

Incorporation of sulphonated cyclodextrins into polypyrrole: an approach for the electro-controlled delivering of neutral drugs

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Abstract: The electro-controlled delivery of drugs based on the doping-dedoping mechanism of Electro-Conducting Polymers is restricted to charged substances acting as dopants. In order to overcome this limitation, this study presents an approach where the trapping/delivering is based on host-guest interaction. As an example of a neutral guest, the molecule N-methylphenothiazine (NMP) is encapsulated in the host, heptasulphonated β -cyclodextrin (β -CDSO₃⁻), which is tailor-made to dope PPy. The original synthetic method for β -CDSO₃⁻ is based on sulphonation of the periodated β -CD in the phase transfer medium. As a consequence of their size and of their multicharged character, β -CDSO₃⁻s are fixed dopants. The stability of the β -CDSO₃⁻ entrapment is checked by Optical Beam Deflection (mirage effect) measurements. The ionic movements associated with the switching of the β -CDSO₃⁻ doped PPy (PPy⁺, β -CDSO₃⁻) film appear to be mainly due to cations with this technique. Cyclic voltammetry experiments confirm the entrapment of neutral NMP by simply dipping the PPy⁺, β -CDSO₃⁻ film in a CH₃CN solution containing NMP. Repeated electrochemical cycling of such a reservoir electrode indicates the progressive elimination of NMP from the (PPy⁺, β -CDSO₃⁻ [NMP]) film.

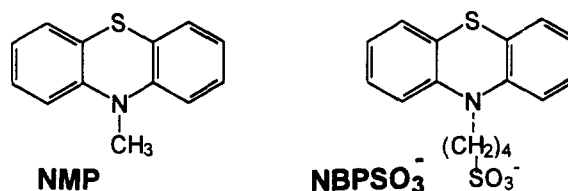
Keywords: Neutral drug sensor, drugs releaser, electro-conducting polymers, polypyrrole, doping by sulphonated cyclodextrin, sulphonated cyclodextrin synthesis, phenothiazine, cyclic voltammetry, optical beam deflection, mirage effect, ionic movements.

INTRODUCTION

Electro-Conducting Polymers (ECPs) are being increasingly studied for application in the field of sensors. ECPs offer a remarkable transduction matrix that can be sensitive to gases, vapours, ions and biomolecular systems, resulting in a straightforward conductance, impedance or redox potential monitoring "via" modulation of their doping level (Bidan, 1992). Another advantage of the reversible doping/dedoping mechanism of ECPs is that it stoichiometrically associates ionic movements with electrical currents (see Scheme 1). This property has previously been exploited by Miller *et al.* (Blankespoor & Miller, 1985; Miller *et al.*, 1987; Miller & Zhou, 1987; Zhou *et al.*, 1989) and others (Josowicz & Janata, 1987; Li & Dong, 1992), for the electro-controlled delivery of charged biological substances that play the role of the doping anions—glutamate (Blankespoor & Miller, 1985), salicylate (Miller *et al.*, 1987) and ATP (Li & Dong, 1992)—or the role of the pseudo-doping cations—protonated dopamine (Miller & Zhou, 1987) and procaine (Zhou *et al.*, 1989), (see Scheme 1b).

It must be noted that there is almost no entrapment of neutral substances during the electrochemical growth or cycling of polypyrrole (PPy). However, Josowicz & Janata (1987) improved the sensitivity of PPy-based SGFET assembly to aromatic hydrocarbon vapours by previously depositing the PPy layer in the presence of nitroarene solvents. The authors proposed incorporation of these nitroarenes into the PPy matrix via the formation of charge-transfer complexes, or even by chemical copolymerization. In addition, Genies *et al.* (1988) were able to incorporate phenazine into polyaniline during the electrosynthesis process. More recently, Mendes-Viegas *et al.* (1992) tested the ability of PPy to incorporate neutral N-methylphenothiazine (NMP). This belongs to a family of neuroleptics that can be identified by their electroactivity (Scheme 2). The

authors showed that the electropolymerization of PPy was redox-mediated by the NMP; however, only a weak entrapment of NMP in the PPy matrix was observed. In fact, there were few changes in the voltammetric response (Fig. 1). Only a slight peak at about 0.45 V indicated the presence of NMP in the PPy film, which was estimated to be 0.4% w/w using ring-disk experiments (Mendes-Viegas *et al.*, 1992). In contrast, the negatively charged derivative, N-butylsulphonate phenothiazine (NBPSO₃⁻), is easily incorporated into PPy films (Lopez *et al.*, 1994) (Fig. 2). The facile release of NBPSO₃⁻ from PPy during redox cycles is comparable to the ferrocenemonosulphonate doped PPy behaviour (Lee *et al.*, 1993).

