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Synthesis, inclusion capabilities, and electrical properties of some asymmetrical cyclophanes

Gheorghe Surpateanu [a,*], Paul Ionut Dron [a,*], David Landy [a], Sophie Fourmentin [a], Marc Bria [b]

[a] *Laboratoire de Synthèse Organique et Environnement, EA 2599 Université du Littoral Côte d'Opale, 145 Avenue Maurice Schumann, 59140 Dunkerque, France*
[b] *CCM-RMN Lille 1, Université des Sciences et Technologies de Lille, Villeneuve d'Ascq 59655, France*

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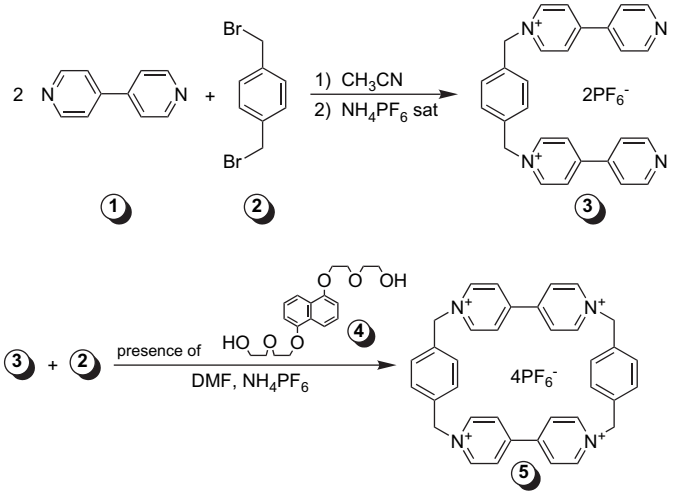
Abstract

For the first time, we announce the synthesis of cyclo(bis-paraquat-*p*-phenylene-*p*-phenylene-carbonyl)tetrakis(hexafluorophosphate), named 'CETOBOX'. This compound exists in three tautomeric forms. These forms were evidenced by NMR data (^{1}H NMR, TOCSY, COSY, and NOESY), UV–vis spectra coupled with pH measurements, and by synthesis. As the 'CETOBOX' gives 'in situ' only the corresponding monoylide, the synthesis of a new fluorescent indolizine cyclophane has been performed by a 3+2 cycloaddition. This cycloadduct, in an amidation reaction with 6-amino-β-cyclodextrin, furnishes the final two-cavity sensor with good yields. All structures of the new compounds presented herein have been established by NMR spectroscopy. Also, theoretical methods (MM3, AM1, AM1 (COSMO), and B88LYPDFT) have been used to determine the most stable conformer structures. For the fluorescent indolizine cycloadduct, we evaluated its inclusion capabilities and for the two-cavity sensor, we measured some of its electrical properties that make it suitable for use in VOCs detection and energy conversion.

1. Introduction

'Blue Box', cyclobis(paraquat-*p*-phenylene)tetrakis(hexafluorophosphate) **5** was synthesized by Stoddart et al.,[1] starting from 4,4′-bipyridine and 1,4-bis(bromomethyl) benzene, in two ground steps, as described in Scheme 1. However, by a template cyclization of the salt **3** in the presence of 1,5-bis[2-(2-hydroxy)-ethoxy] naphthalene, better yields are obtained for the final product **5**.[2]

The molecular recognition properties of 'Blue Box' have recently drawn great attention due to its important applications in the design and synthesis of various electrochemically active molecular systems.[3] Many molecular machines based on 'Blue Box' take into consideration the two key properties of this compound: (i) the ability to interact with guests by π–π stacking and charge-transfer interactions[1,4] and (ii) the presence of a rigid cavity, which helps to trap the guests, giving inclusion



Scheme 1. Synthesis of 'Blue Box'.

* Corresponding authors. Tel.: +33 0328658254; fax: +33 0328237605.
E-mail addresses: surpatea@univ-littoral.fr (G. Surpateanu), ionutdron@yahoo.com (P.I. Dron).

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complexes.[5] The host–guest chemistry of the 'Blue Box' is the traditional starting point to explore its molecular recognition properties. It turns out to be a multipurpose host, which can bind with a wide range of substrates.[6] The early work on the host–guest chemistry of 'Blue Box' was crucial to the ultimate development of artificial molecular machines.

The discovery of its inclusion complexation led to an exploration to find out, which guests are recognized by the tetracationic host. It was found that it is an excellent receptor for a wide range of guests containing π-electron-rich aromatic rings, such as dioxynaphthalene-based compounds,[7] biphenyl,[8] benzidine,[8] and indole[9] and their derivatives,[10] in both organic and aqueous solutions. The tetracationic cyclophane was also found to recognize numerous small bioactive molecules (amino acids possessing electron-rich aromatic subunits,[11] neurotransmitters,[12] and phenyl D-glycopyranosides[13]) by forming stable inclusion charge-transfer complexes. Tetrathiafulvalene and its derivatives[14] are among the very few non-aromatic compounds that complex strongly with 'Blue Box'.

The formation of strong inclusion complexes between 'Blue Box' and π-electron-rich substrates was recognized[15] as the signal to use appropriate donors as templates to direct the formation of the host molecule (template-directed synthesis[16]). The ability of the tetracationic cyclophane to form inclusion complexes provides the unique opportunity to construct large, ordered molecular assemblies such as catenanes and rotaxanes, using the templating actions inherent in the interlocked compounds themselves as they are formed.[17–23]

As a part of our ongoing research program in the construction of new molecular nanomachines for the detection of Volatile Organic Compounds (VOCs), in this paper, we report for the first time the synthesis and some inclusion physical properties of a new type of sensors having in their structures both cyclodextrin and cyclophane inner cavities.

2. Results and discussion

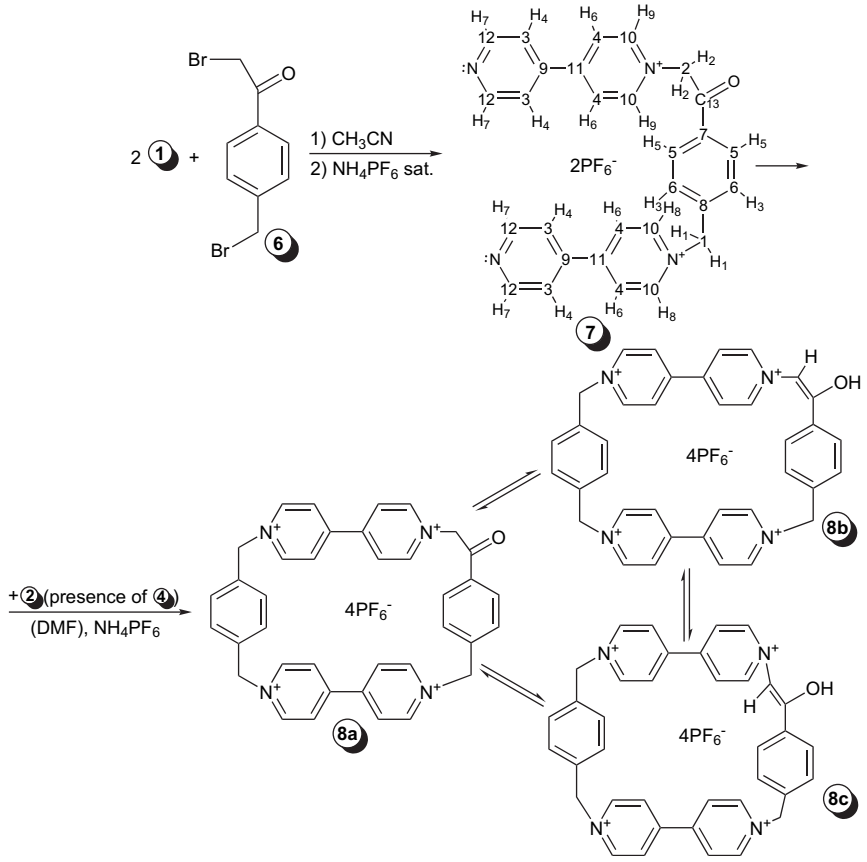
2.1. Synthesis and structural determinations

