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Synthesis, X-ray structure and photophysical properties of a pyrido dithia bridged anthracenophane

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Summary — A dithia pyrido bridged (9,10) anthracenophane (compound **7**) was designed as a luminescent chemosensor for soft cation recognition. The synthesis and the X-ray structure are described. The pyridine ring is tilted by 13° with respect to the anthracene ring and the nitrogen atom lone pair is ≈ 2.7 Å from the anthracene ring centre. This may explain the significant perturbation of the UV spectrum compared to 9,10-di-*n*-propylanthracene, a reference molecule. The structured fluorescence spectrum reflects the absorption characteristics. Compound **7** displays a non fluorescent charge-transfer complex with silver (I).

heteracyclophane / absorption spectra / fluorescence spectra / molecular signalization / silver cation charge transfer complex / X-ray analysis

Résumé — Synthèse, structure radiocristallographique et propriétés photophysiques d'un pyrido anthracénophane à deux ponts soufrés. *Un pyrido (9,10)anthracénophane (composé 7) à deux ponts soufrés a été conçu comme sonde fluorescente chimique pour la reconnaissance des cations mous. La synthèse et la structure radiocristallographique sont décrites. Le noyau pyridine est incliné de 13° par rapport au plan de l'anthracène et le doublet libre de l'atome d'azote est à ≈ 2,7 Å du centre du noyau anthracénique. Ceci peut expliquer l'importante perturbation du spectre UV par comparaison avec le 9,10-di-*n*-propylanthracène, une molécule de référence. Le spectre de fluorescence structuré reflète les caractéristiques du spectre d'absorption. Le composé 7 forme avec l'argent (I) un complexe de transfert de charge non fluorescent.*

hétéracyclophane / spectre d'absorption UV / spectre de fluorescence / signalisation moléculaire / complexe de transfert de charge du cation argent (I) / analyse radiocristallographique

Introduction

Considerable research has been undertaken on the design of receptor molecules that respond to substrate binding by displaying characteristic optical effects [1, 2]. Such processes may be considered to represent substrate-specific generation of photosignals through changes in absorption properties or in luminescence enhancement or quenching. They participate in the development of a *semiochemistry*, the chemistry of molecular signalization [3].

Macrocyclic structures allow the positioning of luminescent groups at given distances and orientations with respect to substrate binding sites. This gives access to the study of the effect of bound species on the photophysical properties of these groups. Conversely, the perturbation of their luminescence also provides a means of detecting the binding of the substrates, in particular of metal ions.

We have shown earlier that the luminescence of macrobicyclic and macrotricyclic anthraceno-cryptands was indeed markedly affected by the binding of metal ions or diammonium substrates [4]. The photophysical changes observed were dependent on the nature and positioning of the species, thus acting as a luminescent probe and providing information about the structure of the complex formed.

We now report the synthesis, crystal structure and photophysical properties of an anthracenophane ligand **7** that contains a dithia-pyridine binding site, and describe the effect of metal ion complexation. A heterotopic macrocycle containing the same dithia-pyridine groups and a phenazine unit have been obtained earlier [5].

Synthesis of the dithiapyrido anthracenophane 7

Acid catalyzed condensation of 1,2-dimethoxybenzene with acetaldehyde afforded the tetrasubstituted anthracene **3** via **2** in 46% overall yield according to