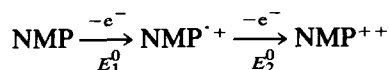


In order to overcome the limitation caused by the obligatory use of charged drugs this study presents the following approach: neutral substances are trapped into ECPs or delivered from ECPs layers by using sulphonated β -cyclodextrins as complex-forming agents with these neutral organic substances. First, an original synthetic method (Gadelle & Bayle, 1993), based on intermediary iodinated β -cyclodextrins, was developed to prepare new heptasulphonated β -cyclodextrins (β -CDSO₃⁻), which were "tailor-made" to dope PPy. In a second step, electrochemical methods coupled with laser beam deflection were used to confirm the incorporation of β -CDSO₃⁻ in PPy films. The aptitude of these films to entrap the neutral NMP was studied by cyclic voltammetry.

EXPERIMENTAL

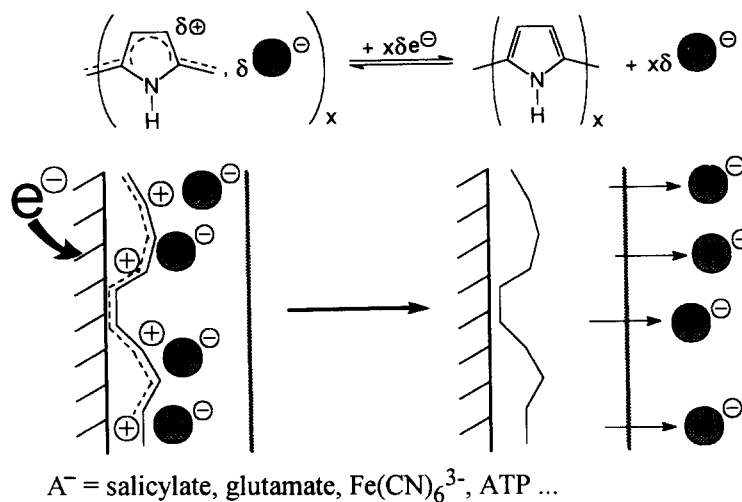
Chemical synthesis of β -CDSO₃⁻

Sodium per(6-deoxy)cyclomaltoheptaose(6-sulphonate): to a stirred aqueous solution of methyltriocetylammmonium sulphate (0.067 N, 120 ml), were added successively sodium sulphite (0.9 g, 7.3 mmol) and per(6-deoxy-6-iodo)cyclomaltoheptaose (0.9 g, 3.3 mequiv.). The clear solution, obtained within 30 min, was

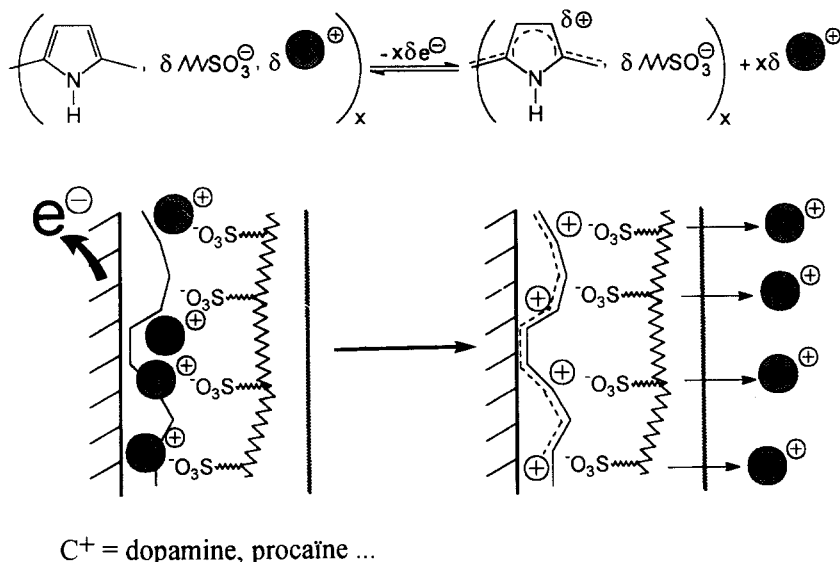


Scheme 2. In CH₃CN, 0.1 M LiClO₄, NMP exhibits two redox couples due to its successive oxidation to its radical cation (reversible) and dication (irreversible), respectively, at $E_1^0 = +0.45$ V and $E_2^0 = +1.07$ V vs. Ag/10⁻² M Ag⁺.

a -Doping by mobile anions :



b - Immobilized doping anions, or pseudo-doping by cations :



Scheme 1. Electrical switching of polypyrrole (PPy) between the doped and the dedoped state: (a) doping by mobile anions: the dedoping results mainly in the release of A^- in solution; (b) doping by immobilized anions, exemplified here by SO_3^- ; = a way of immobilization (covalent binding to PPy skeleton or to ionomers such as poly(styrenesulphonate) or to bulky groups such as persulphonated macrocycles). Consequently, the doping results mainly in the release of C^+ .

