

THE EFFECT OF HYDROGEN BONDING ON THE ELECTROREDUCTION BEHAVIOR OF AMINOBENZIMIDAZOLES

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Abstract

The electroreductions of benzimidazole, 5-aminobenzimidazole, 2-aminobenzimidazole and 4-aminobenzimidazole were investigated on a Pt electrode in acetonitrile containing tetrafluoroborat (TBABF₄) with and without the presence of HBF₄. The presence of a proton donor gives rise to the catalytic reduction of protons through various types of protonated benzimidazoles at less negative potentials than those of the neutral hydrogen bonded benzimidazole clusters. The effect of inter-molecular hydrogen bonding on the electroreduction behavior was elucidated. The feasibility of the formation of the proposed hydrogen bonding was supported by the theoretical calculations.

Keywords: aminobenzimidazoles, hydrogen bond, electroreduction, theoretical investigation

Introduction

The effect of hydrogen bonding on the electrochemical behavior of some electroactive compounds was investigated previously. Reduction of the o-quinones to their radical anions was found to greatly increase the strength of hydrogen bonding between the quinone carbonyl oxygens and the urea N-hydrogens.¹ This was detected by large positive shifts in the redox potential of quinones with no change in electrochemical reversibility upon addition of urea guests. In another study, associative (1:1) complexation through NH-S hydrogen bond between (NEt₄)₂[Fe^{II}(S₂-o-xyl)₂](S₂-o-xyl = o-xylene- α,α' -dithiolate) and a multiamide template, e.g. 2,6-bis(phenyl-acetyl-amino)pyridine, results in the positive shift of redox potential in acetonitrile.² Spectrophotometric and electrochemical investigations have shown that the bis(2,2'-bipyridine)(2,2'-pyridyl)-benzimidazole ruthenium(II) cation and its derivatives interact with aromatic nitrogen heterocycles through hydrogen bonding.³ The Ru(II/III)

oxidation potential was shifted cathodically by 200–400 mV due to the hydrogen bonding interaction.

Some 2-substituted benzimidazoles and their 1-methyl derivatives were investigated theoretically with respect to their tendency to form an intramolecular hydrogen bond.⁴ Hydrogen bonding interaction between poly(benzimidazole) and strong acids in methanol were found to be responsible for thermal stability and proton conductivity of the acid doped polymer complexes.⁵

In a previous study⁶ the electroreduction behavior of benzimidazole in acetonitrile was investigated. In a solution containing tetrabutylammonium perchlorate a broad reduction peak was observed at a peak potential of -1.80 V vs. Ag/AgCl. In the presence of a strong proton donor such as HClO₄, another reduction peak was observed at a peak potential of -0.55 V Ag/AgCl which was assigned to the catalytic reduction of protons through protonated benzimidazole. The electroreduction of imidazoles occurs through the hydrogen bonded oligomers and/or clusters whose formation is promoted by the presence of the tetraalkylammonium salts in the medium.⁷ The absence of such a reduction peak for this compound in a medium which contains lithium ions emphasizes the formation of hydrogen bonded clusters in a medium containing tetrabutylammonium ions.

In this study, the electroreduction behavior of benzimidazole, 2-aminobenzimidazole, 5(6)-aminobenzimidazole, 4(7)-aminobenzimidazole in acetonitrile/tetrabutylammonium tetrafluoroborate (TBABF₄) in the presence and absence of HBF₄ was investigated. The effect of hydrogen bonding on the electrochemical behavior of aminobenzimidazoles was elucidated. The experimental results were compared with those of theoretical calculations.

Results and Discussion

Figure 1a shows the cyclic voltametric reduction behavior of benzimidazole (bi) in acetonitrile containing TBABF₄ as supporting electrolyte. A broad cyclic voltametric peak at around -1.60 V vs Ag/AgCl was observed for the electroreduction of benzimidazole. The reduction of benzimidazole at these potentials can only be interpreted if the formation of hydrogen bonded oligomers or clusters are assumed in acetonitrile solution containing TBABF₄. The broadness of the reduction peak may be

due to the involvement of the various chain lengths in such oligomeric structures during electroreduction. We know from our earlier results that such hydrogen bonded oligomers and/or clusters are not formed in a medium containing lithium salts.⁶