Firstly, our aim was to introduce into the cyclophane structure one more reactive methylene group, able to furnish selectively, only one bipyridinium methylide. Thus, a single site functionalization of a cyclophane structure could be achieved by one of all known chemical reactions involving cycloimmonium ylides.[24]

2.1.1. Cyclo(bis-paraquat-p-phenylene-p-phenylene-carbonyl)tetrakis(hexafluorophosphate)

We synthesized cyclo(bis-paraquat-*p*-phenylene-*p*-phenylene-carbonyl)tetrakis(hexafluorophosphate) **8**, named by us 'CETOBOX', by the template and clipping synthetic procedure used for 'Blue Box' (Scheme 2).

Experimentally, two different chemical ways were tested in order to obtain the asymmetrical product **8**, starting from (i) bipyridyl **1** and 1′-bromo-4-bromomethyl acetophenone **6** (Scheme 2) and (ii) bipyridyl **1** and α,α′-dibromo-*para*-xylene



Scheme 2. Synthesis of 'CETOBOX'.

2 in the first step of the synthesis, followed by the cyclization of salt **7** with α,α′-dibromo-*para*-xylene **2** or salt **3** with 1′-bromo-4-bromomethyl acetophenone **6**.

In fact, only by the first synthetic way, we achieved 'CETO BOX' **8** with yields of 12–16%, calculated relative to the intermediate salt **7**.

The initial salt **7**, as bromide, obtained in the first step of the synthesis is transformed into its hexafluorophosphate form to render it soluble in DMF. Thus, the second step of the synthesis, i.e., the cyclization of **7** with α,α′-dibromo-*para*-xylene **2** in the presence of template **4**, was performed in a homogenous organic media assured by DMF. Normally, the mixture of salts **8** as bromide and hexafluorophosphate resulted initially in the second step, must be transformed integrally into its hexafluorophosphate in order to obtain a unitary final 'CETOBOX' **8**.

On the other hand, the hexafluorophosphate salt of **8** may be converted, by treatment with tetraethyl ammonium chloride in nitromethane, to the corresponding solid chloride[1] salt **8**, which is soluble in aqueous media.

However, it has to be mentioned that, in our hands, all synthetic procedures for product **8** gave a mixture of the tautomeric forms **8a** and **8b**, as evidenced by the aliphatic part of the ^{1}H NMR spectra, depicted in Figure 1.

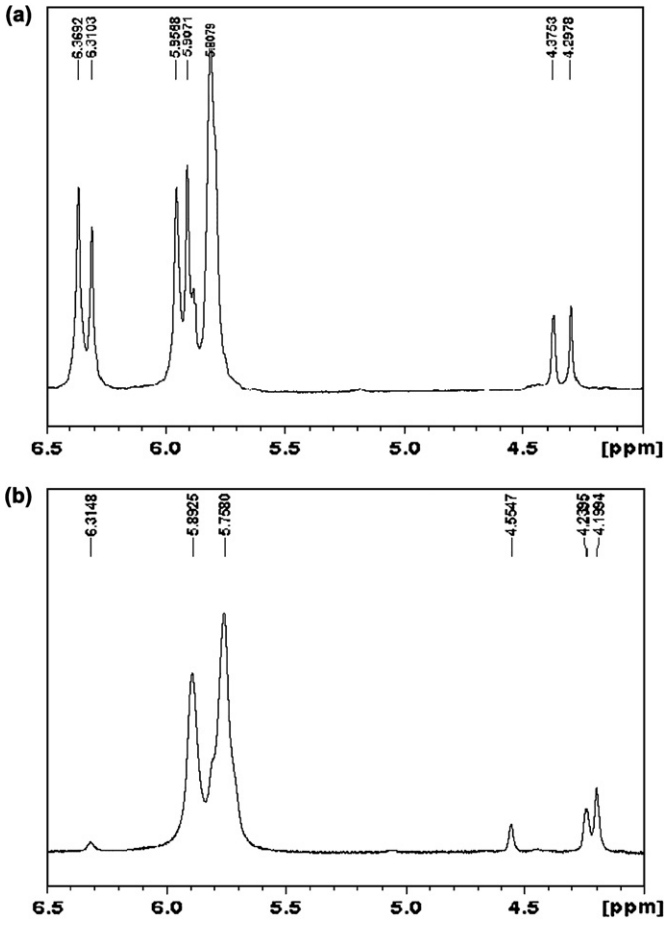


Figure 1. ^{1}H NMR spectra of the synthetic tautomers: (a) in DMSO-d_6 at room temperature; (b) in DMSO-d_6 and D_2SO_4 at room temperature.

Figure 1a corresponds to the spectral measurement in DMSO-d_6 resulting directly from synthesis, while Figure 1b is the spectrum obtained for the same synthetic mixture upon addition of D_2SO_4 (deuteriated sulfuric acid). Indeed, the keto–enol equilibrium is sensitive to the presence of acid,[25] and the addition of D_2SO_4 leads to a displacement in favor of the enolic form. As a consequence, there is an extinction of the signals at around 5.95 and 6.3 ppm, ascribed to the disappearance of the ketonic form (and especially of the methylene group bounded to the carbonyl group). Concomitantly, a new signal appears at 4.55 ppm as a result of the formation, in a little quantity, of the second enolic form **8c**. Indeed, the cis and trans forms of the enol lead to rather different structures (see molecular modeling results in next section), in such a way that chemical displacements are not strictly identical from one enolic form to the other. In addition, the vinylic proton appears as a singlet at 6.31 ppm, but with a low integration, according to the deuteration resulting from the keto–enolic equilibrium in the presence of the labile deuterium of D_2SO_4.

The sample in DMSO-d_6 and D_2SO_4 containing the enol form **8b** in a dominant concentration (approximately 96%) helps without difficulty the assignment of the chemical shifts and couplings for the tautomeric forms **8a** and **8b** (Fig. 2). For both structural determinations of tautomeric forms **8a** and **8b**, we also registered the ^{13}C and DEPT spectra, in order to explain some evident differences in shieldings of methylene groups. The dipole–dipole couplings by NOESY and scalar couplings by COSY and TOCSY 1D were recorded as well, on a tautomeric mixture containing up to 80% keto form.