kept at 373°K. After 24 h, the cooled solution was extracted with dichloromethane (2×200 ml). The organic phase was concentrated *in vacuo* to dryness; the residue was solubilized in DMSO (2 ml), and then a mixture of methanol (250 ml), acetone (150 ml) and sodium hydroxide (4 ml, 1 N) was added. The

turbid solution was centrifugated and the pellet dissolved in water; the filtered solution was freeze-dried (0.7 g, 85%): m.p. 538°K, $[\alpha]_D +30.5^\circ$ (ca. 1.18 in H_2O); correct elemental analysis for $\text{C}_{42}\text{H}_{63}\text{O}_{49}\text{S}_7\text{Na}_7 \cdot 7 \text{H}_2\text{O}$ (find %: C 27.2, H 4.28, S 12.10); f.a.b.⁺ – m.s. (VG-ZAB-SEQ, thioglycerol-NaI): m/z 1759.4 (100,

$[M + Na]^+$), 1737.4 (37, $[M + H]^+$), 1655.3 (82, $[M - NaHSO_3 + Na]^+$), 1633.3 (63, $[M - NaHSO_3 + H]^+$); ^{13}C NMR (50 MHz, D_2O): δ 102.1 (C-1), 83.0 (C-4) 73.8, 72.8, 69.1 (C-2, C-3, C-5), 51.5 (C-6).

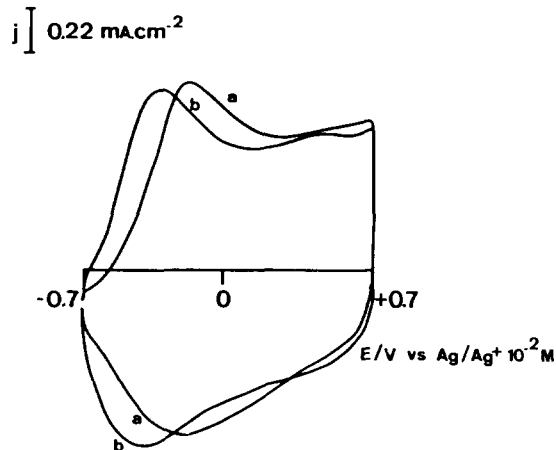


Fig. 1. Cyclic voltammetric curves of two PPy films synthesized under the same synthesis charge (0.163 C cm^{-2}). The films were cycled in a 0.5 M LiClO_4 acetonitrile solution at a sweep rate of 50 mV s^{-1} : (a) film synthesized from CH_3CN , 0.1 M LiClO_4 containing $4 \times 10^{-3} \text{ M pyrrole}$ at $+0.8 \text{ V}$ vs. $Ag/10^{-2} \text{ M Ag}^+$, in the absence of NMP; (b) film synthesized in the same conditions but in the presence of $2 \times 10^{-3} \text{ M NMP}$.

Electrochemical experiments

All experiments were performed at room temperature under an argon atmosphere. Pyrrole (Aldrich) was distilled under argon; N-methylphenothiazine (Kodak), lithium perchlorate (GFS) and acetonitrile (BDH; HPLC grade) were used as purchased, without purification. The organic electrolytic solution used was acetonitrile with 0.5 M LiClO_4 . Aqueous electrolytic solution was water purified by a Milli-Q (Millipore) system plus 0.5 M LiClO_4 . The solutions were always degassed prior to use. A 5 mm diameter platinum disc was used as a working electrode, polished using $2 \mu\text{m}$ and $0.1 \mu\text{m}$ grade diamond paste (Mecaprex) and then carefully rinsed before each electrodeposition. The reference electrode was Ag/Ag^+ (10^{-2} M) in 0.5 M LiClO_4 in acetonitrile or water, depending on the electrolyte used. The potentiostat was a PAR 173 from EG&G, driven by a PAR 175 ramp generator, and coupled to a SEFRAM X-Y recorder.

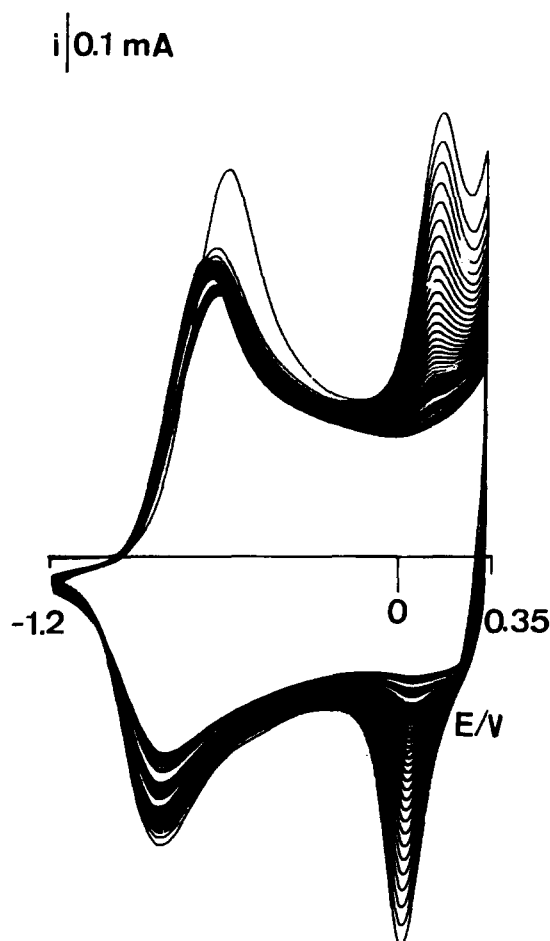


Fig. 2. Voltammetric curves at 50 mV s^{-1} in an 0.5 M LiClO_4 aqueous solution of a PPy film potentiostatically synthesized ($E = 0.4 \text{ V}$ vs. $Ag/10^{-2} \text{ M Ag}^+$) from an aqueous solution containing 0.1 M pyrrole and 50 mM NBPSO_3^- by passing 1.4 C cm^{-2} .