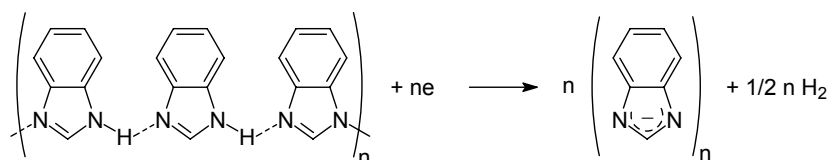
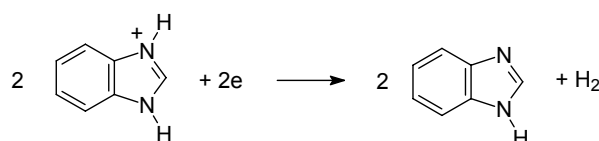


Table 1 shows the calculated heats of formation of benzimidazole and its hydrogen bonded dimer and trimer. These values indicate that the stability of the hydrogen bonded benzimidazoles increase as the number of intermolecular hydrogen bonded units increase. The same table lists the calculated hydrogen bond distance in such systems. As seen in this table hydrogen bond distances increase slightly as the number of hydrogen bonded units increases. These values also support the feasibility of the formation of intermolecular hydrogen bonds in such oligomers.⁸

Table 1. Heats of formation and hydrogen bond lengths for benzimidazole and its hydrogen bonded oligomers. (The values in paranthesis are heats of formation per unit molecule.)

| | H _f (kcal/mol) | Hydrogen bond length (Å) |
|---------|---------------------------|--------------------------|
| Monomer | 66.97 | |
| Dimer | 131.6 (65.79) | 2.53 |
| Trimer | 194.8 (64.93) | 2.50, 2.57 |

When an equivalent amount of anhydrous HBF₄ acid is added an additional cathodic peak at a peak potential of –0.55 V vs. Ag/AgCl was recorded (Figure 1b). The catalytic reduction of protons takes place through the protonated benzimidazoles formed in acidic acetonitrile solutions at potentials less cathodic than the reduction potential of hydrogen bonded neutral benzimidazole clusters.



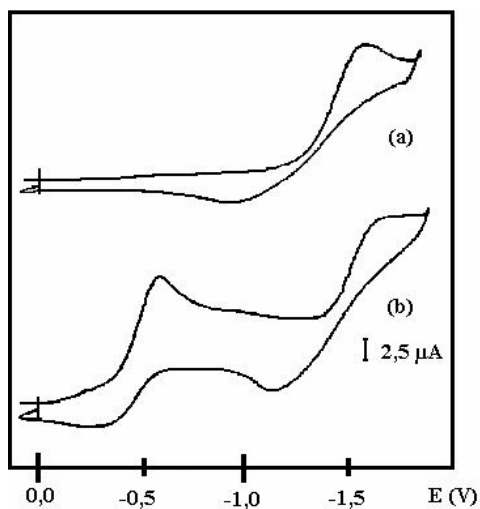


Figure 1. The cathodic cyclic voltammogram of acetonitrile/0.1 M TBABF₄ solution containing
a) 5mM benzimidazole
b) 5mM benzimidazole + 5mM HBF₄. Scan rate: 100 mV/sec.

The electroreduction of 5(6)-aminobenzimidazole (5-abi) is recorded at a peak potential of -1.90 V vs. Ag/AgCl in acetonitrile/0.1 M TBABF₄ as seen in the cyclic voltammogram (Figure 2a). There is no reverse reduction peak.