In order to obtain some structural informations on the three tautomeric forms **8a–8c**, we performed a molecular modeling study, based on molecular mechanics, AM1 semi-empirical, and DFT calculations. These methods were systematically employed[26] for this type of charged molecular systems. In Table 1 are presented the values of ΔH (enthalpy of formation) calculated by AM1 (vacuum), AM1 (COSMO), and B88LYPDFT methods from CAChe library.[27]

To obtain these numerical data, we applied a general procedure presented in the specialized literature.[28] Briefly, the starting structures generated by the CAChe editor were firstly optimized by MM3 method. The most stable conformer obtained for every case was successively optimized by AM1 (vacuum) and AM1 (COSMO) methods. Finally, only for the most stable conformer found by this last method is developed the geometric optimization using the Density Functional Theory and the B88LYP hybrid functionals. DFT and AM1 (COSMO) calculations are still expected to be more desirable for the estimation of molecular stabilities of this type of molecules. As a result, in Figure 3 are given the most stable conformers of the tautomeric forms **8a–8c** obtained by the DFT calculations.

Both methods indicate the same decreasing order of their stabilities: **8a**>**8b**>**8c**. As experimentally observed by NMR, the ketonic form is more stable than the enolic ones, while the enol trans form is predominant when compared to the cis isomer. In addition, on a structural point of view, it is obvious that the

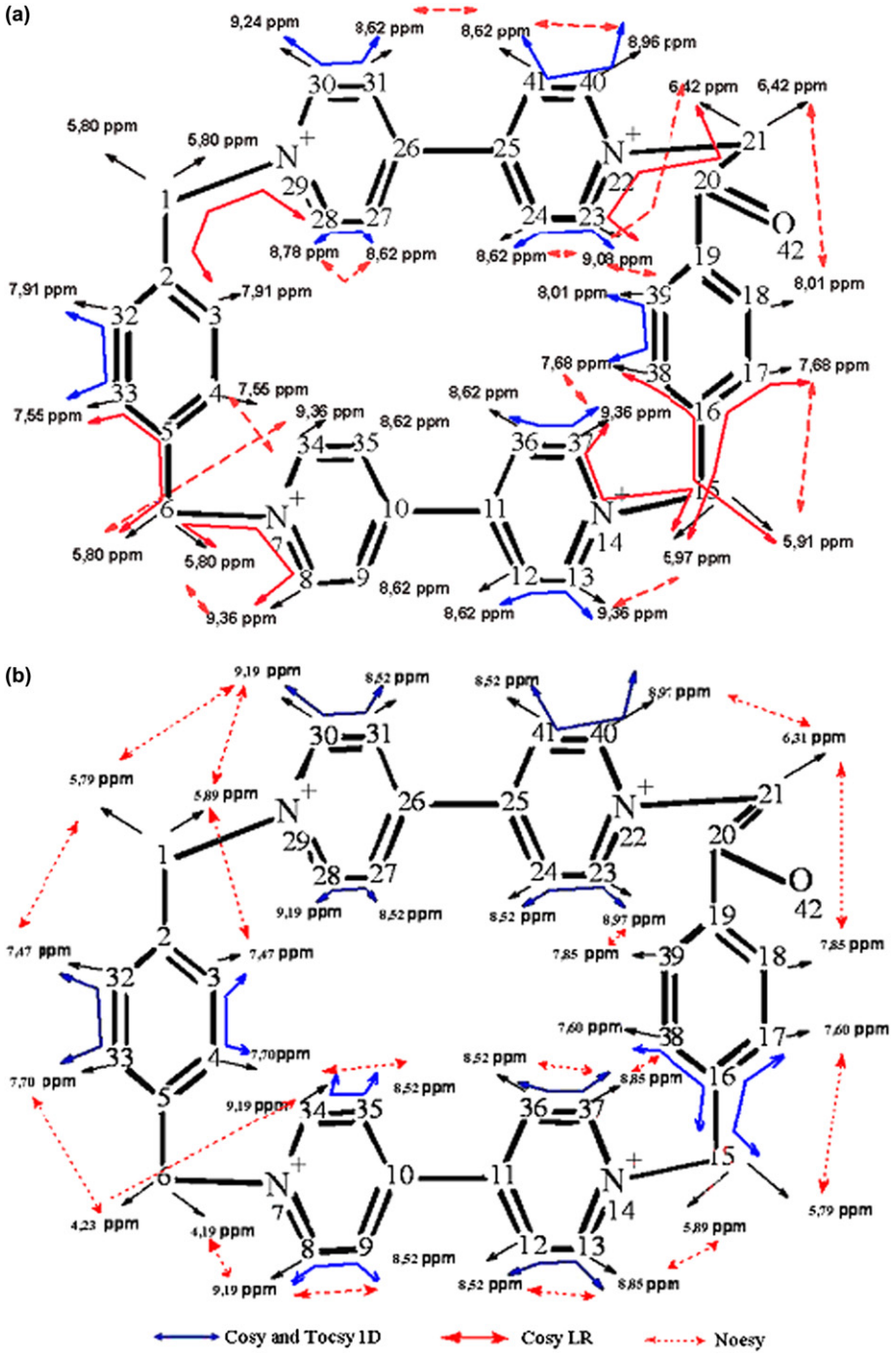


Figure 2. (a) Keto form **8a** (DMSO-d_6, room temperature); (b) enol form **8b** (DMSO-d_6 and D_2SO_4, room temperature).

introduction of the carbonyl unit on the cyclophane leads to deformations of the macrocycle in such a way that methylene groups are not equivalent any more, as found by NMR. These findings also explain that certain methylene groups lead to a doubled signal (5.91 and 5.97 ppm for **8a**, 4.19 and 4.23 ppm for **8b**), the two protons being exposed to different environments.

Moreover, the significant differences in enthalpy of formation (7.66 kcal/mol between **8a** and **8b**, by DFT) suggested us to study this dynamic chemical equilibrium by pH variation. In order to achieve this, we developed a spectrometric study on the passage of enol forms **8b** and **8c** to the keto form **8a** and then to its corresponding cyclophane monoylide **9**. We

Table 1
Enthalpy of formation (kcal/mol)

Method	Structure		
	8a	**8b**	**8c**
MM3	327.98	325.84	338.57
AM1	1064.81	1064.26	1071.03
AM1 (COSMO)	608.68	613.28	626.44
B88LYPDFT	1080379.30	1080371.63	1080364.72

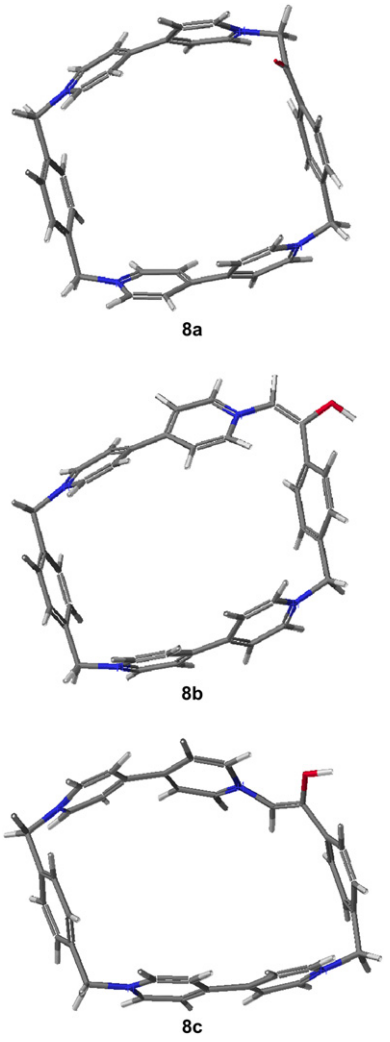


Figure 3. The most stable conformers of product **8**.

recall that ^{1}H NMR spectra of 'CETOBOX' in DMSO-d_6 and D_2SO_4 indicated the presence of enol forms in a great majority.