Laser beam deflection characterization

The electrochemical cell was composed of a glass cuvette of optical path length 30 mm , with an optical transmission higher than 80% in the $400\text{--}2500 \text{ nm}$ range. The cells comprised a square piece of platinum foil as an auxiliary electrode, a platinum disk (area 0.071 cm^2) as a working electrode, and a silver wire, in an aqueous solution containing the electrolytic salt and 0.01 M silver ion, as a reference electrode. The Mirage detection system consisted of a 2 mW He-Ne laser ($\lambda = 632.8 \text{ nm}$, Oriel Co.) with a 2 mm beam diameter. The beam was focused by a 80 mm lens and set parallel to the working electrode, giving an interaction length of 3 mm . The detection was made on a dual photodiode with a

10 μm gap between the two active surfaces. Both electrical current and beam deflection signal were acquired using an EG&G PAR 273 potentiostat-galvanostat, driven by a computer on which data treatment by convolution was also performed.

RESULTS AND DISCUSSION

1. Strategy of $\beta\text{-CDSO}_3^-$ synthesis, and its advantage over a previous method

Sulphonic acid esters (aryl- and alkylsulphonates), particularly *p*-toluenesulphonic and methanesulphonic acids, are among the most common functional groups in carbohydrate chemistry. They are usually introduced not as protecting groups but to serve as leaving groups in substitution or elimination reactions. Usually, per- (Cramer *et al.*, 1969) and mono-6-tosyl-cyclodextrins (Melton & Slessor, 1971) are the most common synthetic intermediates in cyclodextrin modifications. They are obtained by the action of tosyl chloride on cyclodextrins in a pyridine solution.

Synthesis of sulphonic acid salts (sulphonates) is usually achieved by one of the following well-known reactions: (i) insertion or addition of SO_3 to hydrocarbons (Sandler & Karo, 1968); (ii) free radical addition of sulphite to the terminal olefins (Lehmann & Weckerle, 1972); (iii) displacement of a halide by sulphite ion—the Strecker reaction (Helferich & Ost, 1963); (iv) oxidation of the corresponding mercaptan (Whistler & Medcalf 1964), or preferably thioester (Sandler & Karo, 1968); (v) addition of α -lithiated sulphonate to the primary iodide derivatives (Musicki & Widlanski, 1990).

Per(6-deoxy-6-iodo)cyclodextrins are synthesized directly in almost quantitative yields using a Vilmeier-Haack's type reagent (Gadelle & Defaye, 1991). This procedure is selective of primary alcohols. The displacement of an iodide by a sulphite ion occurs in water. Furthermore, hydroxyl groups and glycosidic bonds are stable under the reaction conditions. Unfortunately, these iodide compounds are insoluble in water and the addition of co-solvent (DMSO or DMF) promotes by-product formation (elimination).

The inclusion complexes of vesicle-forming surfactants with cyclodextrins are well documented in the literature (Garcia *et al.*, 1990). And although surfactants form micelles that are

capable of catalyzing organic reactions, neither "emulsion catalysis" or "micellar catalysis" by surfactants has been exploited to any degree in synthetic cyclodextrin chemistry. The ability of ammonium salts to dissolve proteins is well-known; it was found that methyltrioctylammonium sulphate also solubilizes per(6-deoxy-6-iodo)cyclodextrin in water at 373°K. The methyltrioctylammonium ion may become dissolved in the aqueous phase, dragging sulphite counterions with it. In a first step, the sulphite ions become consumed by the reaction in the micellar phase; the sulphate ions are unreactive and the methyltrioctylammonium iodide obtained is insoluble in water. Thus, the equilibrium shifts completely and reaction yield is quantitative. The extracted sulphonate can be unambiguously characterized by its NMR and SM spectra.

This synthetic method, with two selective and quantitative steps is very convenient. It does not require the use of protecting groups and no elimination and/or hydrolysis occurs during the sulphonation step.