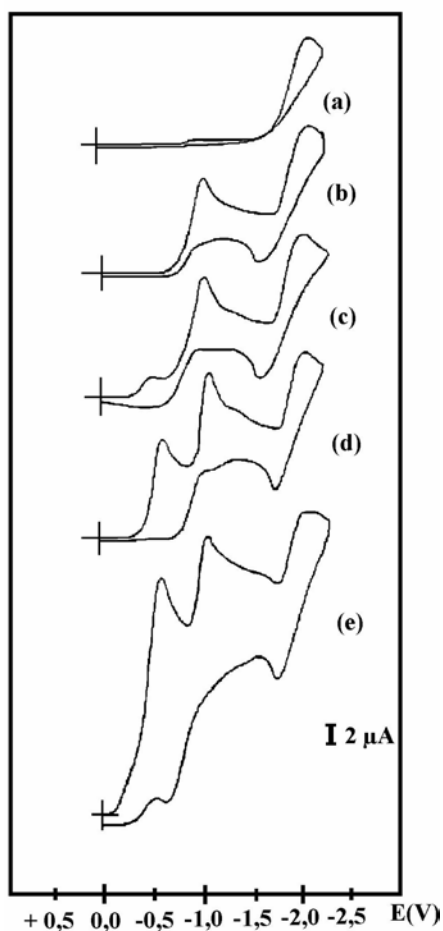
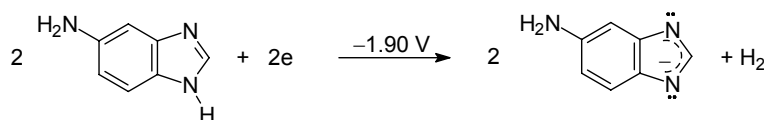


Figure 2. The cathodic cyclic voltammograms of acetonitrile/0.1 M TBABF₄ solution containing
a) 5-mM 5-abi
b) 5-mM 5-abi + 2mM HBF₄
c) 5-mM 5-abi + 3mM HBF₄
d) 5-mM 5-abi + 5mM HBF₄
e) 5-mM 5-abi + 10mM HBF₄.
Scan rate: 100 mV/sec.

When increasing amounts of anhydrous HBF₄ were added to 5mM 5-abi solution up to 2 mM, the second reduction peak was observed at -0.90 V vs. Ag/AgCl (Figures 2b-e). The cyclic voltammogram of aniline in the same medium containing HBF₄ shows one reduction peak at a peak potential of -0.85 V vs. Ag/AgCl (Figure 3). This reduction belongs to the catalytic reduction of protons through the protonated amine group bonded to the aromatic ring.

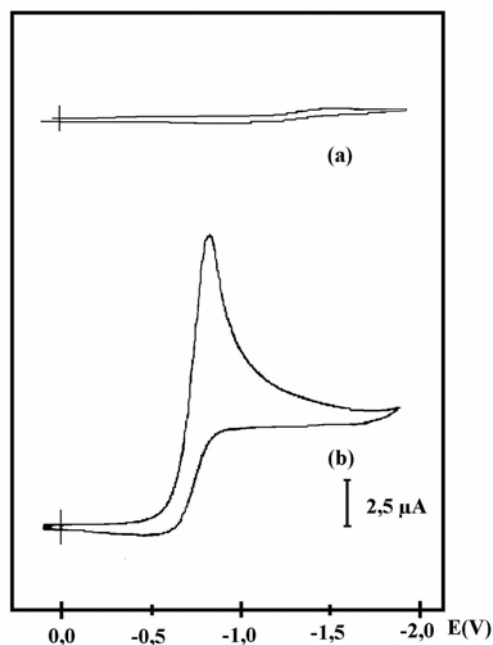
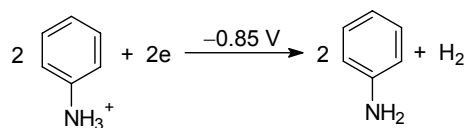
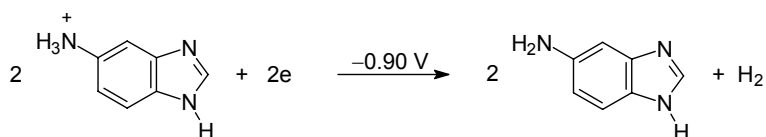
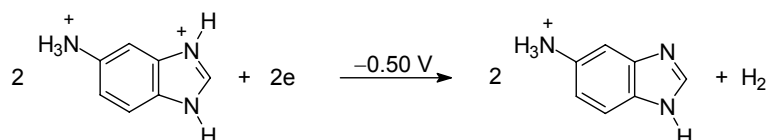


Figure 3. The cathodic cyclic voltammogram of acetonitrile/0.1 M TBABF₄ solution containing
a) 5-mM aniline
b) 5-mM aniline + 5mM HBF₄. Scan rate: 100 mV/sec.

