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Study of the electro-oxidation of a recreational drug GHB (gamma
hydroxybutyric acid) on a platinum catalyst-type electrode through
chronoamperometry and spectro-electrochemistry

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Abstract.

The electro-oxidation of gamma-hydroxybutyric acid (GHB) on a polycrystalline platinum electrode in acidic medium has been studied using chronoamperometry. The study has been performed in a wide interval of potentials and at different concentrations. It was found that at longer times the density currents reached stationary values at more anodic potentials, whereas it is zero at lower potentials. These characteristics in the j - t curves suggest a different mechanism for the electro-oxidation of GHB, potential dependent, with a catalytic process at high potentials and an adsorption process controlled by mass transport at low potential.

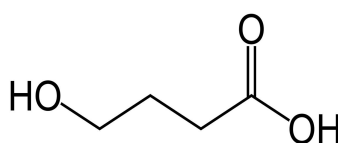
The change in the stationary current obtained at +0.9 V with variable GHB concentrations also suggests an oxidation mechanism catalysed by the platinum surface with platinum hydroxides acting as reaction intermediates to make the final oxidation product for GHB. The results obtained using chronoamperometry are in good agreement with those obtained using cyclic voltammetry where the alcohol group is oxidised at different potentials.

In situ Surface Enhanced Raman Scattering (SERS) spectra corresponding to GHB intermediates and water adsorbed species being formed/consumed at the potential-dependent adsorption processes have been analyzed using spectro-electrochemistry. A peak at 1590 cm^{-1} , corresponding to the asymmetric stretching of carboxylic group in a bridge configuration, increases with the potential. This supports the hypothesis of a mechanism of formation of the succinic acid on the platinum surface as reaction product under the experimental conditions studied.

Keywords: GHB, chronoamperometry, date rape drugs, platinum-catalysed, electro-oxidation, Surface-enhanced Raman spectroscopy (SERS), spectro-electrochemistry.

1. Introduction.

Gamma Hydroxybutyric acid (GHB, scheme 1) is a drug catalogued as a central nervous system depressant able to produce effects ranging from euphoria, sedation, easing, bradycardia and respiratory depression [1-3]. In clinical environments is used for the treatment of cataplexy, and also it can help in the treatments of Alzheimer's disease [1]. The drug has also been used recreationally by young people [4]. Because of its sedative effects and the difficulty of its detection, GHB is a drug associated with cases of sexual assaults [5-7]. The concentration of GHB in therapeutic dose is of 30-100 mg/L and the toxic dose is of 100-1000 mg/L.



Scheme 1

A first paper on the electro-oxidation of gamma hydroxybutyric acid on a polycrystalline platinum electrode by cyclic voltammetry in acidic medium was recently released [8]. The cyclic voltammograms showed two oxidation peaks, A and B, within the potential range of the double layer region and that of the platinum oxide region (Figure 1). The reverse sweep, in the cathodic direction, showed an inverted oxidation peak with an onset partially overlapping with the tail of the cathodic peak for the reduction of the platinum oxide formed during the anodic scan (peak C). The response observed in the electronic current density for the different peaks when GHB concentration and scan rate were changed was used to conclude that the alcohol group is oxidized through a pathway where the corresponding aldehyde and carboxylic acid (succinic acid) are the main products. This previous work is in agreement with the accepted electro-oxidation mechanism of aliphatic alcohols on platinum electrodes [9-14].

It is also well known that alcohols adsorb and dissociate at low potentials on the Pt surface, leaving adsorbed residues (e.g. CO and C_xH_y). These residues are suggested to be the responsible for the Pt poisoning and, consequently, to the lower charge associated to the hydrogen adsorption. At potentials sufficiently positive, some oxygenated species can be produced on the Pt surface and these residues can be oxidized to carbon dioxide

to clean the catalytic surface. Once the surface is free, alcohols can react and get oxidized. This previous work showed that peak A could be related with the oxidation of CO_{ads} together the formation of the aldehyde as oxidation product of GHB. It is also known, alcohols adsorption is inhibited at Pt oxide surface and consequently acids are formed as the main product (peak B). The latter can also be used to understand the anodic peak (C) developed during the negative going potential scan, i.e. after Pt oxide reduction the catalytic surface is completely free of adsorbed residues. Therefore, GHB can easily be oxidized.