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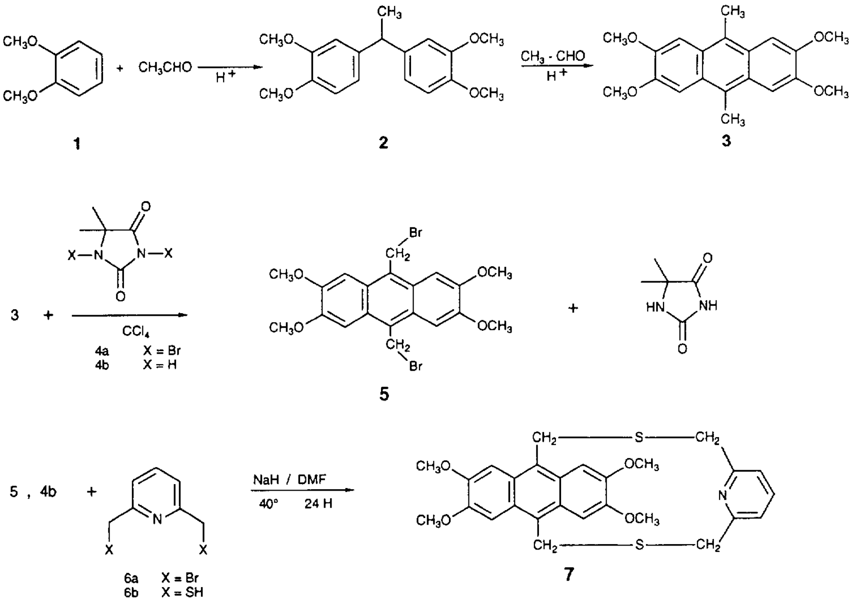
[*] Correspondence and reprints



Scheme 1

literature procedures [6, 7] (see scheme 1). Treatment of **3** with *N*-bromohydantoin **4a** gave the bis-bromomethyl derivative **5** (97% yield) [8]. Pyridine-2,6-dimethanethiol **6b** [9] was obtained by reacting the corresponding bis-bromomethyl precursor **6a** [10] with thiourea (78% yield). Condensation of the bis-sodium salt of **6b** with **5** afforded the dithiapyrido-anthracenophane **7** (54% yield).

Spectral (NMR spectrum, fig 1) and microanalytical data agree with the formulations **5**–**7**. The structure of **7** was confirmed by X-ray crystallography. The dimeric structure that would result from the condensation of two molecules of **5** with two molecules of **6b** was not obtained in experiments performed under several different conditions.

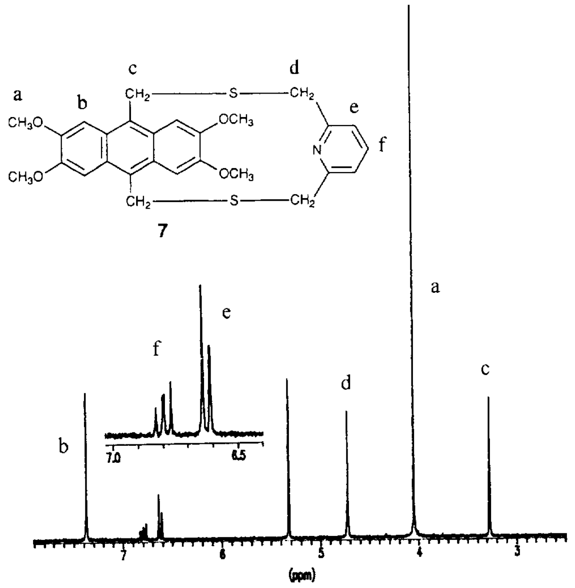


Fig 1. The ^{1}H NMR spectrum of compound **7** in CD_2Cl_2 at room temperature.

X-ray structure of the dithiapyrido anthracenophane 7

Compound **7** represents a macrocyclic system containing both an anthracene unit and a dithiapyridine that bridges the anthracene unit in the 9,10 position (here denoted 1,8; fig 2), thus positioning a metal binding site in close proximity to a luminescent group. Detailed information about the shape of

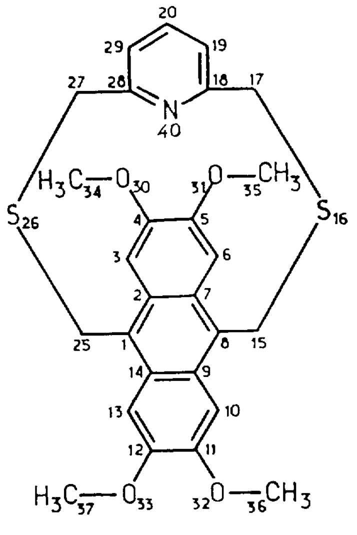


Fig 2. Crystallographic numbering of compound **7**.