Therefore the reduction peak observed for 5-abi at -0.90 V vs. Ag/AgCl should be due to the following reduction process.

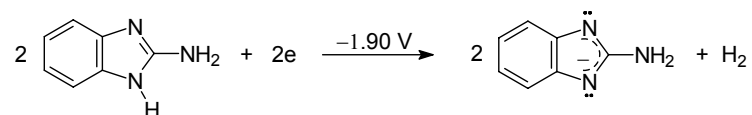


A third reduction peak at -0.50 V vs. Ag/AgCl was recorded for 5-abi belonging to the electroreduction of the following doubly protonated species when excess amounts of acid is added.

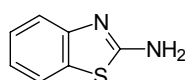


The appearance of the reduction peak at -0.90 V first, indicates that the nitrogen centers of the $-\text{NH}_2$ group is more basic than the nitrogen center in the imidazole ring, and therefore are protonated before the latter.

The electroreduction of 2-aminobenzimidazole (2-abi) is also recorded at peak potential of -1.90 V vs. Ag/AgCl in acetonitrile/0.1 M TBABF₄ as seen in the cyclic voltammogram (Figure 4a). There is no reverse reduction peak.



It is interesting to note that a closely related compound 2-aminobenzothiazole does not give any reduction peak in the same medium.



This again implies that only hydrogen bonded clusters in benzimidazoles are reducible in a neutral medium containing tetraalkylammonium cations.

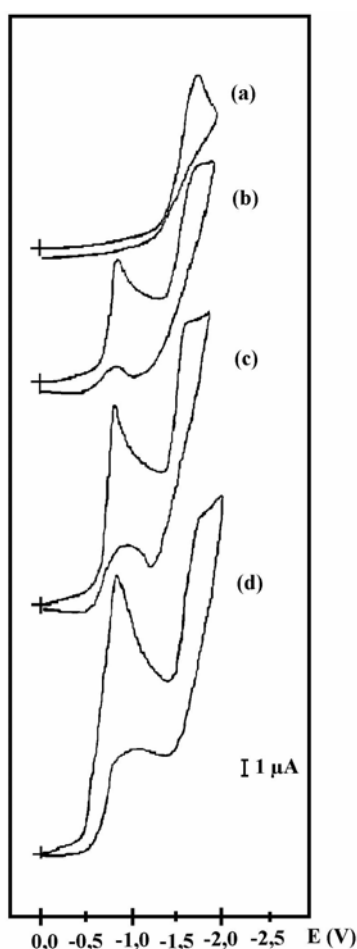
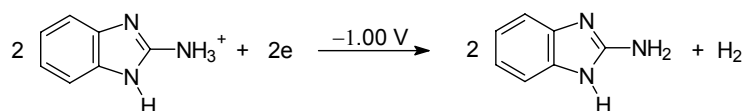


Figure 4. The cathodic cyclic voltammograms of acetonitrile/0.1 M TBABF₄ solution containing
 a) 5 mM 2-abi,
 b) 5-mM 2-abi + 3 mM HBF₄,
 c) 5-mM 2-abi + 5 mM HBF₄,
 d) 5-mM 2-abi + 10 mM HBF₄. Scan rate: 100 mV/sec.

When increasing amounts of anhydrous HBF_4 were added to 5 mM 2-abi a second reduction peak was observed at -1.00 V vs. Ag/AgCl (Figures 4b-d). Only one reduction peak at this potential was observed even when excess amounts of acid were added.



Electroreduction behavior of 2-abi upon protonation shows that only one nitrogen center is protonated. The observation of the reduction peak at -1.00 V vs. Ag/AgCl, gives the evidence that this center is the amine nitrogen in 2-abi instead of the nitrogen center in the imidazole ring, whereas both nitrogen centers in 5-abi are protonated if excess acid is present, giving rise to two additional reduction peaks at -0.90 V and -0.50 V vs. Ag/AgCl. Since two nitrogen centers are not in close proximity in the hydrogen bonded clusters of 5-abi second protonation producing the doubly charged species is possible. The second protonation of the hydrogen bonded clusters on the nitrogen centers of the imidazole rings in 2-abi are avoided due to the close proximity of two positively charged centers in the molecule.

