.91(2)$, $\gamma = 111.31(3)^\circ$, $Z = 2$, $\rho_{calcd} = 1.284\ g\,cm^{-3}$, $\mu(Mo_{K\alpha}) = 0.086\ mm^{-1}$, $F(000) = 284$, $2\theta = 50.5°$, final $R_1 = 0.0657$ for 2483 reflections $[I > 2\sigma(I)]$, $R_1 = 0.1629$ for all 5712 reflections, residual maximum peaks 0.275 e Å^{-3}.

Crystal data for **3**: $2[C_{40}H_{51}C_{12}N_4O_6S_2]$, $M_r = 818.89$, crystal size $0.72 \times 0.15 \times 0.09$ mm, monoclinic space group $P2_1/c$, $a = 15.189(3)$, $b = 23.277(5)$, $c = 11.754(2)$ Å, $\beta = 98.83(3)^\circ$, $Z = 4$, $\rho_{calcd} = 1.325\ g\,cm^{-3}$, $\mu(Mo_{K\alpha}) = 0.310\ mm^{-1}$, $F(000) = 1732$, $2\theta = 50.3°$, final $R_1 = 0.0549$ for 7262 reflections $[I > 2\sigma(I)]$, $R_1 = 0.1260$ for all 43485 reflections, residual maximum peaks 0.252 e Å^{-3}.

Crystal data for **4**: $C_{17}H_{18}C_{l2}N_2O_2$, $M_r = 353.23$, crystal size $0.45 \times 0.24 \times 0.18$ mm, monoclinic space group $P2_1/c$, $a = 7.353(1)$, $b = 21.862(4)$, $c = 11.800(2)$ Å, $\beta = 114.74(3)^\circ$, $Z = 4$, $\rho_{calcd} = 1.362\ g\,cm^{-3}$, $\mu(Mo_{K\alpha}) = 0.387\ mm^{-1}$, $F(000) = 736$, $2\theta = 50.0°$, final $R_1 = 0.0522$ for 2595 reflections $[I > 2\sigma(I)]$, $R_1 = 0.1260$ for all 11028 reflections, residual maximum peaks 0.227 e Å^{-3}.

Crystal data for **5**: $2[C_{23}H_{24}N_2O_2] + Br_2Cl_2$, $M_r = 951.60$, crystal size $0.12 \times 0.10 \times 0.08$ mm, orthorhombic space group $Pccn$, $a = 21.251(4)$, $b = 33.159(7)$, $c = 12.707(3)$ Å, $Z = 8$, $\rho_{calcd} = 1.412\ g\,cm^{-3}$, $\mu(Mo_{K\alpha}) = 1.977\ mm^{-1}$, $F(000) = 3904$, $2\theta = 47.4°$, final $R_1 = 0.1745$ for 4886 reflections $[I > 2\sigma(I)]$.

Results and Discussion

Compound **1** is a well documented PET sensor for protons and metal ions.[21] In the absence of protons and ligating metal ions, **1** is a very weak luminophore (the reported quantum yield is 6.9×10^{-3} in acetonitrile),[21a] with an emission at the red end (382 nm in acetonitrile) of the UV spectral region. The exceptionally low emission is attributed to an efficient PET process that takes place between the photoexcited aromatic skeleton and the lone-pair electrons of the free amine. In the presence of Lewis acids, such as protons or ligating metal ions, the lone-pair electrons of the free amine quencher are engaged in a hydrogen–nitrogen or metal–nitrogen bond. Once engaged in such a new bond with a Lewis acid, the former lone-pair electrons of the amine group can no longer serve as efficient quenchers of the photoexcited aromatic skeleton, since they are dramatically stabilized in the form of a σ bond. When bound to a Lewis acid **1** is a highly luminescent species.[21]

The process of PET sensing of protons and metal ions relies on Lewis acid/Lewis base chemistry and on the fact that the free amine is a rather strong Lewis base. Nevertheless, the same free amine is also a relatively strong nucleophile, and is therefore also capable of reacting with different electrophiles. These types of reactions may result in the formation of a stable carbon–nitrogen covalent bond. In this case, the reaction no longer has a dynamic equilibrium and therefore may report the presence of even extremely low concentrations of the electrophile, provided that the reaction is characterized by reasonable kinetics.