7 was obtained by determination of its crystal structure. Single crystals of **7** ($0.35 \times 0.35 \times 0.65$ mm^3) were grown by slow evaporation of a chloroform/toluene (1:1 v/v) mixture solution (see technical data in the Experimental section). Projections of the structure along two directions are represented in figures 3 and 4.

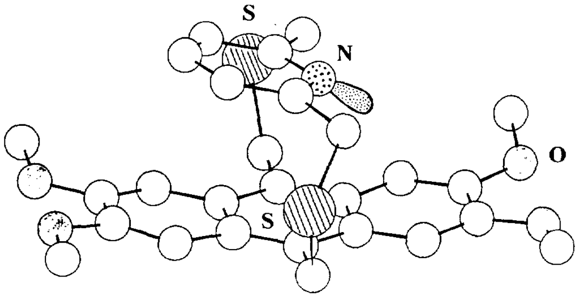


Fig 3. Projection of compound **7** along a direction close to the short axis of the anthracene ring. The hydrogens have been omitted for clarity.

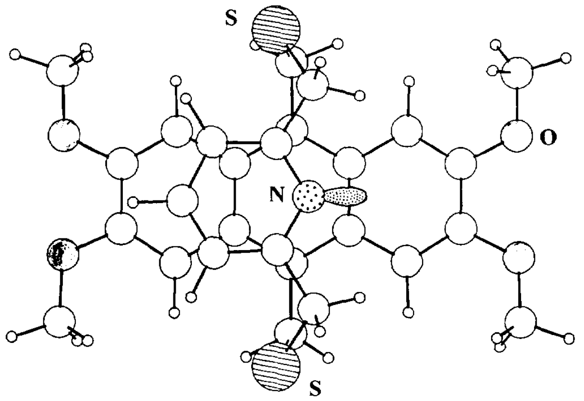


Fig 4. Projection of compound **7** on the anthracene mean plane. Note the position of the N atom near the perpendicular of the anthracene ring centre.

The molecule exhibits a pseudo-mirror containing the long axis of the anthracene nucleus and passing through atoms C(20) and N(40) of the pyridine group (fig 2). The pyridine and anthracene rings are not parallel, making a 13° angle (fig 3). The N atom is situated near the perpendicular of the anthracene ring centre, at a distance of 2.88(1) Å from the mean plane (fig 4). Starting from this position, the calculated distance between the lone pair centre and the anthracene mean plane was found to be 2.7(1) Å. All intramolecular bond lengths and angle were found to be as usually observed, which indicates the absence of any significant molecular strain.

The maximum deviation of the carbon atoms from the mean plane of the anthracene nucleus is 0.16 Å. Comparison with previously reported data [14] shows a slight folding (≈ 5°) of the two side rings, which are oriented inward the cavity; this can be linked with the presence of the four OCH_3 groups which are slightly tilted out of the anthracene ring [0.35–0.40 Å and 0.84 Å for C(37)]. A systematic calculation of the intermolecular distances points to some contacts involving mainly O(30), O(31), S(16) and S(26) with the neighboring hydrogen atoms (table I).

Table I. Selected shortest intermolecular contacts in the crystal lattice of compound **7**.

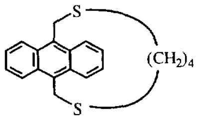
A	*B*	*A···B (Å)*	*Symmetry of B*
S(16)	H(132)	3.0	IV + *a* + *b*
S(26)	H(227)	2.7	III
H(225)	O(30)	2.5	II + *a* − *c*
H(234)	O(31)	2.6	II + *a* − *c*
H(334)	O(30)	2.6	II + *a* − *c*
H(335)	O(33)	2.7	I + *c*
N(40)	H(115)	2.7	IV + *a* + *b* − *c*

I: $x \quad y \quad z$; II: $-y \quad x - y \quad z + 2/3$;
III: $2 - x \quad 1 - y \quad z$; IV: $y \quad y - x \quad z + 2/3$.

