Energetics of neutral and deprotonated (Z)-cinnamic acid

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ABSTRACT

We have performed a study of structural, thermochemical and thermophysical properties of the (Z)-cinnamic acid neutral molecule and its corresponding oxyanion (formed by deprotonation of the carboxylic group). The thermophysical study (heat capacities, temperature and enthalpy of fusion) was made by DSC. The following intrinsic (gas-phase) thermochemical magnitudes have been experimentally determined: (i) standard enthalpy of formation, at $T = 298.15$ K, of the neutral molecule, $\Delta_f H_m^0(g) = (-215.5 \pm 3.2)$ kJ $\cdot$ mol^{-1}, by combustion calorimetry and by the Knudsen effusion technique, (ii) deprotonation enthalpy, $\Delta_{acid} H^0(g) = (1416.4 \pm 8.8)$ kJ $\cdot$ mol^{-1} and acidity, $GA = (1386.7 \pm 8.8)$ kJ $\cdot$ mol^{-1}, by the EKM method using ESI-TQ Mass Spectrometry. From these results we have also derived the enthalpy of formation of the oxyanion, $\Delta_f H_m^0$(oxyanion, g) = (-303.5 ± 9.4) kJ $\cdot$ mol^{-1}. A computational study, through density functional calculations at the B3LYP/6-311++G(d,p) level of theory, was used to check the good consistency of the experimental results. The global results show that (Z)-cinnamic acid is significantly less stable than the corresponding (E)-isomer, which can be related to the greater acidity of the (Z)-form found in both the gas and aqueous solution phases.

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1. Introduction

Cinnamic acids (aryl phenylpropenoic acids) are secondary plant metabolites involved in many biosynthetic pathways of phenolic compounds such as flavonoids, stilbenes, salicylic acid and lignin [1–3]. They play important roles in plant growth and in plant-environment interactions and also function as cell wall components, UV protectors; pigments, herbicides and aroma compounds [2–4]. Furthermore, cinnamic acid derivatives have also been reported to have antibacterial, antiviral and antifungal properties [5]. The cinnamic acids can exist in both (E)- and (Z)-forms (figure 1) [1,2].

In nature, (E)-cinnamic acid has an important role as intermediate of the phenylpropenoid pathway which is synthesized from L-phenylalanine by phenylalanine ammonia lyase and then converted by enzymatic reactions to other metabolites [1,2,6]. On the contrary, the role of (Z)-cinnamic acid is still under discussion. Its presence in root tissue suggests that it may be produced

through either light-dependent and independent pathways or may be transported from a plant organ to another [7]. Some authors suggested that it can be produced by UV light-mediated photo-isomerization of (E)-cinnamic [8] because its concentration is increased by UV irradiation of plant organs. The biological properties of (Z)-cinnamic acid are significantly different from those of (E)-forms. The (E)-form is generally believed to be physiologically inactive and be antagonistic to the effects of auxin in higher plants [8,9]. However, it is known that the (Z)-form inhibits root growth of avena, wheat, lax and arabidopsis, and also induces epinastic curvature in tomato seedlings, in the same way as the plant hormones auxin and ethylene [8,9]. Further studies have shown that (Z)-cinnamic acid acts on plant cells through both ethylene- and auxin-independent signalling pathways [8,9]. The role of the genes may provide some insights into the molecular mechanisms by which (Z)-cinnamic acid regulates plant growth and development as well as plant adaptation to environmental stresses [10].

Recently, we have developed a highly efficient one-pot preparation of (Z)-cinnamic acid involving an (E) → (Z) photoisomerization reaction [11,12]. Furthermore, the spectroscopic properties of (Z)-cinnamic acid have been studied by means of UV-visible absorption spectroscopy and high-level quantum mechanical

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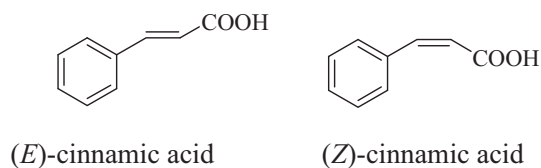E-mail addresses: jdavalos@iqfr.csic.es (J.Z. Dávalos), mlsalum@qo.fcen.uba.ar (M.L. Salum).

FIGURE 1. Chemical structure of (E)-(left) and (Z)-cinnamic acid (right).

computations [13]. The UV-visible absorption spectra of (Z)- and (E)-cinnamic acids reveal noticeable differences regarding the spectroscopic behaviour of both regioisomers in aqueous media. Quantum chemical calculations of the (Z)-form show that in aqueous solution the carboxylate group is largely out-of-plane giving a non-planar structure that modifies the electronic density delocalization, in contrast with the planar structure found for the (E)-form. Therefore, we decided to carry out a complete theoretical and experimental study of the thermal stability of the (Z)-cinnamic acid in both, its neutral and its deprotonated form (anion). The experimental thermophysical and thermochemical properties were determined using differential scanning calorimetry (DSC), static bomb (micro) combustion calorimetry and the Knudsen effusion technique. Furthermore, we determined the deprotonation parameters (acidity GA, deprotonation enthalpy $\Delta_{acid}H^0$ and entropy $\Delta_{acid}S^0$) by the Extended Kinetic Method (EKM), which is an improved version of the kinetic method developed by Cooks et al. [14] using ESI-Triple-Quadrupole Mass Spectrometry.