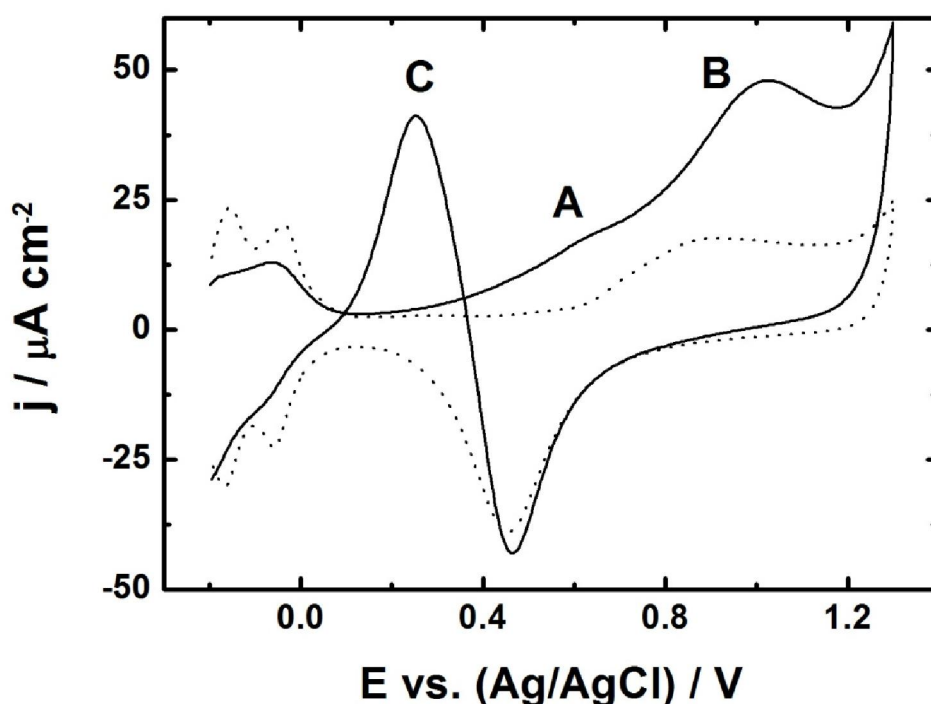


Figure 1. Cyclic voltammograms in 0.1 M phosphoric acid pH 1.9. (—) in the presence of 25 mM GHB, (···) in the absence of GHB. Scan rate 0.02 V/s.

The scientific literature shows some studies in the chronoamperometric behavior of alcohols on platinum surfaces (oxidation of ethanol on platinum [15-18] and modified electrodes [19,20]). The presence of a stationary current density associated with the potential dependent electrocatalysis was described in all cases.

Also, recent reports on the spectroelectrochemical response of alcohols by in-situ Raman (SERS) have been published describing the detection of intermediate fragments and species from the dissociative and non-dissociative electro-oxidation of alcohols [21, 22].

In this paper, GHB chronoamperometry studies on Pt electrodes in acid medium at several concentrations and in a wide region of potentials are shown in order to further understand the electrochemical processes associated to the electro-oxidation of GHB. In addition, spectro-electrochemical in-situ Raman (SERS) measurements were carried out in order to support the mechanism of electro-oxidation of GHB suggested by the chronoamperometric study and to analyze the intermediate species and products formed at several potentials.

Some analytical variables have been also calculated to show the potential for the development of portable and quick sensors for the detection of this drug using electrochemical methods. To the best of our knowledge, this is the first report on the chronoamperometric behaviour of GHB on platinum surfaces and the first spectro-electrochemical study of GHB using Raman and platinum electrodes.

2. Experimental

Gamma-hydroxy butyric lactone (GBL) was obtained from Aldrich (reagent, minimum 99% purity). 1-Butanol ($\geq 99\%$ purity), Butyric acid ($\geq 99\%$ purity) and Succinic acid ($\geq 99\%$ purity) were purchased from Sigma-Aldrich. Perchloric acid (70% purity) was purchased from Aldrich, and sulphuric acid (98% purity) and phosphoric acid (85% purity) from Merck. Semiconductor grade sodium hydroxide was purchased from Sigma-Aldrich. As supporting electrolyte, 0.1 M perchloric acid, 0.2 M sulphuric acid and 0.1 M phosphoric acid were used. All solutions were prepared with deionized water produced by a Millipore system (Millipore, Maryland, US). GHB sodium salt, was prepared and identified as is described in reference [8].

Cyclic Voltammetry (CV) and chronoamperometry analyses were performed with an Autolab (Ecochemie model Pgstat3) instrument attached to a PC with GPES software for the control of the experiments and data acquisition.