2. Laser beam deflection study of the irreversible incorporation of CD-SO_3^- in PPy films

The Optical Beam Deflection (OBD) technique based on the Mirage effect (Boccara *et al.*, 1980), also called the Probe Beam Deflection technique (Barbero *et al.*, 1991a), is a very convenient tool for detecting species concentration gradients in the vicinity of an electrode (Plichon & Besbes, 1990). This technique is also known as Photothermal Deflection Spectroscopy (PDS) (Salazar *et al.*, 1991; Seager *et al.*, 1992), when used for measuring refractive index variations with temperature. Because it can be used as an *in situ* technique, together with an electrochemical technique such as Linear Sweep Voltammetry (OBD-LSV), a very powerful tool is available for studying electrochemical mechanisms and ionic dynamics in electrode deposits or thin films (Plichon *et al.*, 1991). Compared to another *in situ* technique—the Quartz Crystal Balance technique—the OBD-LSV determination of charge carrier motion is not perturbed by the solvent intake, and is less sensitive to film swelling during the redox process. The following electronically conducting polymers have been studied by OBD-LSV for elucidating the charge sign of the ions exchanged with the electrolyte:

polypyrrole and poly(orthophenylenediamine) (Barbero *et al.*, 1993), polythiophene (Merle *et al.*, 1989; Servagent, 1991), polyaniline or polyalkylanilines (Barbero *et al.*, 1991a & b; Matencio & Vieil, 1991) and poly(1-hydroxyphenazine) (Miras *et al.*, 1992).

The principle of the mirage effect is to measure the deviation of a laser beam under the influence of a concentration gradient. The deviation angle θ , along a beam covering a length L , in a medium of refractivity index n , varying with the distance x is given by the formula (Boccara *et al.*, 1980):

$$\theta(x,t) = \frac{L}{n} \frac{dn}{dx}$$

Since a concentration gradient can induce a refractive index gradient of the same sign, the direction of the mirage deviation is representative of the movement of a species, as can be seen in Fig. 3. By choosing a positive sign along the distance from the electrode, a negative deviation will indicate a species output whereas a positive deviation will indicate a species input. Consequently, when an oxidation occurs at the electrode, the positive charges created in the

deposited film will be balanced by cation expulsion when the mirage deviation is negative or by anion insertion for the opposite scenario (see Fig. 3).

Figure 4 shows the result of a mirage experiment during a cyclic voltammetric test of a PPy⁺, β -CDSO₃⁻ film. Figure 4a represents the mirage signal recorded simultaneously with the current and represented as a function of the potential. It is clear from the behaviour of this mirage deviation, as opposed to the current density shown in Fig. 4b, that the ionic movement is mainly ensured by the lithium cation along the whole cycle. This clearly implies that the ECP film behaves exactly as would be expected for a self-doped ECP; such behaviour has already been shown, for example, by a polymer containing negatively charged ionic groups attached to the polymeric chains such as poly{pyrrole-co-(4-(pyrrol-1-yl)-butane sulphonate)} (Lopez *et al.*, 1994). However, a deeper and more quantitative analysis can be carried out as follows.

It has been shown (Vieil, 1994; Vieil *et al.*, 1994) that when the refractive index gradient is due to the ionic flux of a charged species produced

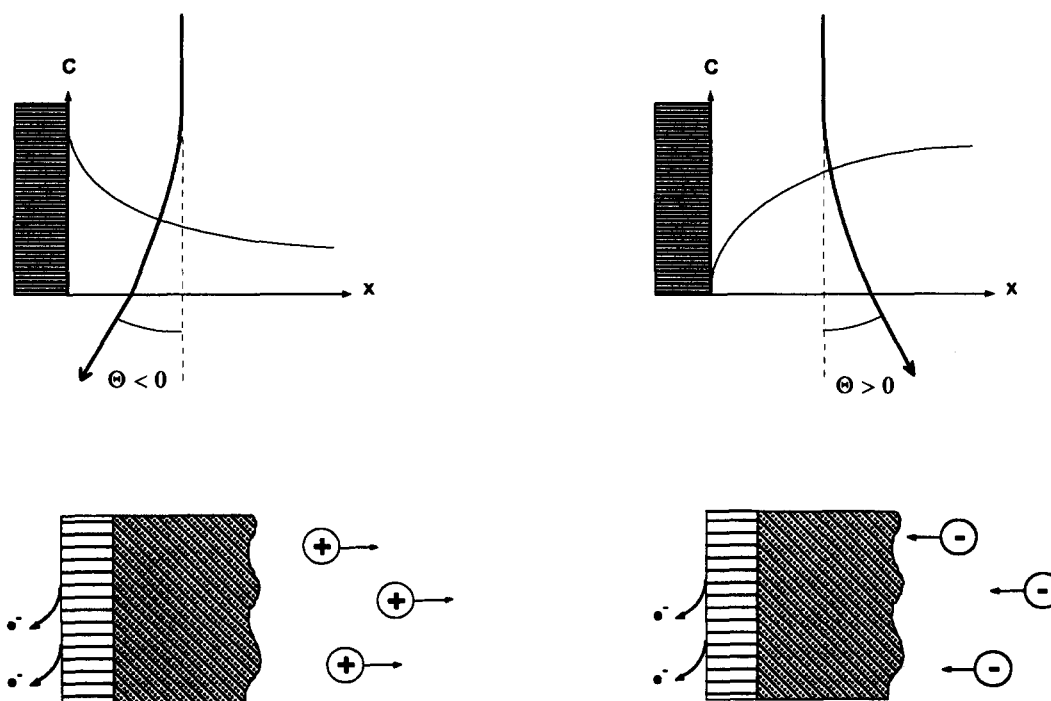


Fig. 3. Principle of the Optical Beam Deflection (Mirage effect) technique. The sign of the beam deviation reflects the direction of the species movement. A negative deviation corresponds to a species output, which can be the case for a cationic expulsion during an oxidation. The opposite behaviour, corresponding to an anionic insertion, is shown on the right.