2. Experimental

2.1. Materials and purity control. DSC measurements

Cis-cinnamic acid or (Z)-cinnamic acid [(Z)-$C_9H_8O_2$, Z-3-phenyl-2-propenoic acid] was synthesized and purified by photoisomerization of (E)-cinnamic acid in acetonitrile solution, such as described elsewhere [11,12], and carefully dried under vacuum at room temperature. Chemical structure of both (Z)- and (E)-cinnamic acids were confirmed by ^1H NMR spectroscopy (see Supporting Information, figure S1a). Purity of the mentioned compounds was checked by their melting points [11], and also estimated by differential scanning calorimetry (DSC), which showed that the mole fraction of impurities was $<7 \times 10^{-3}$. The (Z)-cinnamic acid compound was studied by DSC over the $T =$ (255.15 to 340.1) K (melting point) range, and no phase transitions were found. The heat capacities, temperature and enthalpy of fusion were experimentally determined also by DSC. Full details are given in the Supporting Information (S1). Table 1 summarizes relevant information on sample material purity.

2.2. Combustion calorimetry

The combustion experiments were performed in an isoperibol static micro-bomb calorimeter. A detailed description of this method can be found in reference [15]. The energy equivalent of the calorimeter ε(calor) was determined from the combustion of benzoic acid (NIST standard reference sample 39j), its massic energy of combustion being $(-26,434 \pm 3)\,J \cdot g^{-1}$, under certified conditions. From 10 calibration experiments, we obtained an ε (calor) of $(2105.3 \pm 0.3)\,J \cdot K^{-1}$, where the uncertainty quoted is the standard uncertainty of the mean.

The combustion energy of (Z)-cinnamic acid was determined by burning the solid samples in pellet form in oxygen at $p = 3.04$ MPa, with 0.05 cm^3 of water added to micro-bomb calorimeter. In order to obtain combustion complete reactions, Vaseline was used as auxiliary substance. The massic energy of combustion of Vaseline used was $(-46,086 \pm 5)\,J \cdot g^{-1}$ [16]. This value was confirmed in our laboratory. The empirical formula and massic energy of combustion of the cotton-thread fuse, $CH_{1.740}O_{0.871}$ and $(-17,410 \pm 37)\,J \cdot g^{-1}$ were determined in our laboratory. The uncertainty quoted corresponds to the standard deviation of the mean for ten experiments.

Corrections of apparent mass to mass, conversion of the energy of the actual bomb process to that of the isothermal process, nitric acid formation and correction to standard states were made according to Hubbard et al. [17]. For these corrections were used the values of density $\rho = 1.23$ (taken from XRD base Data), massic heat capacity $c_p = (1.202 \pm 0.002)\,J \cdot K^{-1} \cdot g^{-1}$ (taken from this work. See SI) and $(\partial V/\partial T)_p$ assumed to be $3.85 \times 10^{-7}\,dm^3 \cdot K^{-1} \cdot g^{-1}$ [18]. Complementary details are given in the Supporting Information (S2).

2.3. Enthalpy of sublimation measurements

The vapour pressures of (Z)-cinnamic acid as a function of temperature were measured by the combined Knudsen/Quartz crystal effusion apparatus described in detail by Santos et al. [19]. This methodology is based on the simultaneous gravimetric and quartz crystal microbalance mass loss detection and has the advantages of requiring smaller sample sizes and providing experimental results in shorter effusion times while allowing working temperatures of up to $T = 650$ K. However, due to the significant volatility of (Z)-cinnamic acid at low temperatures (even less than 360 K) the mass loss detection by the quartz crystal microbalance could not be achieved (sublimation of the deposited compound from the cooled quartz crystal was significant). Hence, in this case, the vapour pressures were determined through gravimetric analysis of the Knudsen cell before and after each effusion experiment. The equilibrium vapour pressures of (Z)-cinnamic acid were measured in the following ranges: $T =$ (306 to 326) K and (0.08 to 0.92) Pa.

2.4. Determination of pK_a in water

The experimental titrations of (Z)- and (E)-cinnamic acids were carried out in water using a DL50 graphix (Mettler-Toledo Intl. Inc.) apparatus. A solution of 0.1 M NaOH was used as titrant and the resulting pK_a values were 4.0 and 4.45 for (Z)-and (E)-cinnamic acids, respectively.

TABLE 1
Provence and mass fraction purity of (E)- and (Z)-cinnamic acid.

Chemical	Provenance	CAS number	Mass fraction purity [a]	Purification method	Analysis method
(E)-cinnamic acid	Sigma–Aldrich	140-10.3	0.994	None	TLC, NMR, DSC, m.p
(Z)-cinnamic acid	Synthesis	102-94-3	0.996	Precipitation, filtration, ion exchange resin, evaporation	TLC, NMR, DSC, m.p.

[a] The mass fraction purity of (E)-cinnamic acid is based on information provided by the supplier Sigma–Aldrich. The (Z)-cinnamic acid was further purified as references [11,12]. The purity of both compounds was verified by TLC (thin layer chromatography), m.p. (melting point), and DSC (differential scanning calorimetry). Structural information was confirmed by NMR spectroscopy (figure S1a).