For the chronoamperometry studies, a three electrode configuration was used: platinum electrode acting as a working electrode, a Ag/AgCl as a reference electrode and a platinum electrode as a counter electrode. The working electrode used for the different experiments was a 1.6 mm diameter platinum electrode from Bioanalytical Systems (Kenilworth, UK). The working electrode was polished with 0.05 μm Al_2O_3 slurry, rinsed and sonicated in 18 M Ω Milli-Q water and dried before use. The electroactive surface area was determined using the hydrogen adsorption/desorption voltammetric

peaks of platinum electrode with a known charge density of $210 \mu\text{C}/\text{cm}^2$ in $1.0 \text{ M H}_2\text{SO}_4$. A value of 0.036 cm^2 was found and used for normalise the current intensity in the cyclic voltammograms presented in this work. The open circuit potential of the cell, OCP, was measured in the presence of GHB for the newly-cleaned platinum surface electrode and for the electrode oxidized for the experiments of chronoamperometry at low potentials. The obtained values were 0.178 ± 0.012 and $0.712 \pm 0.014 \text{ V}$, respectively, and the same ones were found in the first minute of the OCP-t curve registered. Nitrogen was bubbled in the electrochemical cell for 20 min before analysis. All the measurements realized in this work with GHB were carried out with a freshly prepared solution.

The Surface Enhanced Raman Spectroscopic (SERS) measurements were performed with a Horiba-Jobin Lab-Ram spectrograph with a holographic grating of 600 grmm^{-1} . The excitation line was provided by a 17 mW He-Ne laser at 633.0 nm. The laser beam was focused through an Olympus 50x long working distance objective (0.5 NA) into a $2 \mu\text{m}$ spot at the electrode surface. Signal averaging two spectra with spectrometer resolution better than 3 cm^{-1} , 60 s acquisition time each, was obtained. The electrochemical setup for the spectroelectrochemical measurements consisted of a three electrode system DropSens (Oviedo, Spain) Screen-Printed Carbon Electrode (SPCE) with previous deposition of Pt on the working electrode (from $0.005 \text{ M H}_2\text{PtCl}_6$ Sigma-Aldrich, ACS reagent) attached to a potentiostat Autolab PGSTAT 302N using NOVA software. The laser beam was focused on one of the Pt agglomerates. There are no differences in the registered spectra when the factor of ruggedness is between the obtained values, 2 and 8, according to the strategy of electrodeposition. The potential was held constant for the necessary time until the stationary current of the j-t curve was reached. This procedure allowed us to ensure that the adsorbed GHB and their fragments are present on the electrode surface at the start of each SERS experiment.

3. Results and discussion

3.1. Chronoamperometry at high potentials

The oxidation studies of alcohols on platinum electrodes using chronoamperometry are scarce in the scientific literature and are usually performed at high concentration. The stationary current density, measured at different potentials and long times, shows an apparent discrepancy between the potential at which the higher stationary current is

reached and the potential at which the voltammetric peak can be observed. This can be explained as water plays a role in forming surface hydroxides able to participate in the dehydrogenation of alcohols [9] and the presence of chemical intermediates able to modify the anodic current [10]. Both effects have been shown to be potential dependant. In the study presented here, contrary to what can be found in the literature for other alcohols, the range of concentration used for GHB is considerably lower. In these conditions a direct relationship in the behaviour is found in both cyclic voltammetry and chronoamperometry. Nevertheless, the oxidation of GHB is in good agreement with the general scheme accepted for the oxidation of alcohols.

The current density vs time curves (j - t curves) for a 25 mM GHB solution in 0.1M phosphoric acid at pH 1.5 in a range of potential from 0.3 to 1.1 V were registered. This range of potentials is the one where the two peaks, A and B, appeared in the anodic sweep when analysed using cyclic voltammetry (Figure 1). Before applying any potential the working electrode was kept in an open circuit for a minute (see experimental section). Figure 2 shows the j - t curve at +0.8V as an example of the results obtained at all potentials. In all these, a curve with the typical faradaic current decay at short times and a stationary density current at long times, were obtained. The current density diminishes abruptly to values below 10% of the original value in less than 10 seconds.