Table 2 shows the heats of formation and hydrogen bond lengths of the hydrogen bonded dimers of 5-abi and 2-abi. Comparing both of these values it is predicted that the dimers are most probably formed as a result of the hydrogen bonding between 1 and 2 positions in both 5-abi and in 2-abi since H_f values and hydrogen bond lengths are minimal in such dimers. For 2-abi and 5-abi the N-H and N centers on the neighboring rings are utilized for cluster formation similar to the intermolecular hydrogen bond formation in benzimidazole (structure A and B).

Table 2. Heats of formation and hydrogen bond lengths for hydrogen bonded 5-abi and 2-abi dimers.

| | Hydrogen bonded dimer formed 1 and 2 position | | Hydrogen bonded dimer formed 2 and 3 position | |
|-------|--|-----------------------------|--|-----------------------------|
| | H_f (kcal/mol) | Hydrogen bond length (Å) | H_f (kcal/mol) | Hydrogen bond length (Å) |
| 5-abi | 130.3 | 2.69 | 130.7 | 4.18 |
| 2-abi | 135.1 | 2.71 | 136.2 | 2.74 |

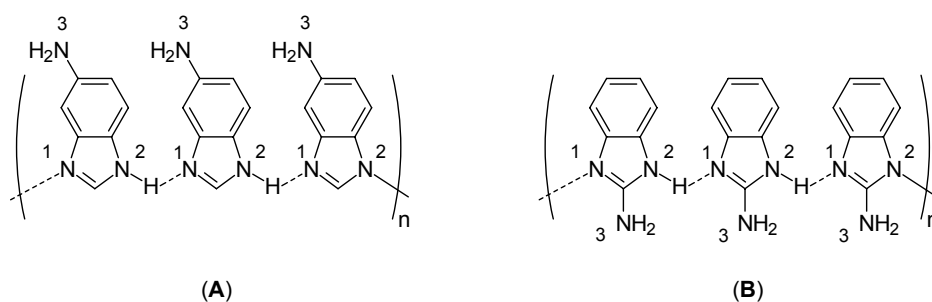


Table 3 lists the heats of formation of monomers of 2-abi and 5-abi and their hydrogen bonded dimers and trimers. The values in parenthesis are again the corresponding values per unit molecule in dimers and trimers. The stability increase of the hydrogen bonded oligomers is evident here also as the number of hydrogen bonded units increase for both 2-abi and 5-abi. The hydrogen bond distances also indicate the feasibility of hydrogen bonding.

Table 3. Heats of formation and hydrogen bond lengths for benzimidazole and its hydrogen bonded oligomers.

| | <u>5-abi</u> | | <u>2-abi</u> | |
|---------|---------------------------|--------------------------|---------------------------|--------------------------|
| | H _f (kcal/mol) | Hydrogen bond length (Å) | H _f (kcal/mol) | Hydrogen bond length (Å) |
| Monomer | 66.59 | | 68.76 | |
| Dimer | 130.3 (65.13) | 2.69 | 135.1 (67.53) | 2.71 |
| Trimer | 193.5 (64.48) | 2.58, 2.61 | 201.1 (67.02) | 2.54, 2.57 |

The electroreduction peaks of 4(7)-aminobenzimidazole (4-abi) are recorded at peak potentials of -1.00 V and -1.60 V vs. Ag/AgCl in acetonitrile/0.1 M TBABF₄ as seen in Figure 5a. The reduction of benzimidazole ring is shifted towards positive potentials by 300 mV compared to that of 5-abi and 2-abi. The strong interaction occurring between NH₂ and NH centers of possible intermolecularly hydrogen bonded structures may cause of this shift. This type of interaction is also reflected by the appearance of the second peak of the neutral 4-abi at a peak potential of -1.00 V vs. Ag/AgCl which resembles to the reduction potential of the protonated amino group in protonated 5-abi and 2-abi. These two peaks do not disappear even in the presence bases, such as anhydrous ammonia, indicating the existence of strong intermolecular interaction.