The reaction of **1** with different alkylating agents with various electrophilic properties makes it fluoresce. Figure 1 depicts the absorption and emission spectra of **1** in acetonitrile with increasing concentrations of chloromethylethyl ether (**6**) as the electrophile. As displayed in Figure 1 (left) the absorption spectrum of **1** is practically insensitive to the addition of the electrophile, indicating that the energy levels that are involved in the electronic process (π and *π orbitals of the aromatic skeleton, which represent the HOMO−1 and LUMO of **1**) are not affected by the alkylation process. In contrast, the presence of the electrophile turns the luminescence on (Figure 1 (right)).

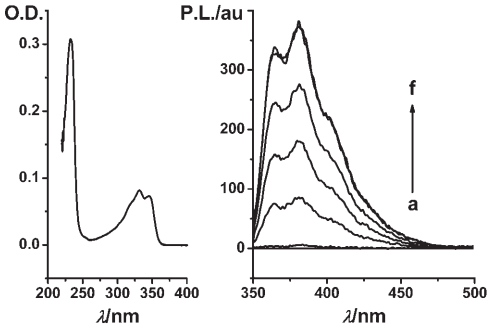


Figure 1. The absorption (left) and photoluminescence emission (right) spectra of **1** in acetonitrile in the presence of triethylamine (1 μL/3 mL of solvent). [**1**] = $2.21 \times 10-5$ M, [chloromethylethyl ether] = a) 0 M; b) 4.27×10^{-6} M; c) 8.54×10^{-6} M; d) 1.71×10^{-5} M; e) 2.56×10^{-5} M; f) 3.41×10^{-5} M.

At saturation, the luminescence is about 130 times stronger than that of the free compound **1**. Saturation occurs at an electrophile/**1** ratio of approximately 1:1, indicating the presence of an efficient reaction that proceeds to completion even at rather low concentrations. This allows detection of micromolar concentrations of electrophiles in solution, Figure 2. Similar results were obtained with other alkylating agents with similar electrophilicity. Even dichloromethane, a rather weak electrophile, is found to react with **1** turning its luminescence on. As expected from the nature of the new bond and in contrast to the case of protonation and most metal complexes, the luminescence of the naphthaleneimide skeleton cannot be turned off simply by reducing the concentration of the alkylating agent or by the addition of a base. It is therefore easy to distinguish between such metal ions and protons, and alkylating agents.

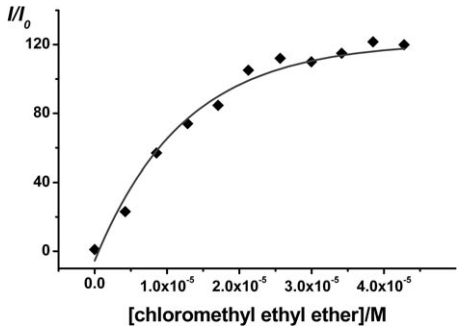


Figure 2. Relative fluorescence intensity of a solution of **1** in acetonitrile ($[\mathbf{1}]=2.2\times10^{-5}$ M) as a function of the concentration of **6**.

Interestingly, the PET process of **1** with a mustard analogue, 1-chloro-2-sthylsulfanylethane (**7**), is found to be solvent dependent. The addition of **7** to a solution of **1** in acetonitrile does not result in a switching-on of the luminescence of **1**, even though NMR studies clearly indicate that an efficient reaction takes place between the two compounds. In contrast, the same reaction in alcohol media, such as in ethanol, results in an intensive switching-on of the luminescence.

With the aim of gaining a better understanding of the process, we grew crystals of **1** and its alkyl derivatives, analyzed their crystal structures by using single crystal X-ray diffraction, and their electronic states by using electronic energy calculations [Gaussian 98[25] software package, b3Lyp/6-31 g(d)[26]]. Figures 3–5 depict the top and side views of the crystal structures of the free compound **1**, its *N*-(2-ethylsulfanylethyl) adduct **3**, and its *N*-chloromethyl adduct **4**.

