Synthesis, SERS, Raman and FT-IR Investigation in Conjunction with DFT Theoretical Simulations on N-(2-cyanoethyl)-imidazole. I

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A thoroughly experimental and theoretical spectroscopic study (Surface-enhanced Raman Spectroscopy (SERS), Raman and FT-IR) concerning the structure of N-(2-cyanoethyl)-imidazole have been performed. Limited information is bringing by Raman Spectroscopy, but when absorbed on the surface of the silver nanoparticles, strong vibrational signals were recorded. The influence of aggregation ions (F<sup>-</sup>, Cl<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>) and the influence of pH on the adsorption mechanism was investigated. Ab initio HF and density functional theory calculation were carried out to compute the wavenumbers of N-(2-cyanoethyl)-imidazole. All theoretical and experimental vibrational frequencies for N-(2-cyanoethyl)-imidazole were carefully assigned, and are in agreement to each other.

Keywords: Surface-enhanced Raman Spectroscopy, FT-IR, DFT, substituted imidazole

Imidazole derivatives are common scaffolds in highly significant natural biomolecules, including vitamins (biotin, cobalamin, etc.), amino acids (histidine, histamine, etc.), alkaloids (hymenine, pilocarpine, etc.) etc, which have been shown to exhibit interesting biological activities such as antimicrobial, and cytotoxic activities [1, 2]. Synthetic imidazoles have also been found to be biologically and medicinally potent anticancer [3, 4], anti-HIV [5, 6], antibacterial and antifungal [7, 8].

The use of these compounds as medicine requires that they have to be identified quickly in very small amounts. Vibrational spectroscopy i.e. FT-IR, Raman and SERS are routinely used in this respect. During the last few years, surface-enhanced Raman Spectroscopy became a useful and powerful method for structural determination of bioorganic compounds [7]. Raman signal is amplified by the roughness of metal surfaces. There are two mechanisms that explain the enhancement of Raman signal: charge-transfer (CT) enhancement that is attributed to the first layer effect and electromagnetic (EM) enhancement which goes beyond the first absorbed layer [9]. Thus, this method allows the detection of very low sample concentration [10, 11]. Also, the SER spectra are enhanced by the presence of chloride anion [12].

Carrying on our work in the field of imidazole derivatives [13-15], and having in view the potential practical applications, we decided to perform a systematic study concerning structure of substituted imidazole. The influence of other anions (F<sup>-</sup>, Br<sup>-</sup>, I<sup>-</sup>) and pH influence over SER spectra of N-(2-cyanoethyl)-imidazole was investigated. Furthermore, the computed vibrational analysis was correlated with the spectral data in order to find how the molecule was adsorbed on the surface of the silver colloid. Our final goal is to construct a data base that could be used for quick and cheap identification of imidazole derivatives.

**Experimental part**

**Synthesis**

25 mmoles (1,744g) imidazole were dissolved at 80°C in 10mL toluene. 25 mmoles (1.325g = 1.625 mL) acrylonitrile and 0.1 mL triethylamine were added and the mixture was refluxed for 30 h. The solvent was distilled and N-(2-cyanoethyl)-imidazole was obtained (yellow-orange oil) with a yield of ~ 99%. The reaction pathway is illustrated in figure 1.

![Fig. 1. Reaction pathway for the synthesis of N-(2-cyanoethyl)-imidazole](image)

**Computational details**

The vibrational wavenumbers were performed using Firefly program [16, 17]. The computations were performed at HF/6-31+G** B3PW91/6-31+G** and B3LYP/6-31+G** levels at theory to get the optimized geometry and vibrational wavenumbers of the normal modes of N-(2-cyanoethyl)-imidazole [18].

**Colloid preparation and instrumentation**

The silver colloid was prepared by heating to boiling 200mL volume of 10⁻⁴M AgNO₃ aqueous solution. 4mL of 1% trisodium citrate solution was added, and the mixture was kept boiling gently for 1h [24]. The resulting colloid shows a turbid grey color. The final concentration of the analyte into the colloid suspension was approximately 1·10⁻⁵ M. NaOH and H₂SO₄ were used in order to adjust the pH values.