Thus, to a solution of 'CETOBOX' in water (10^{-5} mol L^{-1}) containing 0.09 mol L^{-1} hydrochloric acid was added a solution of sodium hydroxide that is also in water. The concentrated solutions of sodium hydroxide used in titration were added in small volumes with a micropipette. The overall dilution error is less than 0.06% (0.5 mL). The titration spectra were recorded for every pH measurement on a common UV–vis spectrophotometer. The evaluation of the apparent pK_a values was performed using the Henderson–Hasselbach equation adapted for spectrometric titration.[29]

$$pk_a = pH - \log \frac{A_{max} - A}{A - A_{min}}$$

where A_{max} is the maximal absorbance of the conjugated acid or conjugated base function in the titration, A_{min} is the minimal absorbance of the same conjugated form, and A represents the average of all recorded absorbances due to the conjugated form. During titration, isobestic points could be observed at 214 and 245 nm, thus demonstrating the simultaneous

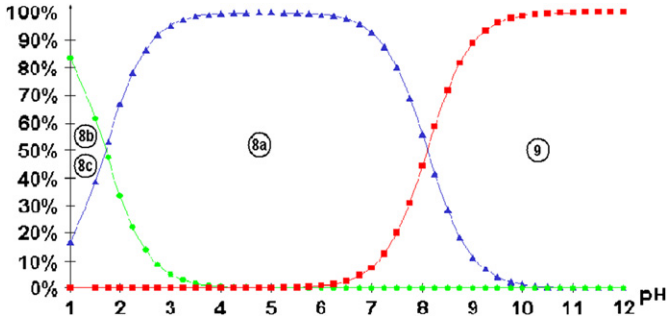


Figure 4. Presence of tautomeric and ylide forms function of pH range: λ_{1i}=214 nm, λ_{2i}=245 nm, pK_{a1}=1.7, pK_{a2}=8.16.

presence of only two species. Two pK_a values were calculated and the mixture composition in tautomeric and ylide forms as a function of pH was evaluated (Fig. 4).

These data show that up to pH=1.71 the enol forms **8b** and **8c** are dominant. For a range of pH comprising between 1.71 and 8.16 the principle product in the mixture is the keto form **8a**. Beyond pH=8.16, we observe the formation of the cyclophane monoylide form **9**.

Normally, we tried to exploit these quantitative data from synthetic point of view. This aspect, reinforcing the existence of a tautomeric equilibrium, will be treated at the end of the next section on the synthesis of fluorescent cyclophane indolizine (compound **12**).

2.1.2. 1-(4-Nitrophenoxycarbonyl)-7-(4′-pyridinium-1′-methyl-p-phenylene-paraquat-p-phenylene-keto)-3-indolizine-tris(hexafluorophosphate)

The procedure employed for the preparation of **12** starting from 'CETOBOX' **8** and 4-nitrophenyl propynoate **10** in the presence of triethyl amine (TEA) is concisely presented in Scheme 3.

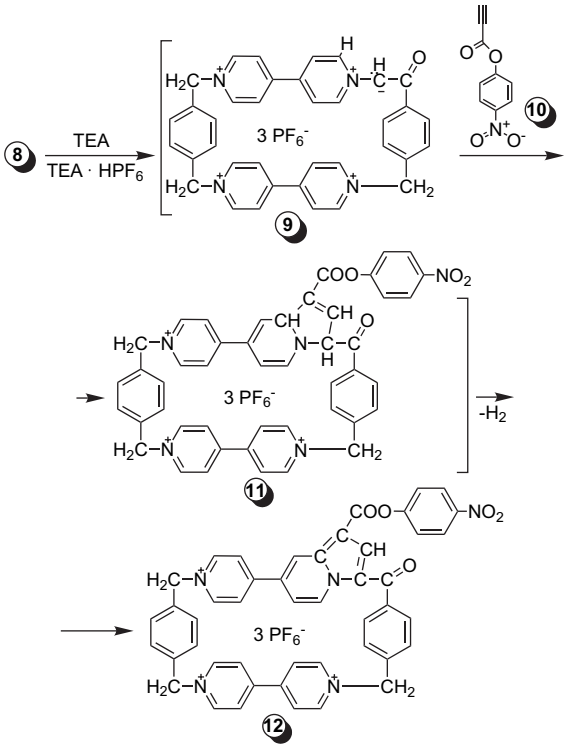
The mixture of **8** and **10** in 1:1 molar ratio dissolved in DMF is gradually treated with TEA. Monoylide **9** generated 'in situ' by a 3+2 cycloaddition with **10** forms initially the unstable cycloadduct **11**, which spontaneously discards the hydrogen to furnish the fluorescent indolizine cyclophane **12**.

The structure of product **12** has been established by NMR spectroscopy in DMSO-d_6. In Figure 5 are given the proton chemical shifts and the couplings found by NOESY, COSY, and TOCSY. The ^{13}C chemical shifts of the carbons 5 and 8 are totally different while their bounded protons show the same chemical shifts.

Also, using the same previous theoretical general strategy, the most stable conformer of compound **12** was investigated in order to consider the possible changes of its inner cavity due to the presence of the indolizine fragment. Thus, in Figure 6a is depicted the most stable structure of **12** established using the Density Functional Theory and the B88LYP hybrid functionals.

Apparently, the inner cavity of compound **12** remains available to form host–guest or charge-transfer complexes.

In addition, we resynthesized the fluorescent indolizine cyclophane **12** starting from a mixture of **8**, **10**, and sulfuric



Scheme 3. Synthesis of the fluorescent indolizine cyclophane.

acid in 1:1:3 molar ratio, respectively. Normally, an excess of TEA was gradually added in order to generate the intermediate ylide **9**. Adduct **12** is obtained with the same yield as in the synthetic procedure described at the beginning of this section, without H_2SO_4. Undoubtedly, this experiment proves the existence of a dynamic equilibrium between tautomeric forms **8a**–**8c**. Only the passage of enol forms into the keto form could explain the formation of the monoylide **9**, which assures the formation of the final fluorescent cyclophane product **12**.

2.1.3. 1-(Carboxyl-amino-6-deoxy-β-cyclodextrin-6-yl)-7-(4′-pyridinium-1′-methyl-p-phenylene-paraquat-p-phenylene-carbonyl)-3-indolizine-tris(hexafluorophosphate)

In previous papers,[30] we reported on the synthesis of a new class of fluorescent sensors based on a β-cyclodextrin fragment and an indolizine unit. To achieve this, an amidation between a substituted indolizine carboxylate of 4-nitrophenyl and a 6-deoxy-6-amino-β-cyclodextrin has been employed. Furthermore, we extended this synthetic way to an indolizine partner attached to a cyclophane derivative.