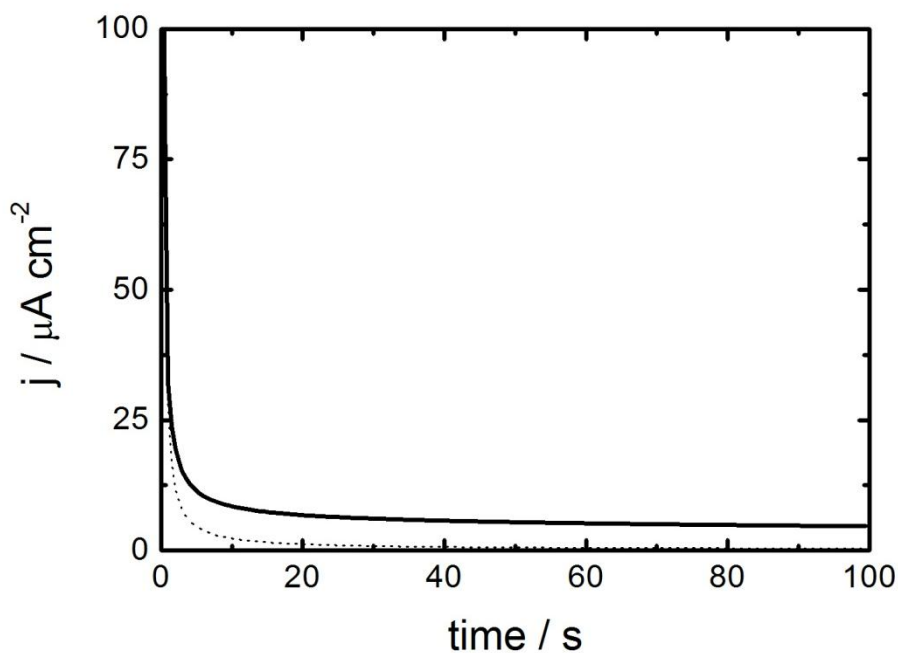


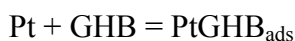
Figure 2. Chronoamperometric curves in 0.1 M phosphoric acid pH 1.5. (—) in the presence of 25 mM GHB, (····) in the absence of GHB. Applied potential +0.8 V.

Figure 2 also shows the transient signal obtained for the blank electrolyte, which permits observing a faster drop (to zero in this case) in the current density associated to the quick oxidation of the surface of the platinum electrode. The latter suggests that the decay curve and the stationary current density observed in the first case are undoubtedly due to the presence of GHB in solution. Table 1 summarizes the stationary current values versus the applied potential.

Table 1. Stationary current intensity at different potentials. 25 mM GHB in 0.1 M phosphoric acid pH 1.5.

E / V	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
I_{SS} / $\mu\text{A cm}^{-2}$	0.15	0.35	0.78	0.80	1.25	3.20	3.81	2.90	2.01

The presence of stationary density current values is common in the scientific literature, as shown in the case of the catalytic oxidation of ethanol [15, 16]. This behaviour is typical in those cases for which there is significant contribution of spherical diffusion. This seems to suggest that the oxidation of GHB occurs on specific sites on the platinum surface due to the presence of oxygenated nuclei such as PtOH or PtOH₂.



Some authors have suggested that the oxidation of alcohols occurs in different stages according to a mechanism similar to that suggested by Langmuir-Hinshelwood involving oxygenated species adsorbed on the metallic surface of the electrode close to alcohol molecules or alcohol intermediates [15]. The results shown in this paper show a peak coinciding with those potentials observed in cyclic voltammetry for the oxidation of GHB (peak B) and the formation of metallic oxides.

The values of the stationary current intensity are very low with regard to those expected for a molecule as GHB at the concentrations and the electrode surface used in the present work. It is also consistent with the low current density observed by cyclic voltammetry [8]. Due to the interaction of GHB on the platinum surface, as can be seen by the partial suppression of UPD of hydrogen by voltammetry, we cannot discard a step of surface diffusion or another diffusion path of GHB towards activated centres of

oxidised platinum (with a finite thickness of the diffusion layer). In this way we can explain the low density current observed both in voltammetry and chronoamperometry experiments even when electrochemical parameters indicate apparent semi-infinite diffusion control as predominant contribution.

3.2. Chronoamperometry at low potentials

The current transient signals at low potentials associated to peak C were registered following this experimental strategy: a first sweep using linear scan voltammetry (LSV) at 0.01V/s following the anodic direction (starting at -0.25V to 1.25 V) producing a platinum oxide layer on the surface of the electrode at the end of the sweep. Secondly, a j-t curve is obtained by applying some potential at +0.2V, where peak C presents a maximum current at pH 1.5.

Figure 3 shows a curve with three clear zones: (i) $t < 3$ s, an increase of the current density from cathodic values indicating a quick reduction of platinum oxides formed during the LSV sweep (see dotted curve corresponding to a blank); (ii) an apparent maximum showing a positive current suggesting GHB oxidation and (iii) $t > 4-5$ s with a current density gradually dropping to zero describing a typical curve. This drop in current is softer than that observed at more anodic potentials. The current density is around 10% of that observed for the current maximum at times around 50 seconds.