With regard to the crystal structure of **1**,[22] the dimethylaminoethyl group is folded in a conformation that brings the nitrogen atom N2 into close contact with the π system of the naphthalene imide, $d(\mathrm{N2\cdots Ct1}_{(\mathrm{N1C11C9C10C1C12})})=$ 3.987 Å. The position of the dimethylaminoethyl group with respect to the naphthalene imide skeleton is not symmetric. The nitrogen atom points towards one of the carbonyl groups, $d(\mathrm{N2\cdots C12})=3.542$ Å, $d(\mathrm{N2\cdots O_2})=3.594$ Å, while the second carbonyl group is further away, $d(\mathrm{N2\cdots C11})=$ 3.792 Å, $d(\mathrm{N2\cdots O1})=4.036$ Å. Though at first glance, the nitrogen atom seems to be interacting with the aromatic skeleton, it appears that the major reason for this specific conformation of the molecule arises from the supramolecular packing of the molecules in the crystal. Molecules of **1** form dimers in which the naphthaleneimide skeletons form a π interaction with one another, with a naphthaleneimide–naphthaleneimide interplane distance of $d=3.395$ Å, Figure 3c. In this dimeric form of **1** the free amine of each molecule interacts with its close neighbor within the dimer structure, through a weak −N···H−C− hydrogen bond, $d(\mathrm{N2\cdots H4})=2.612$ Å, $d(\mathrm{N2\cdots C4})=3.511$ Å, $\alpha(\mathrm{N2\cdots H4{-}C4})=$ 162.83°. Electronic energy calculations (b3lyp/6-31g(d)) clearly indicate that the minimum energy conformation for the free compound **1** in the gas phase is such that the free amine group is distant from the naphthaleneimine group. Furthermore, detailed analysis of the π-HOMO, π-LUMO, and lone-pair orbitals of the free amine clearly indicates that the symmetry mismatch between the π orbitals and the lone pair exclude any possibility for ground-state attractive orbital overlap between the naphthaleneimide skeleton and the lone pair of the free amine. In all the quaternized derivatives of **1** that we examined the nitrogen atom points out of the π system, $\alpha(\mathrm{N1{-}C13{-}C14{-}N2})=177.0°$ and $\alpha(\mathrm{N1{-}C13{-}C14{-}N2})=170.2°$ in **3** and **4**, respectively.

The reappearance of luminescence upon reaction with alkylating agents may be rationalized with the aid of electronic energy calculations. The calculations were performed by using the Gaussian 98[25] software package. First, the structures of the different molecules were optimized at the b3lyp/6-31g(d) level.[27] In the next step, the energies of the LUMO, HOMO, HOMO−1 and any other relevant orbitals

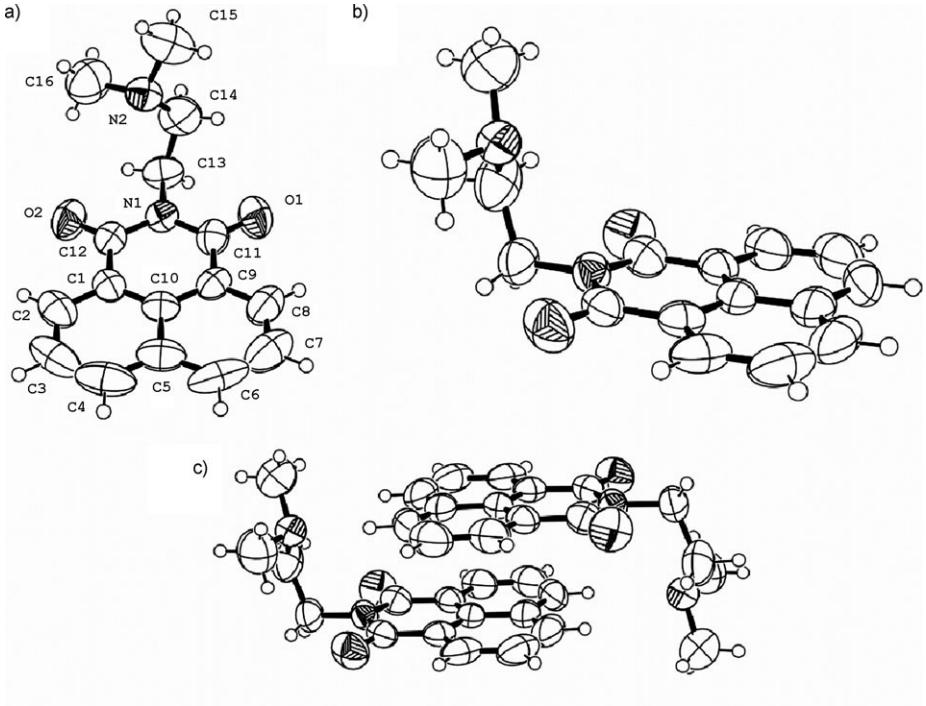


Figure 3. Top (a) and side (b) views of the crystal structure of **1**. c) Crystal structure of the dimeric form of **1**.[28]