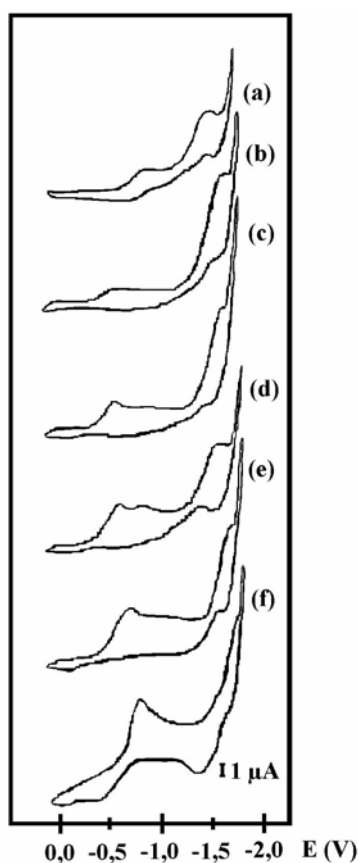


Figure 5. The cathodic cyclic voltammograms of acetonitrile/0.1 M TBABF₄ solution containing
 a) 3 mM 4-abi,
 b) 3 mM 4-abi + 0.5mM HBF₄,
 c) 3 mM 4-abi + 1.5 mM HBF₄,
 d) 3 mM 4-abi + 2.5 mM HBF₄,
 e) 3 mM 4-abi + 3mM HBF₄,
 f) 3 mM 4-abi + 4.5 mM HBF₄. Scan rate: 100 mV/sec.

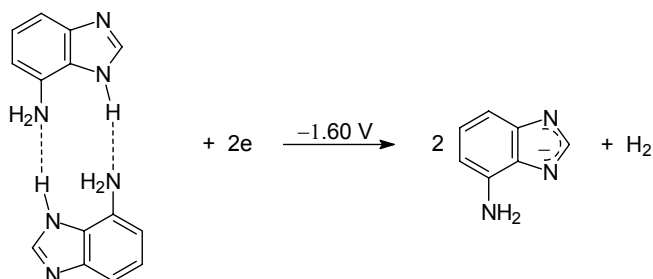
Table 4 lists the calculated heats of formation values of the monomer and all possible intra and intermolecular hydrogen bonded structures for 4-abi. It is clear from these values that structure e is the most stable one among these possibilities. This dimer is formed as a result of the formation of two intermolecular hydrogen bonds at 2 and 3 positions.

Table 4. Heats of formation values of possible hydrogen bonded 4-abi structures (The values in paranthesis are heats of formation per unit molecule).

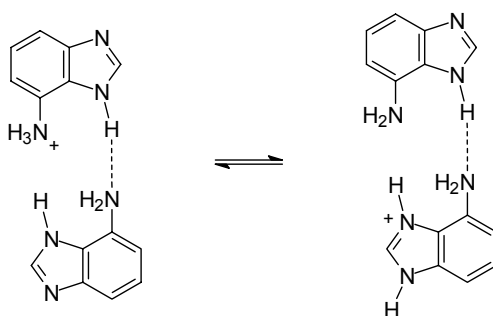
| | | | | |
|------------------|-------|---------------|---------------|---------------|
| | | | | |
| H_f (kcal/mol) | | | | |
| 65.71 | 65.63 | 128.6 (64.32) | 132.5 (66.24) | 127.7 (63.83) |

(Hydrogen bonds lengths are shown in the formula.)

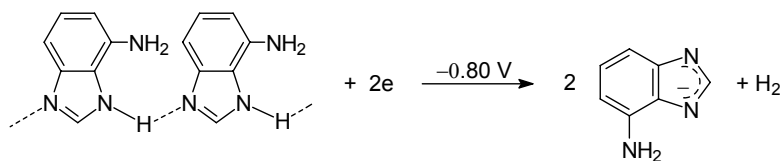
The first reduction peak at -1.60 V vs Ag/AgCl is therefore due to the electroreduction of this dimer.



When increasing amounts of anhydrous HBF_4 were added to 4-abi solution, a third reduction peak was observed at -0.60 V vs. Ag/AgCl as in 5-abi in addition to the peak at -1.00 V vs. Ag/AgCl (Figure 5b-d). The reduction of imidazole peak potential was also shifted gradually from -1.60 V to -1.90 V vs. Ag/AgCl upon protonation. The simultaneous observation of two reduction peaks at -0.60 V and -1.00 V vs. Ag/AgCl means that protonation occurs at the N centers and NH_2 centers of the molecule producing two different protonated species in equilibrium with each other.