No significant interactions were noticed between the anthracene nuclei. Consequently, the single crystal fluorescence emission spectrum (see below) cannot reflect intermolecular interactions in the *ordered* crystal. But as the crystals are relatively unstable (12% decrease while recording the intensities), one can consider intermolecular interactions in the *crystalline defects*, the number of the latter increasing with time.

Electronic absorption and emission spectrometry of 7

Compound **7** is a monoanthracenocyclophane (*ansa* type) [15]. As shown by Rosenfeld [16], a relief of strain occurs for a bridge of at least eight members as observed in derivatives such as **8**; other anthracenophanes of this



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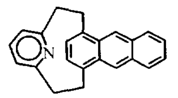

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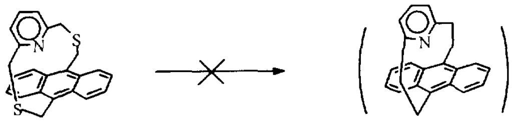
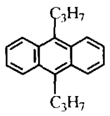


10 **11**



R

type have been prepared [17, 18]. Of special relevance to this work is the study of several pyridinocyclophanes, particularly **9** and **10**, by Haenel and coworkers [18].

In **9**, the pyridine ring of the 1,4 bridge should be almost parallel to the anthracene ring according to the X-ray structure of the naphthalenic analogue [2], (1,4)-naphthaleno [2] (2,6)-pyridinophane [19]. Compound **10** was prepared by the authors as a starting material for the synthesis of **11** which failed; therefore **10** was not described [18]. The absorption and emission spectra of **9** (fig 5a) are those of an anthracene ring slightly perturbed by 1,4-dialkyl substitution [20a,b] and interaction with a non conjugated pyridine ring; the fluorescence emission is not that of an amine–arene exciplex but has a marked monomer character [2, 18–20c].

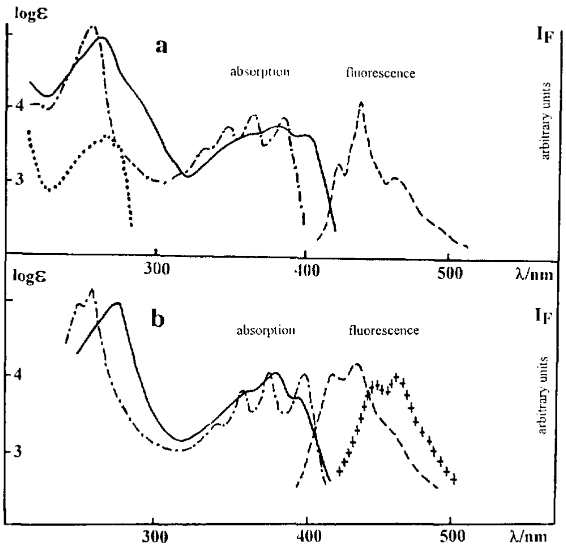


Fig 5. **a** UV absorption spectra of **9** (solid line), 1,4-dimethylanthracene (dot-dash) and 2,6-dimethylpyridine (dotted line) in cyclohexane. Fluorescence emission spectrum of **9** in *n*-octane (dashed line) (adapted from ref [17]). **b** UV absorption spectra of **7** (solid line) (20 °C; $\approx 10^{-4}$ M) and 9,10-di-*n*-propylanthracene (R) (dot-dash) in methanol. Corrected fluorescence spectra of **7** (dashed line) in degassed methanol and from a single crystal (hatched line); λ_{exc} 375 nm.