A mixture of 1:1 molar ratio of fluorescent indolizine cyclophane **12** and 6-amino-β-cyclodextrin **13** in DMF, at room temperature under stirring and argon inert atmosphere for 24 h, furnishes after concentration and precipitation in

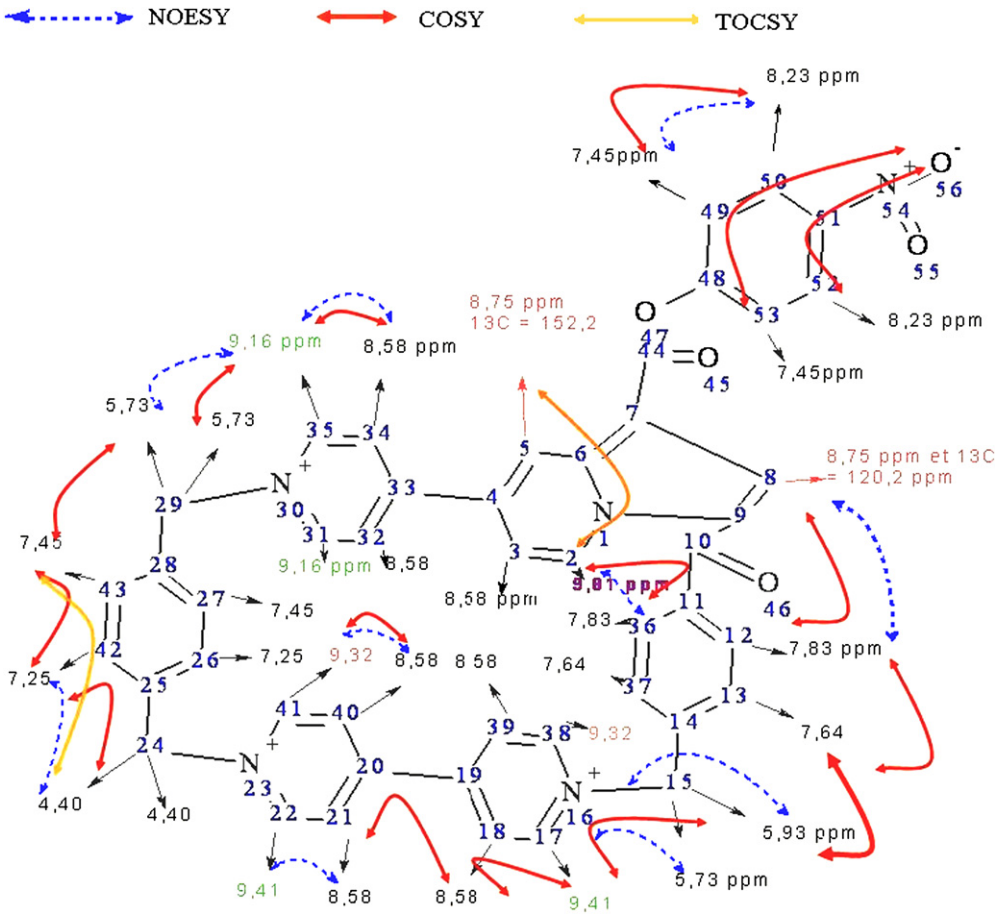


Figure 5. NMR data of compound **12**.

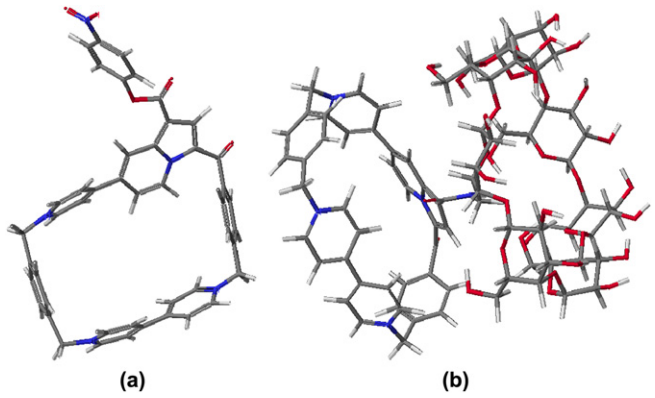


Figure 6. The most stable conformers: (a) the fluorescent indolizine cyclophane **12**; (b) the fluorescent sensor **14**.

acetone the final new sensor **14** with yields of 75–80% (Scheme 4).

Dominantly, the structure of compound **14** has been established by ^{1}H NMR spectra registered in DMSO-d_6.

In Figure 7 are given together for comparison the spectra corresponding to the 6-amino-β-cyclodextrin **13**, the fluorescent indolizine cyclophane **12**, and the final fluorescent sensor **14** in their aromatic domains.

Normally, any chemical shifts for product **13** should be observed (Fig. 7). The presence of the signal corresponding to nitrophenyl moiety (δ=8.23 ppm) in the spectra of **12** and its disappearance in the spectra of the final compound **14** could be considered as a general proof of amidation between compounds **12** and **13**. The similarity of the signals corresponding to both products **12** and **14** in aromatic domain also reinforces the coupling of both cyclophane and cyclodextrin fragments.

Moreover, the analogous ^{1}H NMR analysis for compounds **13** and **14** has been developed, but this time on their aliphatic domains (Fig. 8). Easily can be observed the shapes and the little chemical shift modifications of all the protons of the β-cyclodextrin fragment in both compounds **13** and **14**. Undoubtedly, we can consider in common the presence of both fragments, i.e., cyclophane and cyclodextrin in the structure of final fluorescent sensor **14**.

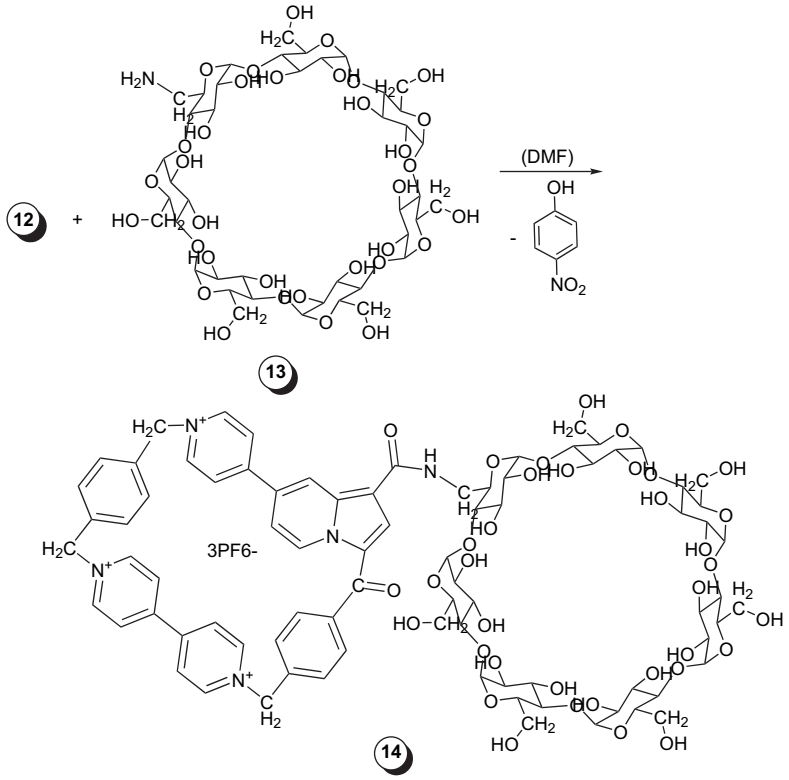
Finally, by a multiconformational search conducted at the level of all exocyclic single bonds connecting the two cavities of the fluorescent sensor **14**, using the MM3 method, we found its most stable conformer. This one was minimized once again using the Density Functional Theory and the B88LYP hybrid functionals (Fig. 6b). Apparently, both cavities remain able to form host–guest complexes by inclusion phenomena.