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The Raman and SER spectra were recorded with a spectrometer Horiba Jobin Yvon RPA-HE 532. A Nd-Yag laser with 532nm frequency was used as source. The nominal power was 100mW, the spectral range between 3600 and 250cm$^{-1}$ with the resolution of 3cm$^{-1}$. The system is provided with a "superhead" fiber optic Raman probe for contactless measurements.

FT-IR spectrum was recorded by KBr disc method in the range 3500 – 270cm$^{-1}$, number of scans 40, resolution 2cm$^{-1}$ on a Brucker Vertex 70 spectrometer.

Results and discussions

In the case of N-(2-cyanoethyl)-imidazole, ordinary Raman spectroscopy showed little observational results due to the strong fluorescence background. Thus, the ordinary Raman spectrum N-(2-cyanoethil)-imidazole shows a very weak signal. Therefore, an appropriate method of investigation must be elected. Raman and SER spectrum of N-(2-cyanoethyl)-imidazole is shown in figure 2. Fluorescence is still present in SER spectrum, but several sharp and clear vibrational peaks occur.

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The role of chloride or other co-adsorbed species on the positively charger Ag surface has been experimentally verified [26, 27]. This enhancement originates from the induction of positive charges on silver surfaces by the co-adsorbed chloride, which leads to an increase in the interaction between the molecule and the silver surface [25]. This yields to a considerable enhancement of the SERS signal [12] as seen in figure 5.

Vibrational analysis

The schematic structure of N-(2-cyanoethyl)-imidazole with the labeling of the atoms is illustrated in figure 6.
DFT methods include electron correlation in the study of the vibrational wavenumbers of moderately large molecules [28, 29]. The DFT hybrid B3LYP functional tends to overestimate the fundamental modes, therefore scaling factors have to be used for obtaining a considerable better agreement with the experimental data [30, 31]. Thus, according to the work of Rauhut and Puley [32] and Scott and Radom [30] scaling factor according to the method used has been uniformly applied to HF, B3LYP and B3PW91 calculated wavenumbers values from the table 1. All scaling factors have been kept fixed. For the HF method the scaling factor of 0.8953 was used while for the B3LYP and B3PW91 methods the scaling factor of 0.9614 was used. The disagreement between the theory and the experiment could be a consequence of the anharmonicity and of the general tendency of the quantum chemical methods to overestimate the force constants at the exact equilibrium geometry [30]. The scaled theoretical calculation in the table 1, reproduce well the experimental data and allow the assignment of the vibrational modes.

The observed (IR and SERS) and calculated frequencies by \textit{ab initio} and DFT methods and their probable assignments are summarized in table 1.

\textbf{FT-IR spectrum}

The FT-IR spectrum is characterized by sharp and clear band bellow 2500 cm\(^{-1}\). The large band at 1628 cm\(^{-1}\) is due to the water absorption which indicates that the N-(2-cyanoethyl)-imidazole is slightly hygroscopic.

\textbf{Carbon – carbon and carbon - nitrogen vibrations}

The \textit{C-H} vibrations can be divided into aromatic \textit{C-H} vibrations and aliphatic side chain \textit{C-H} vibrations. The aromatic \textit{C-H} stretching vibrations are normally found between 3100 and 3000 cm\(^{-1}\). Above 2500 cm\(^{-1}\), in the domain of \textit{C-H} vibrations, the bands are quite low in intensity. The aromatic \textit{C-H} stretching vibrations are recorded at 3145 and 3117 cm\(^{-1}\). The aromatic \textit{C-H} in-plane bending modes are observed at 1512, 1453, 1288, 1234, 1108 and 1083 cm\(^{-1}\). The aromatic \textit{C-H} out of plane bending modes are observed at 825 and 694 cm\(^{-1}\).