The absorption and fluorescence spectra of compound **7** in MeOH manifest a clear perturbation compared with the spectrum of 9,10-di-*n*-propylanthracene (R) taken as reference molecule. The usual ^1B_b band which peaks at 260 nm (ε: 165.000) is replaced by a lower intensity absorption at 276 nm, presumably resulting from the interaction of pyridine and anthracene along the long axis (fig 5b). The ^1La transition (300–400 nm) is also perturbed as shown in figure 5b; in particular the band at 398 nm (ε: 11.500) in R undergoes a hypochromic effect and a hypsochromic shift. This perturbation is reflected in the fluorescence emission which exhibits only little fine structure with no typical exciplex band, indicating a moderate interaction with another chromophore, particularly the nitrogen lone pair. But, even though the spectrum is not strongly red-shifted as it would be for a fluorescing exciplex, compound **7** undergoes an important fluorescence quenching (ϕ_F: 0.045; see table II). Interestingly, the single crystal fluorescence spectrum displays a similar shape but is red shifted by ≈ 28 nm ($\Delta v \approx$ 1 500 cm^{-1}). This shift, in addition to the frequently observed bathochromic crystal effect, could be due to an additional intermolecular interaction between the pyridine ring and the closest anthracene ring occurring not in the ordered crystal bulk (see the section on X-ray structure) but rather in dislocation zones and crystal defects where it is known that the structure may be different [21].

Table II. Fluorescence quantum yield in degassed methanol of 9,10-di-*n*-propylanthracene (R), taken as reference molecule, **7**, and **7** with a large excess of $AgNO_3$ or $TlNO_3$.

	R	*7*	*7 + Ag⁺*	*7 + Tl⁺*
ϕ_F	0.8	0.045	0.01 [5]	0.06

Electronic absorption and emission spectra of 7 in the presence of soft cations

The presence of two sulfur atoms and an sp^2 nitrogen (pyridine) in the close environment of a π system substituted by electron donating groups seemed to be well suited to binding soft metal cations; such a tridentate chelating unit has been incorporated previously in heterotopic macrocyclic ligands [5, 11–13]. We tried to grow crystals of charge-transfer complexes in order to determine their X-ray structure. Unfortunately, all attempts to isolate good crystals met with failure.

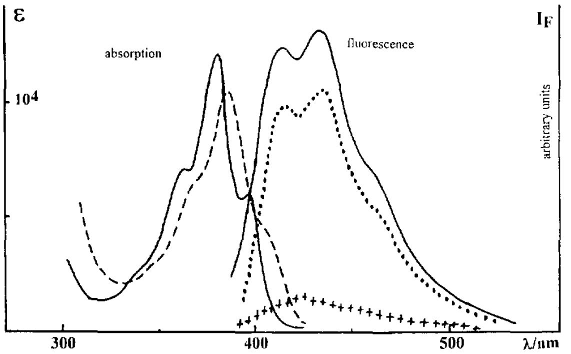


Fig 6. Absorption spectra in MeOH of **7** (solid line) and of a mixture of **7** and $AgNO_3$ (in equimolar amounts, conc $\approx 10^{-4}$ M (dashed line). Corrected fluorescence spectra of **7** (solid line); **7** + $AgNO_3$ (1:1) (dotted line); **7** + $AgNO_3$ (1:12) (crosses), in degassed methanol; λ_{exc} 375 nm.

The UV absorption spectrum undergoes slight modifications in the presence of $Cd(Cl)_2$, Th $(NO_3)_4$ $4H_2O$, or Tl NO_3. The effects were found to be more significant with $AgNO_3$ and are described hereafter. The spectra are reproduced in figure 6. A charge transfer absorption band appears at $\lambda_{max} \sim 405$ nm for an equimolar amount of $AgNO_3$ in MeOH at $\approx 10^{-4}$ M. For this mixture, the fluorescence emission spectrum was unchanged in shape but less intense; the excitation spectrum was that of pure **7**, not of the CT complex. One concludes that the CT complex is not fluorescent, as already observed with an anthracenocryptand [4]. In the presence of a large excess of $AgNO_3$ (> 10 molar equiv), the fluorescence quantum yields drops down to $\approx 10^{-2}$. With $TlNO_3$, the fluorescence yield is enhanced (table II). Coordination of Tl^+ with sulfur and nitrogen can decrease the quenching interaction of the heteroatoms lone pairs with the aromatic ring but this is compensated by the heavy atom quenching effect. It is difficult to evaluate quantitatively the contribution of each effect.