2.2. Applications

Two specific applications based on the spectral and electrical properties of these cyclophanes could be envisaged.

2.2.1. Sensing ability of indolizine *12*

The interaction between the fluorescent indolizine **12** and 1-naphthol has been studied. The host–guest complexation was proved by the fluorescence spectra of indolizine **12** in the absence and presence of 1-naphthol (Fig. 9), the employed methodology being described in previous papers.[31] Thus,



Scheme 4. Synthesis of the final sensor **14**.

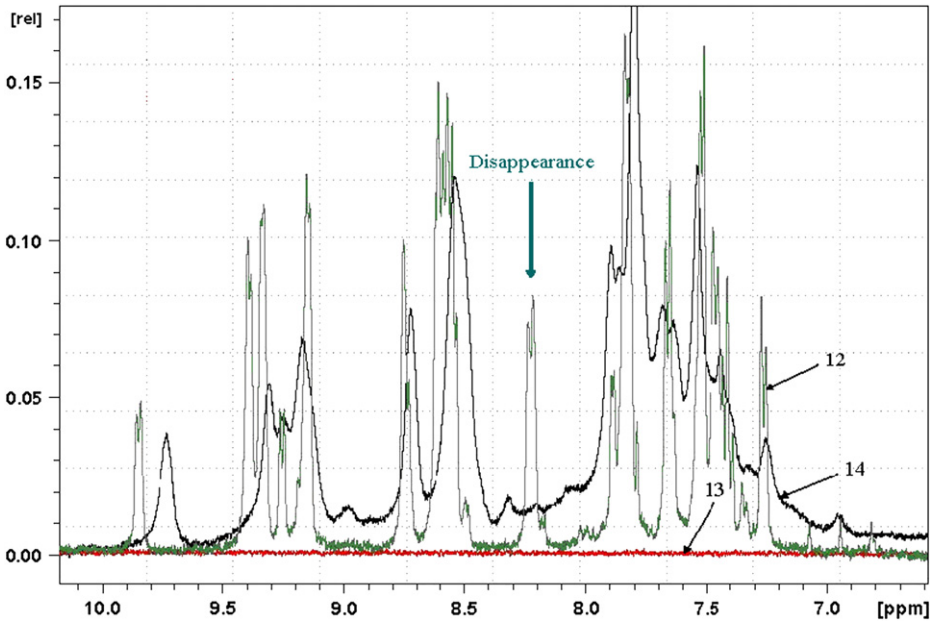


Figure 7. NMR spectra of compounds **12**–**14** in their aromatic domains.

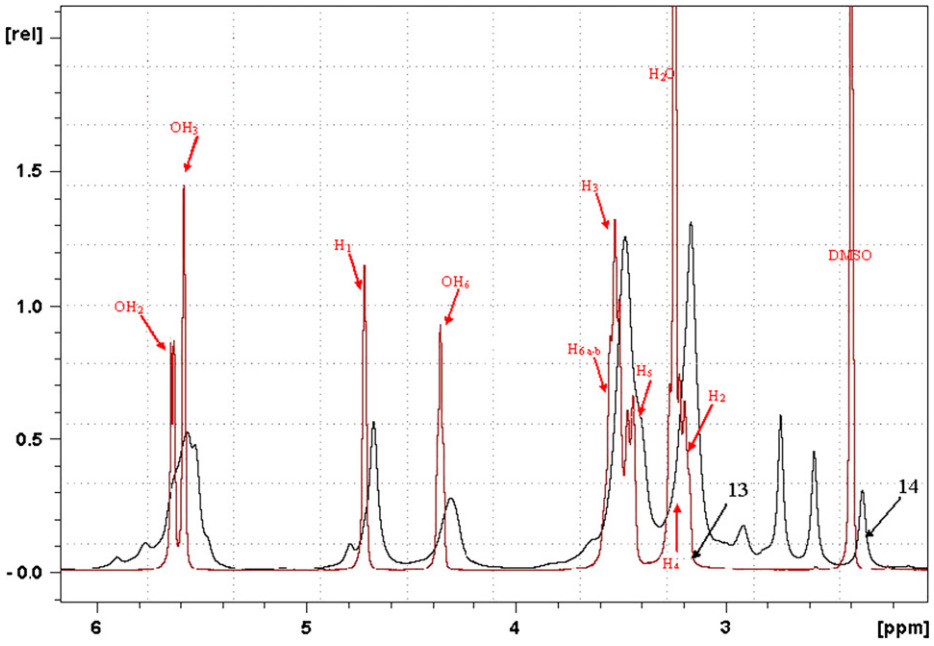


Figure 8. ^{1}H NMR spectra of compounds **13** and **14** on their aliphatic domain.

a sensitivity factor of $(\Delta I/I_0)=-0.48$ could be estimated. Such a value is comparable to the sensitivity observed for indolizino modified cyclodextrins. Furthermore, using a specific docking procedure,[32] the most stable structure of the inclusion complex has been simulated (Fig. 10). The computed complexation energy found in this case is 25.90 kcal/mol.

More detailed aspects concerning the inclusion of various VOCs into this type of cyclophanes will be published soon.

2.2.2. *Electrical properties*

The conductances of sensor **14** were measured at different frequencies and different temperatures. The experiments were performed on product **14** as compacted pastilles. The assembly used for measurements comprises an impedance analyzer, a temperature sensor, and a heating system. All components are connected to a PC. The general assembly was described in previous papers.[33]

As an example, Figure 11 shows the variation of the conductance function on temperature at a frequency of 100 Hz. After an initial increase of conductances (up to 45 °C) they decrease with increasing temperature and remain constant at around 100 °C. As a very interesting experimental aspect, we found that samples reach their initial conductivities when cooled to room temperature. This experiment is time

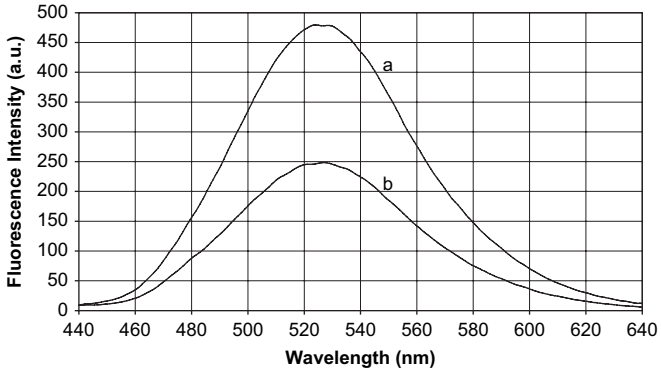


Figure 9. Fluorescence spectra of indolizine **12** (0.01 mM): (a) in the absence and (b) in the presence of 1-naphthol (0.1 mM).