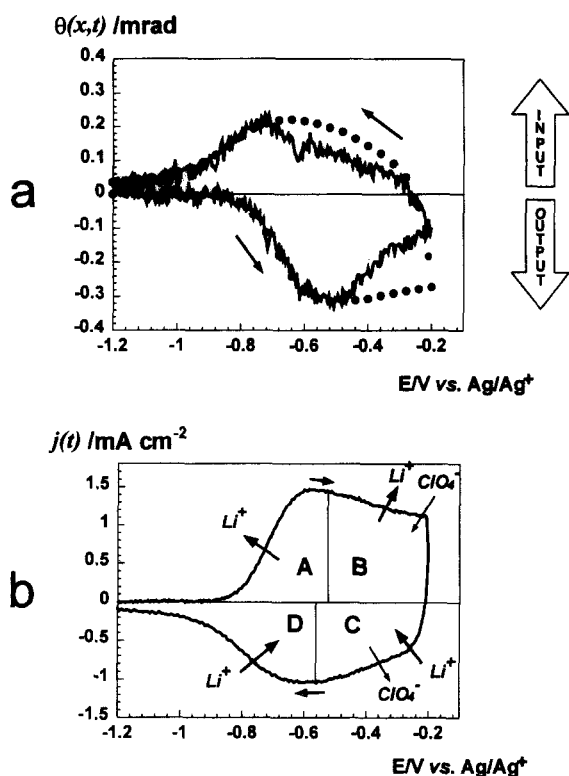


Fig. 4. (a) Deflectogram and (b) voltammogram of a PPy^+ , $\beta\text{-CDSO}_3^-$ film (electrosynthesized in 10^{-2} M $\beta\text{-CDSO}_3\text{Na}$ aqueous solution; $q_s = 0.7 \text{ cm}^{-2}$) simultaneously recorded during a linear potential scan at 20 mV s^{-1} . In the deflectogram are represented the experimental mirage signal (—) and the convoluted current density (\cdots). In the voltammogram the direction and the relative importance of the ionic fluxes deduced from the deflectogram analysis are indicated.

by the exchange of n electrons per molecule at an electrode, the deviation angle and the current density $j(t)$ are linked by the relationship:

$$\theta(x,t) = \frac{h}{nF} \mathcal{F}(x,t) * j(t)$$

where F is the Faraday constant and h is a coefficient encompassing the refractive index gradient of concentration c , optical interaction length L and diffusion coefficient of the species D :

$$h = \frac{L}{n} \frac{dn}{dc} \frac{1}{D}$$

The function $\mathcal{F}(x,t)$ represents mass-transfer by diffusion between the film/solution interface and the probe beam which is typically located at

approximately $x \cong 100 \mu\text{m}$. This function is given by:

$$\mathcal{F}(x,t) = \frac{x}{2\sqrt{\pi Dt^3}} \cdot \exp\left(-\frac{x^2}{4Dt}\right)$$

The function is convoluted with the current density in order to correct the current density signal from the propagation delay induced by ionic diffusion in the electrolyte. This convoluted current density represents the fictitious mirage deviation that should be observed if only cations are exchanged between the film and the electrolyte. By comparing this convoluted curve with the experimental mirage deviation, it is possible to know if this is occurring or not. This is shown in Fig. 4a, where it can be seen that, depending on the potential region, there is only a cationic exchange for potentials less than the peak potentials and a mixed behaviour for higher potentials.

Figure 4b shows a classical voltammogram of this film; an indication of the nature of the ionic species exchanged during the cycling is superimposed. Four different areas can be distinguished according to this criterion: area A at the beginning of the potential scan is a pure cationic expulsion region; after the anodic peak, area B is a region with mixed cationic expulsion and anionic insertion movements, but with a dominance of the cationic expulsion; by reversing the potential scan direction, one enters area C in which a mixed behaviour is also observed, but with opposite directions; finally, area D, after the cathodic peak, is a pure cationic insertion region. It should be mentioned that this behaviour is observed for all successive cycles, meaning that the ionic exchange is only potential dependent and reproducible.

The conclusion of the mirage characterization is that absolutely no movement of the $\beta\text{-CDSO}_3^-$ can be detected during the whole redox cycling of this material.