The requirement for an excess of salt in order to observe large fluorescence changes indicates weak binding of the metal ions to ligand **7**. This may be related to the fact that, as shown by the crystal structure (fig 3, 4), the sulfur sites of the NS_2 chelating unit are oriented away from the pyridine site.

Conclusion

Anthracenophane ligand **7** incorporating a dithiapyridine binding site has been synthesized to characterize soft cations by fluorescence modulation. The X-ray structure of **7** has been described, as well as its absorption and fluorescence spectra. **7** forms charge-transfer complexes with various soft cations, particularly with silver (I).

Experimental section

Melting points were measured on a Kofler Heizbank or on a DSC 2 Perkin-Elmer calorimeter. Column chromatography was carried out on Merck 230–400 mesh Kieselgel 60. Anal and prep TLC were carried out on Merck or Machery–Nagel silicagel plates. The NMR spectra were determined on a Bruker AM-200-SY spectrometer. Mass spectra and microanalyses were performed by the Service de spectrométrie de masse and the Service central d'analyses du CNRS, Vernaison, France.

Synthesis

Compounds **2** (mp 78–79 °C; lit 77–77.5 °C) [6] and **3** (mp 327 °C; lit 316 °C) [7] were prepared according to literature procedures in yields of 52 and 89% respectively.

9,10-Bis(bromomethyl)-2,3,6,7-tetramethoxy anthracene **5** *[8]*

A suspension of **3** (0.652 g; 2 mmol) and **4a** (0.572 g; 2 mmol) in CCl_4 (80 mL) was stirred and heated to reflux under nitrogen for 6 h. After cooling, the yellow solid was filtered and washed with CCl_4. This crystalline material was found to consist of equimolar amounts of **5** and **4b** (0.940 g; 97%) and was used as such. mp > 260 °C.

^{1}H NMR (200 MHz,$CDCl_3$) δ_H 1.47–1.59 (d, 2 CH_3 of **4b**); 4.12 (s, 12H, OCH_3); 5.36 (s, 4H, CH_2); 7.41 (s, 4H, aromatics).

Anal calc for $C_{25}H_{28}O_6N_2Br_2$: % C, 49.09; H, 4.61; N, 4.57; Br, 26.10. Found: C, 48.75; H, 4.51; N, 4.44; Br 25.68.

Pyridine-2,6-dimethanethiol **6b**

A suspension of dibromide **6a** [10] (0.980 g; 3.7 mmol) and thiourea (0.646 g; 8.5 mmol) in H_2O (20 mL) and EtOH (10 mL) was refluxed under nitrogen for 4 h. The reaction mixture was cooled in an ice bath and then acidified with H_2SO_4 (6 N) to pH 2. The mixture was extracted with CH_2Cl_2 (3×20 mL) and washed with H_2O and brine. After drying (Na_2SO_4) and filtering, the solvent was removed under vacuum, yielding crude **6b** (0.493 g; 78%) as a yellow oil, which was used without further purification.

1-(2,6)Pyridina-5(9,10)-2,3,6,7-tetramethoxy-anthracena-3,7-dithiacyclooctaphane **7**

To a suspension of NaH (50% dispersion in mineral oil; 0.075 g; 1.5 mmol) in dry DMF (20 mL) was added dropwise, under nitrogen over 8 h, a solution of **5** + **4b** (0.275 g; 0.45 mmol) and **6b** (0.077 g; 0.45 mmol) in dry DMF (330 mL). The reaction mixture was stirred vigorously at 40 °C for 24 h. After removal of the DMF under vacuum, the residue was taken up in CH_2Cl_2, washed with H_2O and brine, dried over Na_2SO_4, filtered and the solvent removed under vacuum, yielding a brown-yellow solid (0.312 g) which was purified by preparative TLC [9:1 CH_2Cl_2/Et_2O]. The major chromophoric band ($Rf = 0.67$) fluorescing at 350 nm (green) afforded **7** as a pale yellow powder (0.120 g; 54%) $\mathrm{mp_{inst}}$ = 260 °C.