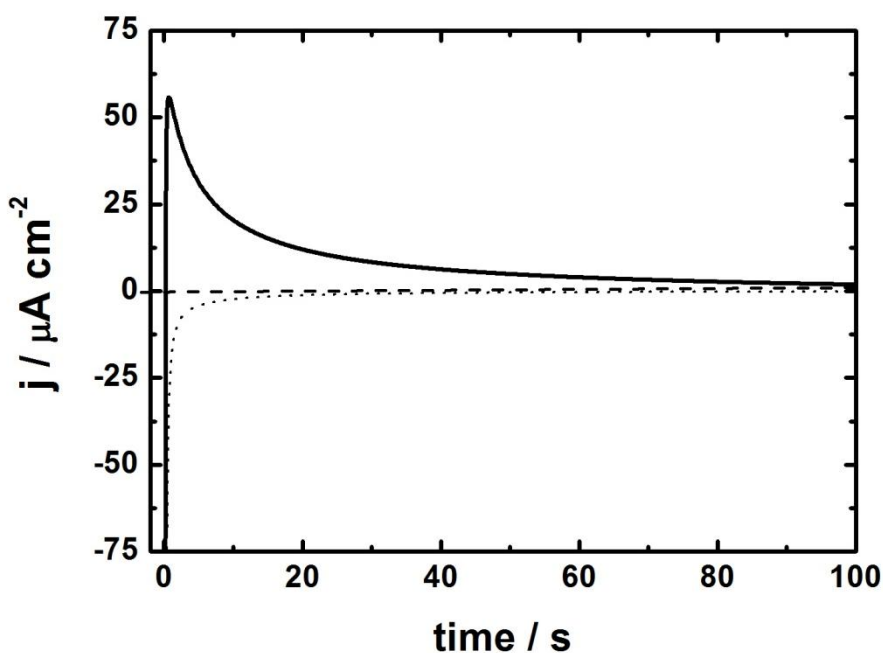
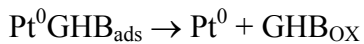
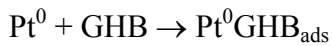


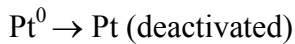
Figure 3. Chronoamperometric curve of 25 mM GHB in 0.1 M phosphoric acid pH 1.5. Applied potential +0.2 V on platinum oxide surface (see text).

This difference with respect the behaviour at high potential seems to suggest adsorption of GHB on the surface of the electrode with an additional positive contribution in the j-t curve at low time. It has been reported previously in a study by cyclic voltammetry [8]. Also, the variation of the charge density with the potential in the vicinity of peak C, obtained by integration of each curve, describes a similar profile to j-E curve. On the other hand, the fact that the stationary current drops to zero supports the idea that the oxidation of GHB at low potentials (peak C) occurs through a re-activation of the platinum surface during the reduction of the surface oxides ($\text{PtOx} \rightarrow \text{Pt}^0$). GHB is adsorbed on the surface where it undergoes oxidation and the subsequent reaction products are desorbed shortly after. At the same time, the platinum surface seems to become deactivated through a process of ionic adsorption and/or GHB residues or fragments that might have been formed at low potentials competing with the GHB oxidation [14]. All these processes occur in a time scale where is possible to state that the GHB oxidation process is controlled by the diffusion to the electrode surface.

Summarising:



Competing with:

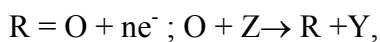


3.3. Stationary current with the concentration

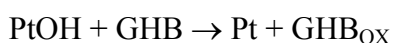
According to the results shown in table 1, a potential of +0.9V was chosen to recording j-t curves at different GHB concentrations ranging from 0.001-0.1 M. Figure 4 shows some of the chronoamperograms obtained for which an increase of the stationary current with increasing GHB concentrations can be observed. A plot of the stationary current density versus concentration (inset figure 4) describes a curve that fits well with the following equation:

$$j_{\text{st}} = K \cdot c^{1/2} \tag{1}$$

with $K = (8.63 \pm 0.23) \cdot 10^2 \mu\text{A} \cdot \text{mol}^{-1/2} \cdot \text{cm}^{-1/2}$. This behaviour agrees well with the general scheme observed for catalytic electro-oxidations [23]



Where, in pure kinetic region conditions, the current density is proportional to the square root of the concentration of species Z. In the case of GHB we can express the whole process as:



The electrocatalysis scheme previously described is fully compatible with the explanation offered in section 3.1 in the chronoamperometric study at high potentials.