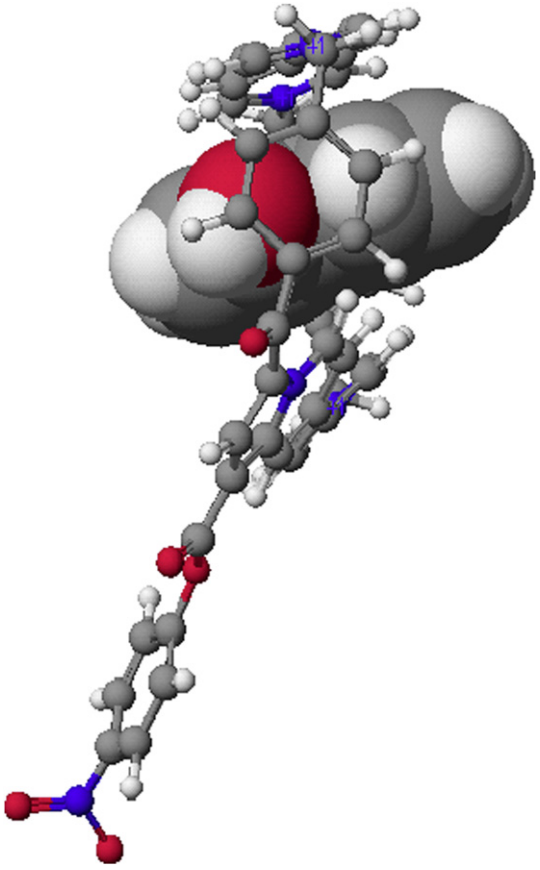


Figure 10. The most stable computed structure of the inclusion complex between indolizine **12** and 1-naphthol.

reproducible without any modification of conductivity values. According to our theoretical model[33] this is caused by the transformation of sensor **14** charged (3+) in its corresponding less conductor charge-transfer complex (2+•). Indeed, a charge transfer between a sensor **14** and an intramolecular biradical corresponding to the monoylide of **14**—by heating or light exposure—forms the less conductor species $\mathbf{14}^{(2+\bullet)}$.

As a conclusion, the light or thermal energy involved in the decrease of conductances is recovered while the compound reaches its initial electronic pattern and conductivity. This experiment must be explored by developing devices that realize

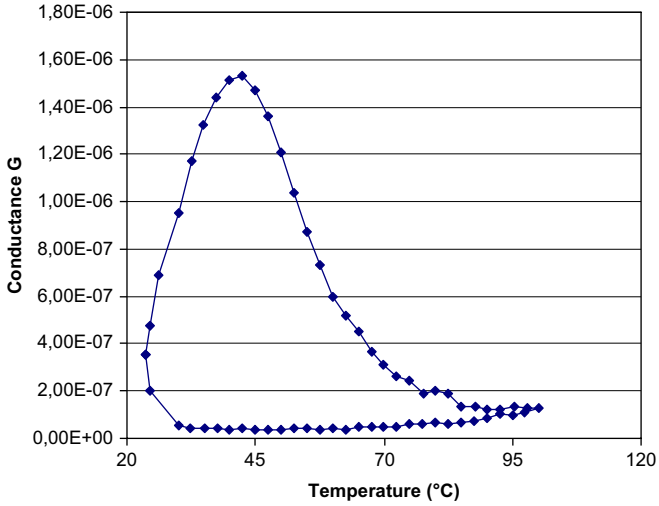


Figure 11. Conductance measurements at different temperatures at 100 Hz.

the stockage of thermal energy or convert light energy into thermal energy.

Also, the experimental results presented briefly in this last section will be published soon in a more developed manner.

3. Conclusions

For the first time, the template synthesis of 'CETOBOX' **8** has been achieved. The 'CETOBOX' exists in three tautomeric forms. Experimentally, their presence was proved by NMR spectroscopy, UV–vis spectroscopy coupled with pH titration, and by synthesis. Theoretically, using MM3, AM1, AM1 (COSMO), and B88LYPDFT procedures, the most stable conformers of every tautomeric form have been established. 'CETOBOX' **8** furnishes only the corresponding monoylide **9**, which by a 3+2 cycloaddition permits the synthesis of a fluorescent indolizine cyclophane **12**. Cycloadduct **12** by amidation with 6-amino-β-cyclodextrin **13** gives the two-cavity fluorescent sensor **14** with good yields. Principally, all structures of the new compounds presented in this paper have been determined by NMR spectroscopy (^{1}H and ^{13}C NMR, TOCSY, COSY, and NOESY). The fluorescent indolizine **12** shows inclusion capability. It forms a host–guest complex with 1-naphthol. Also, sensor **14** presents interesting electrical properties, which permit us to take it into consideration for uses in stockage or converting energy processes.

4. Experimental section

4.1. 1,1′-(1-Methylene-carbonyl-phenylene-4-methylene)bis(4,4′-bipyridinium)-bis(hexafluorophosphate) (7)

A solution of **6** (3.42 mmol) in acetonitrile (40 mL) was added over 1 h to a solution of 4,4′-bipyridyl **1** (17.15 mmol) that is also in acetonitrile (70 mL) heated under reflux. The reaction mixture is kept under reflux and nitrogen atmosphere, with stirring, for another hour. After cooling to room temperature, the

crude blue precipitate was filtered off and washed with a large amount of acetonitrile before being dissolved in a small volume of methanol (4–5 mL). The resulted solution was passed through a silica gel column with a mixture of MeOH–aqueous NH_4Cl 2 mol L^{-1} solution (3:2) as the eluant. The fractions containing the salt (R_f=0.32) were combined and concentrated under vacuum. Finally, the resulted solid was then dissolved in water (400 mL) and a saturated aqueous solution of NH_4PF_6 was added until no further precipitation was observed. The obtained orange solid salt **7**, as hexafluorophosphate, was filtered and successively washed with large quantities of water (50 mL) and ethyl ether (30 mL).

Yield=60%; melting point: 222 °C; IR (cm^{-1}): 555.6, 620.2, 996.5, 1219.6, 1407.6, 1642.8, 1701.6, 3130.8, 3647.9; ^{1}H NMR spectra, DMSO-d_6, δ (ppm): 6.09 (s, 2H, H_1), 6.55 (s, 2H, H_2), 7.84 (d, 2H, H_3, J=8.0 Hz), 8.06 (m, 4H, H_4), 8.15 (d, 2H, H_5, J=8.0 Hz), 8.76 (m, 4H, H_6), 8.90 (m, 4H, H_7), 9.08 (d, 2H, H_8, J=8.0 Hz), 9.44 (d, 2H, H_9, J=8.0 Hz); ^{13}C NMR spectra, DMSO-d_6, δ (ppm): 61.3 (C_1), 66.8 (C_2), 121.3 (C_3), 123.3 (C_4), 126.2 (C_5), 127.0 (C_6), 130.2 (C_7), 134.9 (C_8), 142.6 (C_9), 146.5 (C_{10}), 151.1 (C_{11}), 153.7 (C_{12}), 191.1 (C_{13}).

4.2. Cyclo(paraquat-p-phenylene-paraquat-p-phenylene-carbonyl)tetrakis(hexafluorophosphate) (*8*)

In a 100 mL round-bottomed flask, the template **4** (3.6 mmol), 1,4-bis(bromomethyl)benzene **2** (1.2 mmol), and the salt **7** (1.2 mmol) were dissolved in dry DMF (50 mL). The homogenous reaction mixture was stirred over 6 days, in the absence of light, under nitrogen atmosphere and at room temperature. By vacuum distillation of DMF, a brown viscous solid was separated. This one was dissolved in 20 mL aqueous ammonium chloride solution (2 mol L^{-1}). In order to eliminate the template **4**, a liquid–liquid extraction between this solution and chloroform was performed over 3 days. Next, the aqueous phase is concentrated and passed on a silica gel column using a mixture of MeOH–aqueous NH_4Cl 2 mol·L^{-1} solution–nitromethane (4:4:2) as the eluant. The fractions containing the salts (R_f=0.16) were concentrated. The crude solid was dissolved in water (350 mL) and 'CETOBOX' **8** was precipitated by adding a saturated aqueous solution of NH_4PF_6 until no further precipitation was observed. The solid salt **8** after filtration was successively washed with large quantities of water (50 mL) and ethyl ether (50 mL). The yield in dry pale yellow salt **8** is 12%.