UV: methylcyclohexane/chloroform (9:10 v/v) λ_{max}/nm (ε): 276 (128 000); 363 (9 800); 380 (15 150); 396 (8 000).

^{1}H NMR (200 MHz, CD_2Cl_2) δ_H 3.27 (s, 4H, CH_2S); 4.00 (s, 12H); 4.27 (s, 4H, CH_2-S on C9 and C10); 6.62 (d, 2H, pyridine H3 and H5); 6.80 (dd, 1H, pyridine H4).

MS (CI, NH_3) *m/e* 494 [MH^+], (100%).

Anal calc for $C_{27}H_{27}O_4NS_2$: C, 65.40; H, 5.51; N, 2.83; S, 12.99. Found: C, 65.40; H, 5.57; N, 2,57; S, 12.47.

Spectrometry

Ultraviolet spectra were measured on a Cary 219 spectrometer. The fluorescence spectra (and fluorescence excitation spectra) were recorded with a Hitachi Perkin-Elmer MPF 44 spectrofluorimeter. The fluorescence quantum yields were determined by comparison with quinine sulfate in 1 N sulfuric acid [22]. In all experiments, the solutions (conc $< 10^{-5}$ M) were degassed by the freeze–pump–thaw technique.

Solvents for spectroscopic measurements were of spectroscopic grade and used as received. Pure methanol was carefully distilled with a 1 m distilling column filled with Raschig rings. No fluorescent impurities were detected under our experimental conditions.

X-ray crystallography

Preliminary analysis by Weissemberg and precession cameras revealed a hexagonal symmetry with the unique condition $1 = 2n$ on the 001 reciprocal row, corresponding to the $P6_2$ spatial group. Intensities were collected on an automatic diffractometer. From 22 reflections the following crystallographic data were computed and refined:

system: hexagonal	spatial group: $P6_2$
$a = b = 19.910$ Å	$V = 4049.6$ Å^3
$c = 11.796$ Å	$Z = 6$

Intensities were measured with h varying from -24 to 24, k from 0 to 25, and l from 0 to 14, and were corrected for absorption effects by empirical methods. Consequently each value used for the structure determination was the average of three measurements. However it should be noted that the intensities decreased by 12% during the collection of data; an appropriate correction was performed. 2 953 average independent reflections were selected, of which 2 616 corresponded to the criterion $I > 3\sigma(I)$.

The structure was solved by the heavy atom method using the coordinates of the two sulfur atoms located by the Patterson method. The refinement of the structure by the least-squares method (block diagonal) was realized using isotropic thermal parameters. At this stage, hydrogen atoms were introduced in theoretical positions (including those of the CH_3-groups, using steric hindrance considerations) and the refinement of the positions of the non-H atom was completed using anisotropic thermal parameters; H atoms were refined (isotropically) at the last cycle.

The final factor of reliability is $R = 0.083$. Nevertheless the final Fourier-difference map shows maximum residual electronic densities of 0.4 $e^-/Å^3$ near the S atoms. The relatively high value of the R factor is probably due to the decrease of the intensities during the collection of data and the difficulty of correction for this effect.

$\lambda = 1.54178$ Å (Cu $K\alpha$)

$T = 293$ K

Polyhedral (0.35 × 0.35 × 0.65 mm) yellow crystals from a warm chloroform/toluene (1:1) solution

density: 1.215 g.cm^{-3}

$M = 493.6$ g.mol^{-1}

$\mu = 1.991$ mm^{-1}

$F\phi\phi\phi = 1\,560$ e$^-$/maille

Enraf-Nonius CAD4 diffractometer

$\theta/2\theta$ scans

3 standard reflections monitored every 100 reflections

intensity variation: 12%

absorption correction: empirical

Refinement on F.