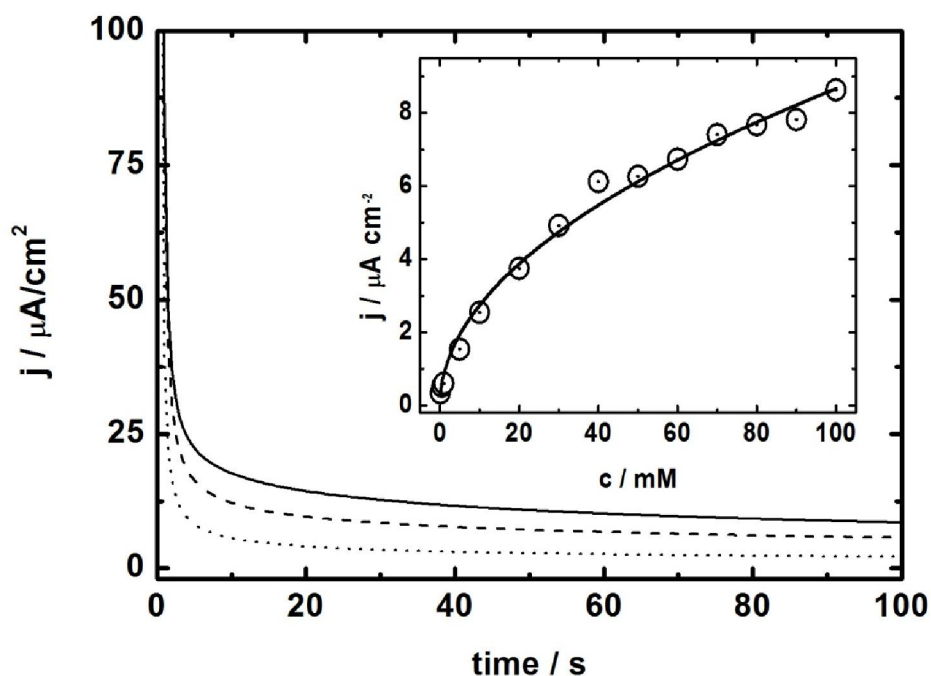


Figure 4. Chronoamperometric curves at several concentrations of GHB in 0.1 M phosphoric acid pH 1.5: 10 mM (\cdots), 50 mM ($- - -$), 100 mM ($—$). $E_{AP} = +0.9$ V. Inset: representation of j_{st} vs c .

3.4. In Situ Surface Enhanced Raman Scattering (SERS) Spectro-Electrochemistry

Figure 5 shows the SERS spectrum collected for the platinum electrode in 0.5 M GHB and 0.5 M phosphoric acid solution. As it was explained in the experimental section, the spectrum was registered after applying the potential (-0.1 V in the measurement of figure 5) for the time needed to reach the stationary condition (stationary density current in a j - t curve). This procedure allowed us to ensure that the adsorbed GHB and their fragments are present on the electrode surface at the start of each SERS experiment.

With the exception of the bands corresponding to the adsorbed phosphoric acid at 367 cm^{-1} [24] and 770 cm^{-1} (see blank electrolyte spectra in the same conditions), the bands in these spectra correspond to GHB and water adsorbed species being formed/consumed in the potential dependent adsorption processes.

First, weak bands at 520 cm^{-1} and 1935 cm^{-1} can be observed and associated to the bridge CO, although a contribution of lineal CO also cannot be categorically rejected [21, 22, 25]. The CH stretching mode at 2841 cm^{-1} [26], and the OH stretching of the adsorbed water at 3149 and 3320 cm^{-1} (not shown in spectra of figure 5) [27] are also present. On the other hand a peak at 950 cm^{-1} is assigned to the symmetric stretching of C-C bond [22]. Also, at 830 cm^{-1} , a band overlapping with that corresponding to the phosphate electrolyte is assigned to the deformation scissoring mode of the carboxylic group [28]. The weak bands in the range between 1000 and 1400 cm^{-1} present an important overlapping and correspond to the adsorption stretching band of C-OH, the bending bands of groups CH_2 and OH, and the symmetric stretching of OCO group [22].