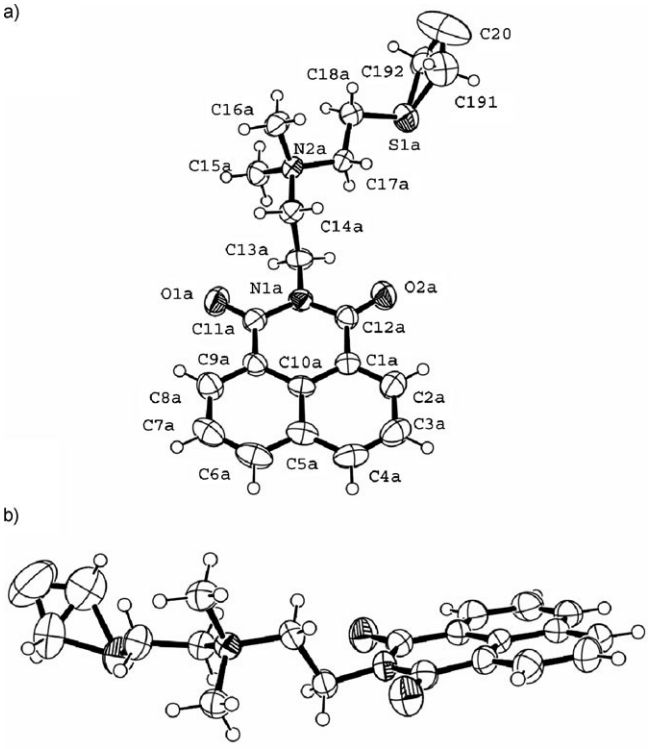


Figure 4. Top (a) and side (b) views of the crystal structure of **3**. [28]

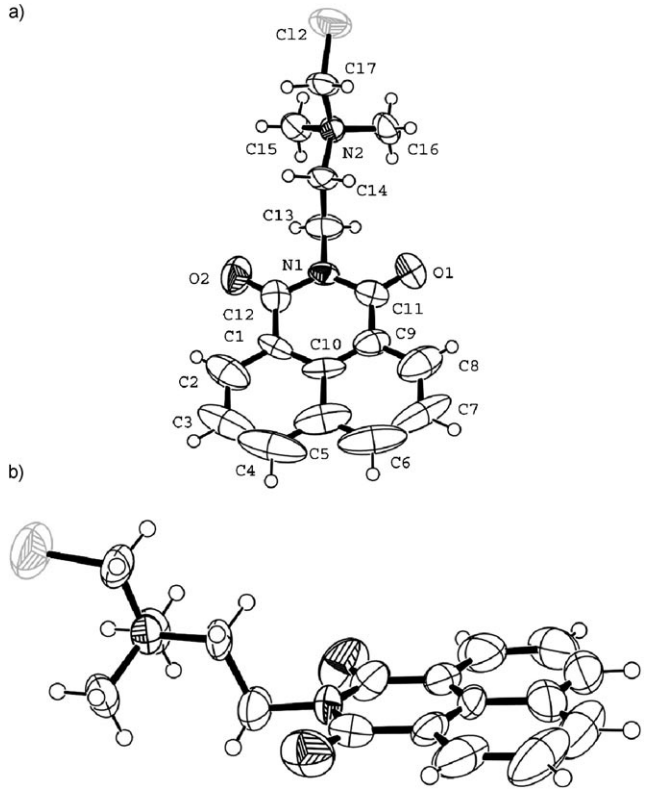


Figure 5. Top (a) and side (b) views of the crystal structure of **4**. [28]

of the energy-minimized systems were extracted from the calculations. The energy levels of the different systems, including all relevant orbitals, are presented in Figure 6.

The energy levels of the free compound **1** are arranged in a way that the lone-pair electrons of the amine group occupy the HOMO and are located in between the LUMO (a π^* orbital) and the highest occupied π orbital, HOMO−1. In all cases, upon quaternization of **1**, the lone-pair electrons become engaged in a new σ bond and are considerably stabilized. Consequently, these electrons can no longer serve as quenchers for the photoexcited naphthaleneimide fluorophore. Nevertheless, in all the alkylation processes we have studied in this work, quaternization of the amine group adds new nonbonding electrons (**2**, **3**, and **4**) or π electrons (**5**) to the system.