3. Voltammetric study of NMP entrapment in $\beta\text{-CDSO}_3^-$ doped PPy (PPy^+ , $\beta\text{-CDSO}_3^-$) film

Cyclodextrins (CDs) are cyclic oligosaccharides with a toroidal structure. $\beta\text{-CD}$ contains seven glucose units of internal diameter 0.62 nm , and depth 0.8 nm (Saenger, 1980). The cavity of $\beta\text{-CD}$ provides a space that allows the inclusion of a variety of appropriately sized guest molecules. In addition, CDs exhibit an amphiphilic character:

the internal cavity is hydrophobic, whereas the external surface appears hydrophilic. Consequently β -CDs function as hosts and allow, or increase, the solubilization of aromatic guest molecules, such as azobenzene (Tanaka *et al.*, 1987), ferrocene (Opallo *et al.*, 1989; Kutner & Doblhofer, 1992; McCormack *et al.*, 1992; Suzuki *et al.*, 1993), and viologen (Sivagnanam & Palaniandavar, 1992) derivatives in aqueous medium.

In order to verify the reservoir ability of a PPy^+ , $\beta\text{-CDSO}_3^-$ modified electrode, the following procedure was carried out:

After electrodeposition of a PPy^+ , $\beta\text{-CDSO}_3^-$ film ($q_s = 0.3 \text{ C cm}^{-2}$) from an aqueous solution of 10^{-1} M pyrrole and 10^{-2} M $\beta\text{-CDSO}_3\text{Na}$ at $E = +0.4 \text{ V}$, the modified electrode was dipped for 90 min in a 10^{-1} M NMP solution in CH_3CN , then thoroughly rinsed in CH_3CN , and subsequently in aqueous 0.5 M LiClO_4 for 45 min.

Figure 5 shows the first seven cycles of a cyclic voltammetric test of the PPy^+ , $\beta\text{-CDSO}_3^-$ modified electrode incorporating NMP (PPy^+ , $\beta\text{-CDSO}_3^-$ [NMP]). Two well-separated systems

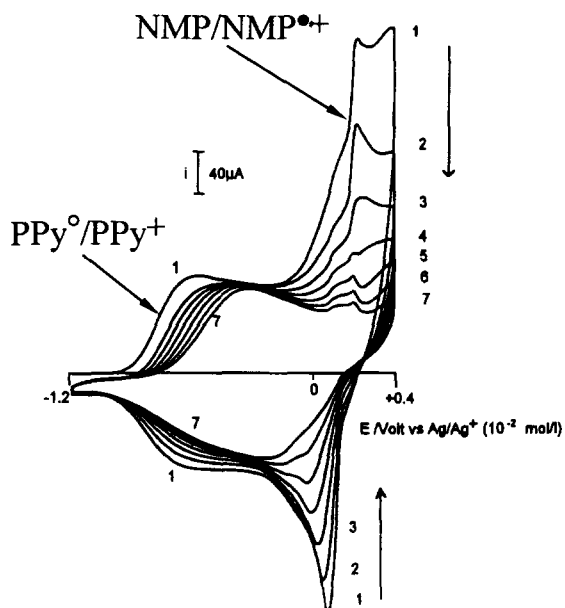
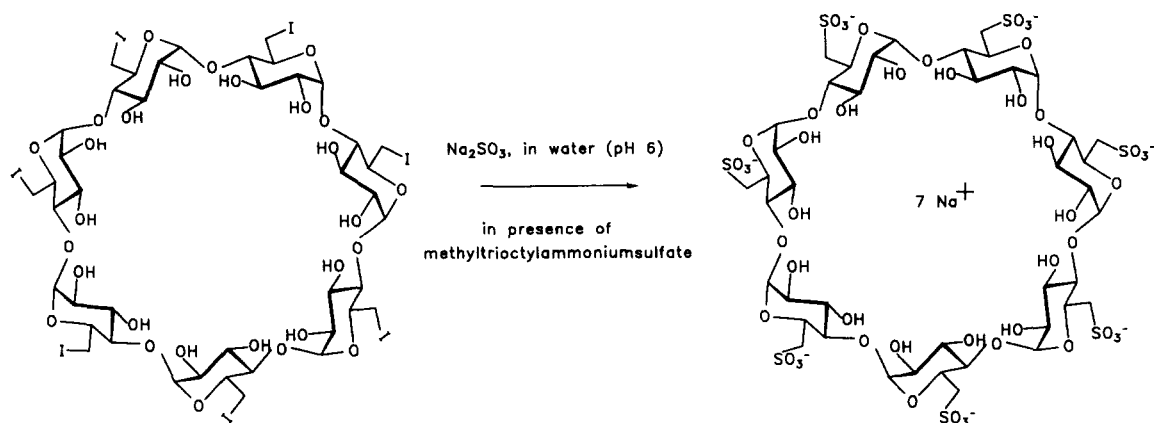


Fig. 5. Voltammetric curves at 20 mV s^{-1} in aqueous 0.5 M LiClO_4 of a PPy^+ , $\beta\text{-CDSO}_3^-$ [NMP] modified electrode prepared by dipping a aqueous PPy^+ , $\beta\text{-CDSO}_3^-$ film (0.3 C cm^{-2}) in CH_3CN (0.1 M) in NMP for 1.5 hours, then rinsing in CH_3CN and H_2O 0.5 M in LiClO_4 during 45 mn.