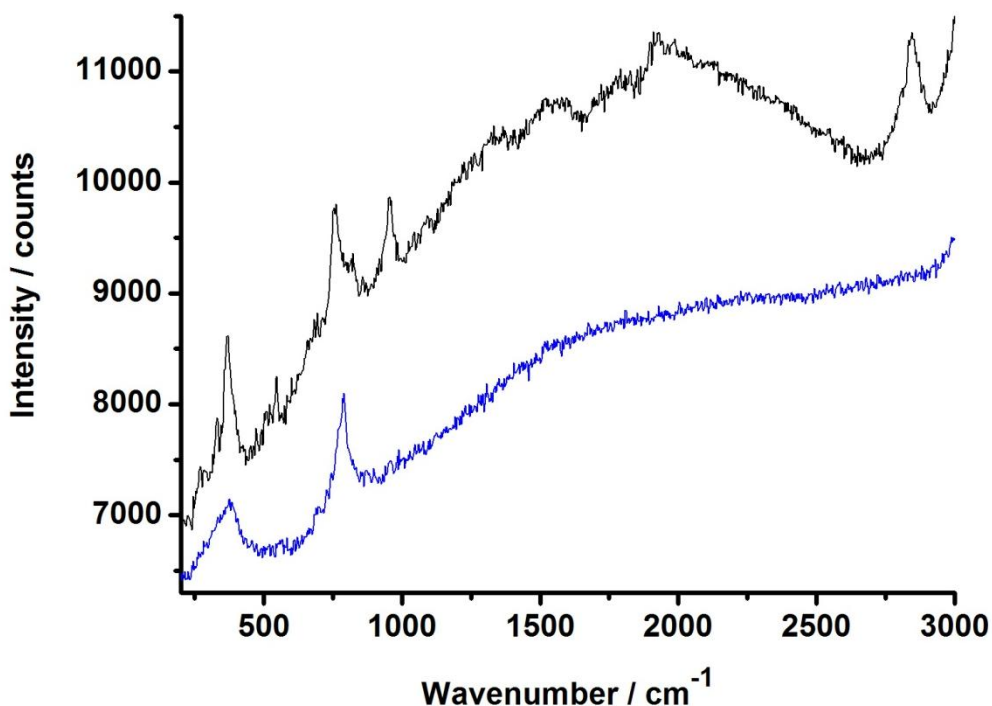


Figure 5. SERS spectrum collected with a platinum film deposited on carbon electrode. Applied potential is -0.1 V vs Ag/AgCl. Test solution: 0.5 M GHB + 0.5 M phosphoric acid. Two spectra collected with an acquisition time of 60 s were averaged.

It is necessary to emphasize the presence of adsorbed CO despite the known fact that in phosphoric media the formation of CO_{ads} from dissociative oxidation of alcohols and their further oxidation is strongly inhibited [14]. On the other hand, the presence of the bands associated with interfacial water molecules can relate to the catalytic role of the solvent in the electro-oxidation of GHB on Pt electrodes. Finally, in this general inspection, we observed weak signals at $1740\text{-}1770\text{ cm}^{-1}$, the zone for carbonyl groups associated to aldehyde intermediates [29].

It is important to bring the attention on the appearance of weak bands in the zone $1500\text{-}1600\text{ cm}^{-1}$ at several potentials where the presence of the GHB, or an intermediate adsorbed on the platinum surface, can be recognised by a weak peak at 1510 cm^{-1} corresponding to the fingerprint chain vibration (bending of $-\text{CH}_2-$) [30,31]. This peak is present in all the potentials range, according to the role that the GHB intermediate plays in the catalytic electro-oxidation (Figure 6). In the same way, when the potential increases, we observe that a peak is visible at 1590 cm^{-1} (only as a shoulder below 0.5 V) corresponding to the asymmetric stretching mode of the carboxylic group and one that corresponds with the selective conjugated $\text{C}=\text{C}$ stretching mode [28, 32]. This supports the idea of a possible formation, together with succinic acid, of a conjugate compound (probably maleic acid).

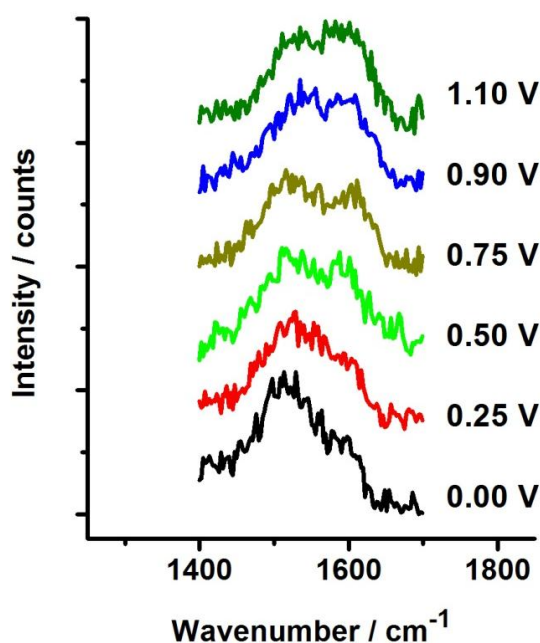


Figure 6. Series of SERS partial spectra for GHB on platinum film deposited on carbon electrode. Potential is indicated alongside.

Compounds such as butyric and succinic acids showed a predominant peak close to 1590 cm^{-1} (Figure 7, top spectra) at 0.75 V , whereas for the 1-butanol the predominant band corresponded to the fingerprint chain vibration (H-C-H deformation) on the platinum surface (Figure 7, bottom spectra). On the other hand, GBL showed two bands at 1500 and 1650 cm^{-1} , the latter assigned to the carbonyl group of the compound [33]. From the group of studied compounds, only the lactone showed a band at 1650 cm^{-1} , even for the Raman spectra obtained in acidic aqueous solutions (spectrum not shown). The profiles of the spectra in figure 7 are not dependent on the applied potential (only with butanol a shoulder can be appreciated at high potential corresponding with the formation and adsorption of butyric acid). Thereby, the evolution with the potential observed for the GHB peaks is evidence of the formation of succinic acid as reaction product.