The only system in which the new orbitals are located in an energy level that can result in a PET process is the mustard analogue adduct **3**. In this case, the energy level of the lone-pair electrons of the newly introduced sulfur atom are situated just 0.05 eV below the lowest occupied π orbital, which is also the HOMO orbital. As already mentioned above, regain of the luminescence upon reaction between the mustard analogue **7** and **1** is found to be sensitive to the medium in which the reaction is performed. When the reaction is performed in THF or acetonitrile, the gain in fluorescence intensity is negligible, although the reaction occurs efficiently. However, when the reaction is performed in ethanol, the gain in luminescence is almost as high as in the case of **6**. This solvent dependence of the luminescence may be attributed to hydrogen bonds that are formed between the sulfur atom, which acts as a Lewis base, and the alcohol, which acts as a Lewis acid. This effect stabilizes the lone-pair electrons of the sulfur atom and prevents them from participating in the PET process.

This hydrogen-bond stabilization of the lone-pair electrons of the sulfur atom could be demonstrated by calculating the energy-level position in a model system that consists of one dimethyl sulfide molecule and two solvent molecules, each of them interacting with one lone-pair orbital of the dimethyl sulfide, Figure 7. The energy level of the lone-pair orbitals of an isolated dimethylsulfide molecule is located at $E_{lp} = -5.91$ eV. The addition of two dimethyl ether molecules does not yield any type of significant attractive interaction with the sulfur atom. The energy level of the lone-pair orbital was found to be located at $E_{lp} = -5.43$ eV, indicative of the destabilization of these orbitals by the presence of the ether molecules. Addition of two molecules of acetonitrile results in the formation of a weakly hydrogen-bonded complex of dimethyl sulfide·2(acetonitrile). The formation of the complex does not significantly influence the energy level of these lone pairs, although some stabilization results from the apparently very weak −C−H···S− hydrogen bonds, $E_{lp} = -5.97$ eV. In contrast, addition of two ethanol molecules results in the formation of a dimethyl sulfide·ethanol hydrogen-bonded complex. The formation of this complex results in significant stabilization of the energy level of the lone-pair orbitals of the sulfur atom through −C−H···S− hydrogen bonds, $E_{lp} = -6.29$ eV. This rather simple calculation clearly demonstrates the solvent-dependent PET process we observed in the case of the mustard analogue.

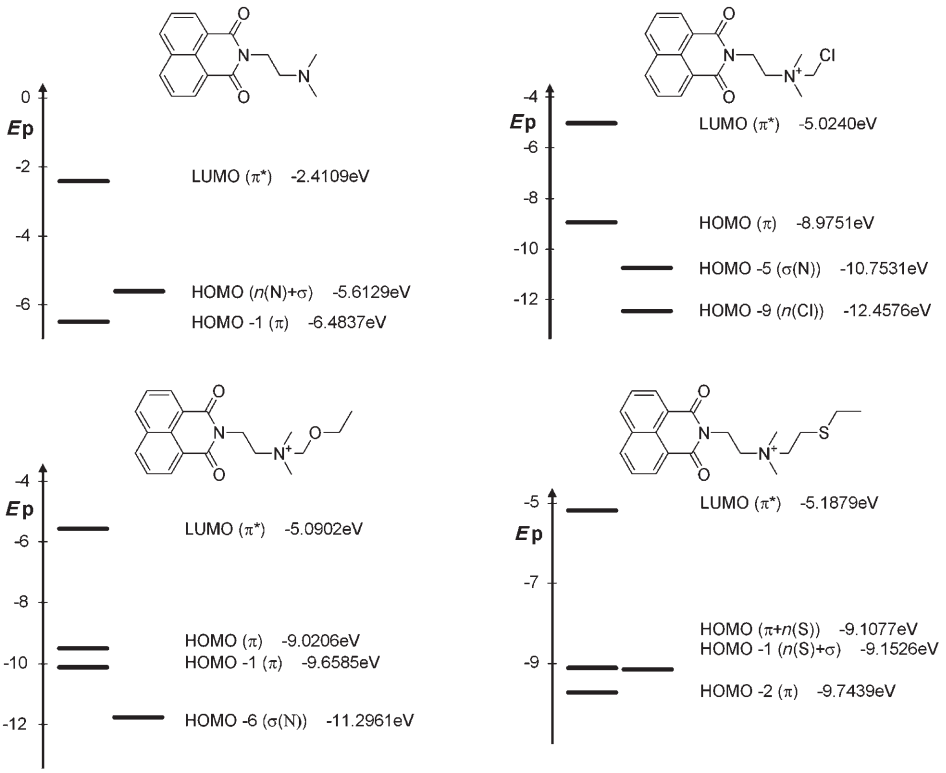


Figure 6. Orbital energy diagrams for **1**, **2**, **3**, and **4** (Gaussian 98[25] software package, b3lyp/6-31g(d)). The dominant nature of each orbital is provided in brackets.