$w = [\sigma^2(F) + 0.0004F2]^{-1}$

Atomic scattering factors from *International Tables for X-ray Crystallography* (1974, Vol IV, Table 2.3.1).

Supplementary material

Supplementary data have been deposited with the British Library, Document Supply Centre at Boston Spa, Wetherby, West Yorkshire, UK, as supplementary publication N° = SUP 90407 and is available on request from the Document Supply Centre.

References

1. For reviews see for instance: Löhr HG, Vögtle F, *Acc Chem Res* (1985) 18, 65; Bissell RA, de Silva AP, Gunaratne HQN, Lynch PLM, Maguire GEM, Sandanayake KRAS, *Chem Soc Rev* (1992) 21, 187
2. Desvergne JP, Fages F, Bouas-Laurent H, Marsau P, *Pure Appl Chem* (1992) 64 1231
3. Lehn JM, *Angew Chem* (1990) 102, 1347; *Angew Chem Int Ed Engl* (1990) 29 1304
4. Fages F, Desvergne JP, Bouas-Laurent H, Marsau P, Lehn JM, Kotzyba-Hibert F, Albrecht-Gary AM, Al-Joubbeh M, *J Am Chem Soc* (1989) 111, 8672; Fages F, Desvergne JP, Bouas-Laurent H, Lehn JM, Konopelski JP, Marsau P, Barrans Y, *J Chem Soc, Chem Commun* (1990) 655
5. Lehn JM, Schmidt F, Vigneron JP, *Tetrahedron Lett* (1988) 29, 5255
6. Arcoleo A, Natoli MC, *Ann Chim* (Roma), (1967) 57, 716; *Chem Abstr* (1968) 60, 2269C
7. Boldt P, *Chem Ber* (1967) 100, 1270
8. Ardecky RJ, Dominguez D, Cava MP, *J Org Chem* (1982) 47, 1609
9. *Chem Abstr* (1976) 85, 94335t (Jap Patent)
10. Offermann W, Vögtle F, *Synthesis* (1977) 272
11. Parker D, Lehn JM, Rimmer J, *J Chem Soc, Dalton Trans* (1985), 1517
12. Gunther MJ, Mander LN, Muray KS, Clark PE, *J Am Chem Soc* (1981) 103, 6784
13. Carroy A, Lehn JM, *J Chem Soc, Chem Commun* (1986) 1232
14. Drew GBM, Lairns C, Macfail SG, Nelson SM, *J Chem Soc, Dalton* (1980) 2020
15. a) Vögtle F, *Cyclophane Chemie*, Teubner, Stuttgart, 1990
    b) Tobe Y, In: *Topics in Current Chemistry*, Springer, Berlin, 1994, Vol 172, pp 1-40
16. Chung J, Rosenberg SM, *J Org Chem* (1983) 48, 387
17. Castellan A, Daney M, Desvergne JP, Riffaud MH, Bouas-Laurent H, *Tetrahedron Lett* (1983) 24, 5215
18. Haenel MW, Lintner B, Schweitzer D, *Z Naturforsch* (1986) 41b, 223
19. Haenel MW, Lintner B, Benn R, Rufinsha A, Schroth G, Krüger C, Hirsch S, Irngartinger H, Schweitzer D, *Chem Ber* (1985) 118, 4884
20. a) Brotin T, Waluk J, Desvergne JP, Bouas-Laurent H, Michl J, *Photochem Photobiol* (1992) 55, 335
    b) Brotin T, Desvergne JP, Fages F, Utermöhlen R, Bonneau R, Bouas-Laurent H, *Photochem Photobiol* (1992) 55, 349
    c) Fages F, Desvergne JP, Bouas-Laurent H, *J Am Chem Soc* (1989) 111, 96
21. Thomas JM, Morsi SE, Desvergne JP In: *Adv Phys Org Chem*, (Gold V, Bethell D Eds), Academic, New York, 1977, Vol 15, pp 63-151
22. Meech SR, Phillips D, *J Photochem* (1983) 23, 193