IR (cm^{-1}): 549.9, 855.4, 1211.0, 1443.1, 1631.1, 1701.6, 3130.8, 3648.0. Elemental analysis: C 39.36% (39.39% found), H 2.84% (2.88% found), N 4.96% (4.93% found), O 1.42%, P 11%, F 40.42%. Keto form, ^{1}H NMR spectra, DMSO-d_6, δ (ppm): 5.80 (4H, H_1, H_6), 5.91 (1H, H_{15}), 5.97 (1H, H_{15}), 6.42 (2H, H_{21}), 7.55 (2H, H_4, H_{33}), 7.68 (2H, H_{17}, H_{38}), 7.91 (2H, H_3, H_{32}), 8.01 (2H, H_{18}, H_{39}), 8.62 (8H, H_9, H_{12}, H_{24}, H_{27}, H_{31}, H_{35}, H_{36}, H_{41}), 8.78 (1H, H_{28}), 8.96 (1H, H_{40}), 9.08 (1H, H_{23}), 9.24 (1H, H_{30}), 9.36 (4H, H_8, H_{13}, H_{34}, H_{37}). Enol form, ^{1}H NMR spectra, DMSO-d_6, δ (ppm): 4.19–4.23 (2H, H_6), 5.79–5.89 (4H, H_1, H_{15}), 6.31 (1H, H_{21}), 7.47 (2H, H_3, H_{32}), 7.60 (2H, H_{17}, H_{38}), 7.70 (2H, H_4, H_{33}), 7.85 (2H, H_{18}, H_{39}), 8.52 (8H, H_9, H_{12}, H_{24}, H_{27}, H_{31}, H_{35}, H_{36}, H_{41}), 8.85 (2H, H_{13}, H_{37}), 8.97 (2H, H_{23}, H_{40}), 9.19 (4H, H_8, H_{28}, H_{30}, H_{34}).

4.3. 1-(4-Nitro phenoxycarbonyl)-7-(4′-pyridinium-1′-methyl-p-phenylene-paraquat-p-phenylene-carbonyl)-3-indolizine-tris(hexafluorophosphate) (*12*)

In a 100 mL round-bottomed flask, 'CETOBOX' **8** (0.09 mmol) was dissolved in dry DMF (30 mL). To this solution, under nitrogen atmosphere and stirring, a second solution of 4-nitrophenyl propynoate **10** (0.09 mmol) in dry DMF (10 mL) was added. The reaction mixture was kept at 0 °C and a solution of freshly distillated triethyl amine (0.27 mmol) in dry DMF (1 mL) was added gradually over 10–15 min. Then stirring was maintained over 20 h, under nitrogen atmosphere, in the absence of light and at 10 °C. DMF and the excess of TEA were removed by vacuum distillation up to a volume of 10 mL. The crude liquid was passed on a silica gel column using a mixture of MeOH–aqueous NH_4Cl 2 mol L^{-1} solution–nitromethane (4:4:2) as the eluant. The fractions containing the salt (R_f=0.4) were concentrated. The crude solid was dissolved in water (200 mL) and then precipitated by adding a saturated aqueous solution of NH_4PF_6 until no further precipitation was observed.

Yield=30%; melting point: 269 °C; IR (cm^{-1}): 549.8, 826.1, 1172.8, 1343.2, 1519.4, 1637.0, 1719.2, 3130.8. Elemental analysis: C 47.13% (47.09% found), H 2.90 % (2.94% found), N 5.97% (5.94% found), O 6.83%, P 7.94%, F 29.20%. ^{1}H NMR spectra, DMSO-d_6, δ (ppm): 4.40 (2H, H_{24}), 5.73–5.79 (3H, H_{15}, H_{29}), 5.93 (1H, H_{15}), 7.25 (2H, H_{26}, H_{42}), 7.45 (4H, H_{27}, H_{43}, H_{49}, H_{53}), 7.64 (2H, H_{13}, H_{37}), 7.83 (2H, H_{12}, H_{36}), 8.23 (2H, H_{50}, H_{52}), 8.58 (7H, H_3, H_{18}, H_{21}, H_{32}, H_{34}, H_{39}, H_{40}), 8.75 (2H, H_5, H_8), 9.16 (2H, H_{31}, H_{35}), 9.32 (2H, H_{38}, H_{41}), 9.41 (2H, H_{17}, H_{22}), 9.81 (1H, H_2).

4.4. 1-(Carbonyl-amino-6-deoxy-β-cyclodextrin-6-yl)-7-(4′-pyridinium-1′-methyl-p-phenylene-paraquat-p-phenylene-carbonyl)-3-indolizine-tris(hexafluorophosphate) (*14*)

In a 50 mL round-bottomed flask, the cycloadduct **12** (0.01 mmol) and 6-amino-β-cyclodextrin **13** (0.01 mmol) were dissolved in dry DMF (20 mL). The reaction mixture was stirred over 20 h, in the absence of light, at room temperature and under nitrogen atmosphere. By vacuum distillation, the mixture volume was reduced to 10 mL and then it was poured drop wise in acetone (75 mL). The separated solid product with a yellow-orange color was filtered and dried out to furnish the fluorescent final sensor **14** with a yield of 80%.

Melting point: 287 °C; IR (cm^{-1}): 465.1, 577.4, 755.3, 1027.9, 1411.9, 1660.8, 2362.2, 2928.9, 3410.1. Elemental analysis: C 45.45% (45.42% found), H 4.61% (4.65% found), N 3.23% (3.20% found), O 26.60%, P 4.3%, F 15.8%. ^{1}H NMR spectra, DMSO-d_6, δ (ppm): 3.13–3.80 (42H, H_{2cyclo},

H_{4cyclo}, H_{3cyclo}, H_{5cyclo}, $H_{6a-b\ cyclo}$), 4.20–4.40 (6H, OH_{6cyclo}), 4.63–4.82 (7H, H_{1cyclo}), 5.40–5.71 (14H, OH_{3cyclo}, OH_{2cyclo}), 5.75–5.80 (4H, H_{29}, H_{24}), 5.88 (1H, H_{15}), 5.91 (1H, H_{15}), 7.41 (2H, H_{42}, H_{26}), 7.52 (2H, H_{43}, H_{27}), 7.66 (2H, H_{13}, H_{27}), 7.83 (3H, H_{36}, H_{12}, H_3), 8.54–8.60 (6H, H_{34}, H_{32}, H_{40}, H_{21}, H_{39}, H_{18}), 8.75 (2H, H_5, H_8), 9.17 (2H, H_{35}, H_{31}), 9.33 (2H, H_{41}, H_{21}), 9.39 (2H, H_{38}, H_{17}), 9.85 (1H, H_2).

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2007.11.006.

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