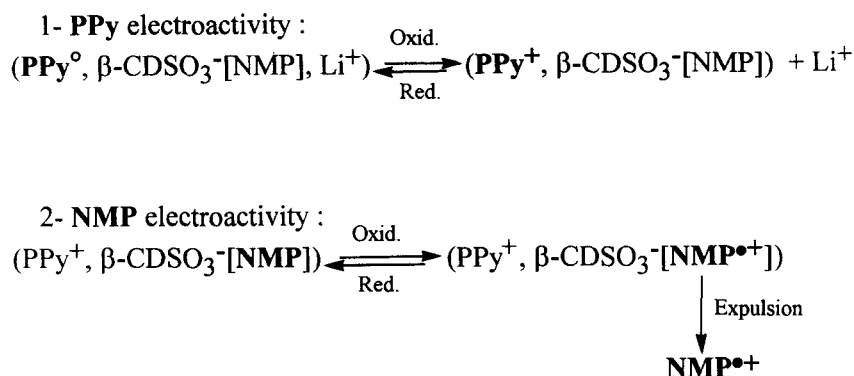
appeared, corresponding to the PPy and NMP electroactivities (Scheme 4). It must be emphasized that the well-known cathodic shift of sulphonated doped polypyrrole (Bidan *et al.*, 1988) allowed a good separation between NMP and PPy electroactivities which were evident at around -0.5 V and between $+0.3 \text{ V}$ and $+0.4 \text{ V}$, respectively. A rough evaluation of the charge of the $\text{NMP}/\text{NMP}^{\bullet+}$ and $\text{PPy}^0/\text{PPy}^+$ systems of the first voltammetric cycle indicates a ratio of 1. A complete incorporation level of NMP by the hepta-negatively charged $\beta\text{-CDSO}_3^-$ should give a maximum ratio of 1/7. Consequently, it must be concluded that a large part of the sulphonate groups of the $\beta\text{-CDSO}_3^-$ were not compensated by the PPy doping charge, but by extractions. As a matter of fact, blank experiments (Lopez *et al.*, 1994) using PPy^+ , PhSO_3^- film, submitted to the same NMP-incorporation procedure, confirmed that the entrapment in the porous structure of the PPy matrix is a side-incorporation phenomenon, limited to 35% of the total amount of NMP in the PPy^+ , $\beta\text{-CDSO}_3^-$ [NMP] film.

During electrochemical cycling of the two systems, the $\text{NMP}/\text{NMP}^{\bullet+}$ system slowly collapsed, indicating the release of $\text{NMP}^{\bullet+}$. Evidence for the physical removal of $\text{NMP}^{\bullet+}$ can be found in the fact that the PPy redox system gradually recovered its native behaviour. There are several explanations for this $\text{NMP}^{\bullet+}$ disappearance:

- The coulombic repulsion between the $\text{NMP}^{\bullet+}$ radical and the positively charged PPy matrix, heavily doped at the NMP oxidation potential (Scheme 4).
- The neutral NMP was more strongly bound to the hydrophobic and non-polar $\beta\text{-CDSO}_3^-$ cavity than the polar $\text{NMP}^{\bullet+}$. A similar situation has been observed with various organic redox systems such as *p*-nitrophenolate (Kano *et al.*, 1990), ferrocene (Kutner & Doblhofer, 1992), ferrocene carboxylate (Matsue *et al.*, 1985a), methyl viologen (Matsue *et al.*, 1985b) and 2,2'-diazino bis(3-ethyl-6-sulphonate benzothiazole) (Essalim & Serve, 1992), in which the more charged species bind more loosely in the CD cavity than the neutral parents do.
- The "naked" $\text{NMP}^{\bullet+}$ reacted slowly in the aqueous medium by disproportionation, providing the NMP and the electro-inactive



Scheme 3. Synthetic strategy for the $\beta\text{-CDSO}_3^-$ preparation based on a one-step sulphonation from iodinated CD in an aqueous phase-transfer medium.



Scheme 4. The PPy and NMP electroactivities. The oxidation of NMP appears in potentials when the PPy is in its heavily doped-state.

sulphoxide of NMP (Cauquis *et al.*, 1977; Bidan & Genies, 1981).

applying a suitable potential to the polymer-modified electrode.

CONCLUSIONS

The facile preparation of negatively charged heptasulphonated β -cyclodextrins, $\beta\text{-CDSO}_3^-$, provides an easy procedure for introducing cyclodextrins as dopants in conducting PPy films. As a consequence of their size and multi-charged character, $\beta\text{-CDSO}_3^-$ are fixed dopants: laser beam deflection measurements demonstrated the main cationic movement associated with the redox switching of the PPy^+ , $\beta\text{-CDSO}_3^-$ films. Cyclic voltammetry experiments provided clear confirmation for the entrapment of neutral NMP. The release of $\text{NMP}^{\bullet+}$ from the guest-preloaded polymer may be triggered electrochemically by

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