There remains still one intermolecular hydrogen bonding between 2 and 3 positions in these protonated structures. Further protonation upon the addition of excess acid causes the conversion of this oligomer (structure e) into a structure where hydrogen bonding exists only between 1 and 2 position (structure c, Figure 5f). The latter type of clusters (structure c) are electroreduced at a peak potential of -0.80 V vs. Ag/AgCl as was the case in protonated 2-abi (Figure 5f).



Conclusion

It can be concluded that the hydrogen bonded clusters enable the reduction of these compounds in neutral medium. Upon addition of an acid only amine nitrogens are protonated in 2-abi giving rise to an additional reduction peak at less cathodic potentials. In 5-abi and 4-abi the second protonation on imidazole nitrogens also occurs producing a third reduction peak at even less cathodic potentials. Intermolecular hydrogen bondings are similar in 5-abi and 2-abi, whereas double hydrogen bonding is apparently formed in the case of 4-abi.

Experimental

2-Aminobenzimidazole (Aldrich, 97%) was used directly without any purification. 5(6)-aminobenzimidazole and 4(7)-aminobenzimidazole were synthesized from 5-nitrobenzimidazole⁹ and 2,6-dinitroaniline¹⁰ by chemical reactions respectively. Diethylether complex of tetrafluoroboric acid (HBF₄) (Aldrich) were kept at –10 °C in darkness under a nitrogen atmosphere and used directly. Tetrabutylammonium tetrafluoroborate (TBABF₄) was used as a supporting electrolyte. TBABF₄ was prepared by reacting tetrafluoroboric acid (Aldrich) with a 40% aqueous solution of tetrabutylammonium hydroxide (TBAOH) (Aldrich). It was recrystallized from 70% ethanol several times and kept a nitrogen atmosphere after vacuum drying for 24 hours at 120 °C. The purification of acetonitrile (Merck) is described elsewhere.^{11,12} The amount of water in acetonitrile was 10 ppm after purification. Acetonitrile was purged with nitrogen prior to use.

Electrochemical measurements were carried out under a nitrogen atmosphere in a three-electrode cell. A polished Pt disk electrode with a diameter of 0.13 cm inlaid in a glass capillary was used in cyclic voltametric experiments as a working electrode. The counter electrode was a Pt wire (2 cm²) immersed in acetonitrile/0.1 M TBABF₄, separated from the electrolysis solution by a sintered glass disc (G 4). The reference electrode consisted of an AgCl-coated Ag wire in acetonitrile/0.1 M TBABF₄ which was also separated from the electrolysis solution by a sintered glass disc. Electrochemical instrumentation consisted of a PAR Model 173 potentiostat coupled to a PAR Model 175 universal programmer and a PAR Model 179 digital coulometer. Current-voltage curves were recorded on a Model SE-790 BBC Goertz Metrawatt X-Y recorder.

Theoretical calculations were performed using semi-empirical Austin Model 1 (AM1)¹³ in the Hyperchem 7.0 program package and using a Pentium III 600 MHz computer. This method is used to investigate the aromatic character of compounds, to study some complex structures such as polymers and to investigate the formation of hydrogen bonds between molecules. The hydrogen bonds lengths are computed after AM1 geometrical optimization.

Acknowledgements

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Povzetek

Raziskovali smo elektoredukcijo benzimidazola, 5-aminobenzimidazola, 2-aminobenzimidazola in 4-aminobenzimidazola na Pt elektrodi v raztopini acetonitrila, ki je vseboval tetrafluoroborat (TBABF₄), ob in brez prisotnosti HBF₄. Ugotovili smo, da prisotnost donorja protonov poveča katalitično redukcijo protonov posameznih protoniranih benzimidazolov pri bolj negativni vrednosti potenciala kot v primeru nevtralnih benzimidazolov. Iz tega lahko sklepamo, da so molekule nevtralnih benzimidazolov povezane v klastre z vodikovimi vezmi. Možnost tvorbe vodikovih vezi smo potrdili tudi s teoretičnimi računi.