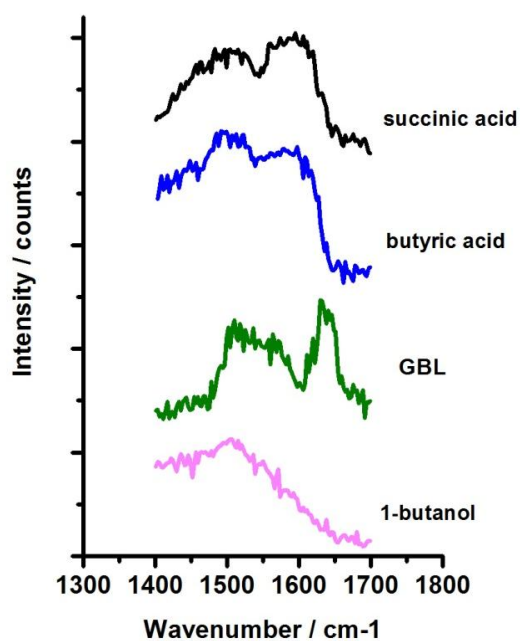


Figure 7. SERS spectra between $1400\text{-}1700\text{ cm}^{-1}$ of 1-butanol, GBL, butyric acid and succinic acid collected at 0.75 V with a platinum film deposited on carbon electrode. Test solution: 0.5 M solute compound + 0.5 M Phosphoric acid. Two spectra collected with an acquisition time of 60 s were averaged.

Inspection of the potential dependence for the spectra in the zone of low wavenumbers (Figure 8) showed an evolution of the band at 370 cm^{-1} corresponding to the interaction of phosphoric electrolyte with platinum surface at potentials lower than 0.0 V , as it was indicated above. A band at $430\text{-}470\text{ cm}^{-1}$ started gradually appearing at 0.5 V , most

likely from the Pt-OH and Pt-Ox vibrations [34, 35]. The increasing intensity of this last band in a parallel way to the formation of Pt oxides and hydroxides on the surface of the electrode is in good agreement with the observed peaks in the voltammogram of the blank electrolyte.

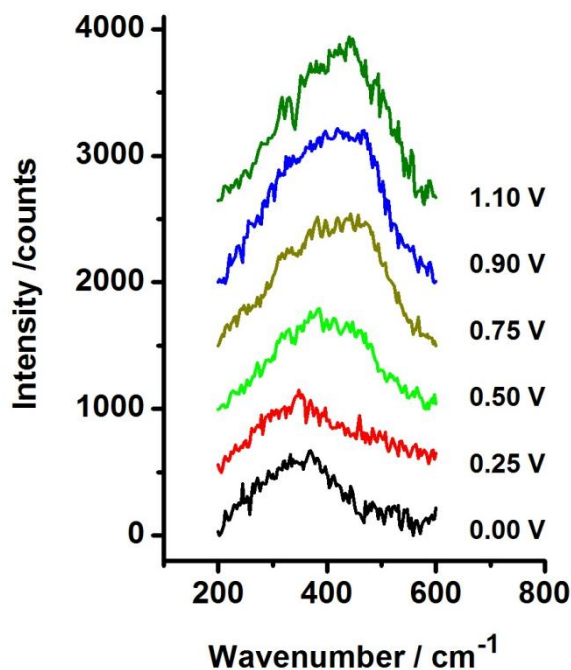


Figure 8. SERS spectra between 200-600 cm^{-1} of GHB with a platinum film deposited on carbon electrode. Test solution: 0.5 M solute compound + 0.5 M phosphoric acid. Two spectra collected with an acquisition time of 60 s were averaged

The set of results obtained are also concordant with the Raman bands observed for the reaction products of the electro-oxidation of GHB as well as with the conclusions deduced from this study by means of voltammetry and chronoamperometry.

4. Conclusions

The chronoamperometry studies seem to suggest that the curves j-t, obtained for potentials corresponding to the three peaks observed in the GHB oxidation on platinum electrode in acid media, explain the general way of reaction on platinum electrode of GHB. At more anodic potentials (peaks A and B) the curves reach, at longer times, a stationary current typical of catalytic processes, whereas at lower potentials (peak C) the current falls to zero. The corresponding study at potentials in the vicinity of peak C also

indicates that the oxidation of GHB is a process of adsorption controlled by the mass transport.

The dependence of the stationary current density with the square root of the GHB concentration agrees with a scheme of catalytic oxidation in which platinum hydroxide species acts as catalysis intermediates.

Raman (SERS) spectra corresponding to GHB (intermediates and products) and water adsorbed species formed/consumed in the potential dependent interfacial processes agree with the electrochemical results. It is necessary to emphasize that, in the experimental conditions of this work, the spectro-electrochemical results demonstrated that succinic acid plays the role of both intermediate (to produce the conjugate derivative) and product in the GHB oxidation.

The chronoamperometric results described in this paper are in good agreement with the previously reported behavior for the electro-oxidation of GHB on platinum electrode in acidic medium observed by cyclic voltammetry. Also, the Raman spectro-electrochemistry of the GHB in the described conditions, described for the first time, supports the results obtained for both voltammetry and chronoamperometry studies.

5. Acknowledgments

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