For the aliphatic side chain C₆N₉ the C-H vibrations are observed as scissoring vibrations at 1453 and 1420 cm⁻¹. The rocking vibrations are observed at 1041, 998 and 751 cm⁻¹. The wagging vibrations are observed at 1370 cm⁻¹. The twisting vibrations are observed at 1288, 1234 and 1167 cm⁻¹. The stretching vibrations occurred at 3145, 3117 and 2969 cm⁻¹ in FT-IR spectrum.

**SER spectra and adsorption on the Silver surface**

Overall, the SER spectra show clear and sharp bands. In order to investigate the adsorption mechanism of N-(2-cyanoethyl)-imidazole onto the surface of silver nanoparticle, SER spectra at different values of pH were recorded.

SER spectra of N-(2-cyanoethyl)-imidazole at different pH values are presented in figure 7.

As NaCl was added to the silver colloid, H₂SO₄ was used to achieve acidic conditions instead of HCl to avoid the influence of the chloride ion. The basic pH was achieved by adding NaOH.

Variations in the SER spectra with the change of pH values are attributed to a change in orientation of adsorbates in respect with the surface of metal. According to the selection rules [33, 34] the most intense bands are those given by vibrations which induce a polarization of the adsorbate electron cloud perpendicular to the metal surface [35]. When the molecule adopts a perpendicular orientation on the surface of silver nanoparticle, the in-plane vibrations would be increased, while out-of-plane vibrations would be decreased.

By looking at SER spectra recorded at different values of pH we can observe that new bands occurred in neutral and basic conditions while in acidic conditions the intensity of SER signal decreased.

The molecule of N-(2-cyanoethyl)-imidazole can be adsorbed onto the surface of silver nanoparticle in three ways: through the lone pair-electrons of nitrogen atom N₃, through the π-system of the imidazole ring or through the unshared pair of electrons of nitrogen atom from nitrile group Nᵣ. The nitrogen atom Nᵣ is sterically hindered by the side chain, therefore the molecule cannot be adsorbed onto the metal surface through this atom.

The signal of nitrile group at 2254 cm⁻¹ in all SER spectra of N-(2-cyanoethyl)-imidazole i.e. acidic, neutral and basic conditions as shown in figure 5 does not present shifts larger than 2 cm⁻¹, therefore is unlikely that the molecule of N-(2-cyanoethyl)-imidazole is adsorbed via the nitrogen atom in nitrile group.

We assume that the molecule of N-(2-cyanoethyl)-imidazole in basic conditions is adsorbed on the surface of the silver nanoparticles via the unshared electrons from nitrogen atom Nᵣ, in basic and neutral conditions.

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Conclusions

An experimental and theoretical spectroscopic study (SERS, Raman and FT-IR) concerning the structure of N-(2-cyanoethyl)-imidazole have been performed. The fundamental vibrational frequencies of N-(2-cyanoethyl)-imidazole have been obtained from ab initio and DFT calculations. The FT-IR and SER spectra at different values of pH were recorded for N-(2-cyanoethyl)-imidazole. As this molecule presents a very strong fluorescence at 532 nm, the SER spectroscopy is a very useful tool for detecting a very small amount of these components (10⁻³ M). The data obtained from quantum mechanical methods are in good agreement with the data obtained by experimental observed spectra. Both types of calculations are useful to explain vibrational spectra of N-(2-cyanoethyl)-imidazole, but we have found that ab initio calculations RF/6-31+G** level gives overestimated results, even after scaling, compared with DFT-B3LYP/6-31+G** and B3PW91/6-31+G**.

The N-(2-cyanoethyl)-imidazole molecule is adsorbed on the silver surface via the delocalized aromatic electrons from imidazole ring, parallel with the surface in acidic conditions. In neutral and basic conditions, the N-(2-cyanoethyl)-imidazole molecule is adsorbed on the surface of the silver nanoparticles via the unshared electrons from nitrogen atom N₃ perpendicular onto the surface.

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