The reaction between **1** and alkylating agents is not limited to solutions and could also be performed very efficiently when **1** was adsorbed on a simple filter paper, Figure 8. Compound **1** was adsorbed onto filter paper by dipping the paper into a solution of **1** in acetonitrile. Upon drying, the filter paper turned very weakly luminescent ($\lambda_{ex}=366$ nm, UG11 filter) in the blue region. The vapor that is generated by an alkylating agent (10 mg, in the presence of sodium carbonate powder (10 mg)), such as chloromethylethyl ether, was sufficient to turn on the luminescence of **1** that was loaded onto the filter paper even after a few seconds of aspiration. The reaction between the vapors of the alkylator and the adsorbed compound **1** induced a dramatic increase in the luminescence and a red-shift in its color. Passing triethylamine vapors through the luminescent filter did not turn the fluorescence off. This result implies an irreversible alkylation process rather than protonation. Similar experiments that were performed with hydrochloric acid and different metal ions did not change the luminescence of the filter paper owing to the presence of the base (which eliminates the effect of hydrochloric acid) and low vapor pressure (which eliminates the effect of metal ions). It is therefore suggested that such systems may serve as very simple but highly sensitive and selective sensing elements for different alkylating agents.

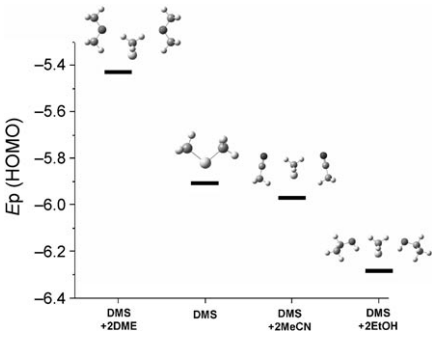


Figure 7. Energy-minimized structures and respective lone-pair energy diagram of dimethyl sulfide and two representative solvent molecules (DMS, DME, MeCN, EtOH). [28]

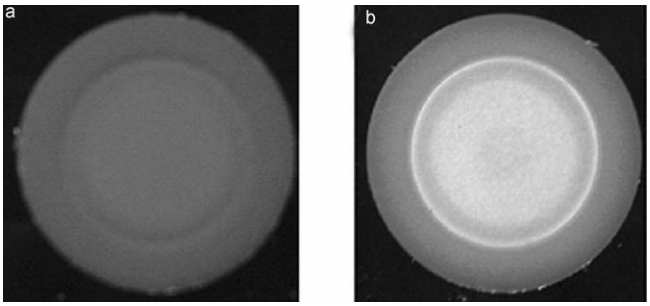


Figure 8. Gas-phase detection of chloromethylethyl ether: a) **1** adsorbed on filter paper, b) **1** adsorbed on filter paper after exposure to vapors of **6**. [28]

Conclusions

Application of the PET-based chemosensing concept for efficient and selective detection of alkylating agents has been demonstrated. Compound **1** was found to be a highly selective and effective PET chemosensor that turns irreversibly fluorescent upon reaction with different alkylating agents. PET-based sensing of alkylating agents was performed in solution and was capable of detecting even rather weak alkylating agents such as dichloromethane. A combined experimental–theoretical approach was applied to rationalize the results.

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[27] The adequacy of the level of calculations we selected (b3lyp/6–31g(d)) for calculating the relative energies of the different molecular orbitals was confirmed by comparing this level of calculations with a higher level of calculations (mp2/6-31++g(df,pd)) on a model system. The model system consisted of one dimethyl sulfide molecule and two solvent molecules of either dimethyl ether, acetonitrile, or ethanol. The model system was geometrically optimized by using b3lyp/6-31g(d), and then the energy levels of the lone pair orbitals of the dimethyl sulfide were calculated by using the two different methods. Though the absolute energies were considerably different, the two methods reproduced the same orbital energy order, DMS–DME > DMS > DMS–MeCN > DMS–EtOH, and the relative energy gaps agreed within ±0.045 eV.

[28] Color versions of Figures 3–5, 7, and 8 are available in the Supporting Information.

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