Experimental and computational thermochemistry of the isomers: Chromanone, 3-isochromanone, and dihydrocoumarin

M. Agostinha R. Matos a,*, Clara C.S. Sousa a, Victor M.F. Morais a,b

a Centro de Investigação em Química, Departamento de Química, Faculdade de Ciências da, Universidade do Porto, Rua do Campo Alegre, 687, P-4169-007 Porto, Portugal
b Instituto de Ciências Biomédicas Abel Salazar, ICBAS, Universidade do Porto, P-4099-003 Porto, Portugal

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ABSTRACT

The standard ($p^* = 0.1$ MPa) molar enthalpies of formation in the condensed state of chromanone, dihydrocoumarin, and 3-isochromanone were derived from the standard molar energies of combustion in oxygen at $T = 298.15$ K, measured by combustion calorimetry. Calvet microcalorimetry was used to derive the standard molar enthalpies of sublimation and vaporization.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Delta_{f}U^{\circ}_{m}(\text{cr}, l)/$(kJ/mol)</th>
<th>$\Delta_{f}H^{\circ}_{m}(\text{cr}, l)/$(kJ/mol)</th>
<th>$\Delta_{f}G^{\circ}_{m}(\text{cr}, l)/$(kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromanone</td>
<td>4393.3 ± 1.6</td>
<td>289.1 ± 2.0</td>
<td>84.6 ± 1.3</td>
</tr>
<tr>
<td>Dihydrocoumarin</td>
<td>4364.6 ± 1.9</td>
<td>317.8 ± 2.2</td>
<td>69.9 ± 0.5</td>
</tr>
<tr>
<td>3-Isochromanone</td>
<td>4348.7 ± 1.4</td>
<td>333.7 ± 1.8</td>
<td>97.3 ± 1.4</td>
</tr>
</tbody>
</table>

From these values the standard molar enthalpies in the gaseous phase, at $T = 298.15$ K, were derived. Additionally estimates were performed of the enthalpies of formation of all the studied compounds in gas-phase, using DFT and other more accurate correlated calculations, together with appropriate isodesmic or homodesmic reactions. There is a reasonable agreement between computational and experimental results.

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1. Introduction

As a class of compounds, chromones and chromanones have been attracting much attention among chemists in different fields.

Chromanone derivatives have been found to exhibit broad-spectrum biological activities, such as insecticidal, antifungal, antibacterial activities [1], and as perfuming ingredients [2]. 6-Methyl-4-chromanone was found to exhibit strong activity in inhibiting in vitro cell growth of human K562 cells [3].

Dihydrocoumarin derivatives have also applications in cosmetics; 7-methyl and 7-ethylidihydrocoumarin are used to obtain a coumarin type of odour [4].

In the present work, we report the standard molar enthalpies of formation of the three isomers in the gaseous phase, at $T = 298.15$ K. Our current results were obtained from measurements of combustion energies, at $T = 298.15$ K, using a static bomb calorimeter. The standard molar enthalpies of vaporization/sublimation were measured by Calvet microcalorimetry, at $T = 298.15$ K.

2. Experimental

2.1. Materials and DSC

All the compounds were commercial products from Aldrich Chemical Co., chromanone [CAS 491-37-2], dihydrocoumarin [CAS 119-84-6], 3-isochromanone [CAS 4385-35-7]. All the samples were purified by repeated distillation or sublimation under...
reduced pressure before the experimental studies began. For the solid compounds, the purity (table 1) was derived from d.s.c. (Setaram DSC 141) analysis by a fractional fusion technique [5]. The samples, hermetically sealed in stainless steel crucibles, were heated at a rate of 1.67 \( \cdot 10^{-2} \) K \( \cdot \)s\(^{-1}\). The temperature scale of the calorimeter was calibrated by measuring the melting temperature of three high-purity reference materials (naphthalene, benzoic acid, and indium) [6] and its power scale was calibrated with high-purity indium (mass fraction > 0.99999). The recorded thermograms did not show any phase transition between \( T = 298 \) K and the melting temperature of the compounds studied.

The mass fraction purity of the liquid compound, dihydrocoumarin, was evaluated as 0.9989 by gas–liquid chromatography (Agilent 4890 D chromatograph).

The purity of the samples was also confirmed through the carbon dioxide gravimetry results. The average ratios of the mass of carbon dioxide recovered after each combustion experiment to that calculated from the mass of sample, together with the standard deviation of the mean, were: chromanone (0.9994 ± 0.0002), dihydrocoumarin (0.9992 ± 0.001), 3-isochromanone (0.9997 ± 0.02). The density of the liquid dihydrocoumarin 1.169 g \( \cdot \)cm\(^{-3}\) was taken from literature [7] while the densities of the crystalline compounds were estimated, from the mass and the dimensions of samples in pellet form, as chromanone (1.14 g \( \cdot \)cm\(^{-3}\)), 3-isochromanone (1.14 g \( \cdot \)cm\(^{-3}\)).

### 2.2. Combustion calorimetry

The combustion experiments were performed with a static bomb calorimeter, using a twin valve bomb, type 1108 of Parr 15 K, \( \Delta U(\text{IBP}) = -(\Delta c_{\text{cal}} + \Delta m(H_2O) \cdot c_p(H_2O,l) + \epsilon_i) \Delta T_{\text{ad}} + \Delta U_{\text{ign}}, \) (1)

where \( \Delta U(\text{IBP}) \) is the energy associated to the isothermal bomb process, \( \epsilon_i \) is the energy of the bomb contents after ignition and \( \Delta T_{\text{ad}} \) is the adiabatic temperature raise calculated using the program LABTERMO [11]. For the cotton-thread fuse, empirical formula CH\(_1\)\(_{16}\)\(_{16}\)\(_{0}\)\(_{8.643}\), the value of \(-16250 \pm 0.1\) [12] was taken for the massic energy of combustion, \( \Delta U(\text{HNO}_3) \) was based on \(-59.7\) kJ \( \cdot \)mol\(^{-1}\) [13] for the molar energy of formation of 0.1 mol \( \cdot \)dm\(^{-3}\) HNO\(_3\) (aq) from N\(_2\), O\(_2\), and H\(_2\)O(l). The mass of compound, \( m(\text{compound}) \), used in each experiment was determined from the total mass of carbon dioxide, \( m(\text{CO}_2) \), produced after allowance for that formed from the cotton-thread fuse and Melinex.

An estimated pressure coefficient of specific energy: \( \epsilon_u = -0.2 \pm 0.1 \) J \( \cdot \)g\(^{-1}\) \( \cdot \)MPa\(^{-1}\). The standard molar enthalpies of sublimation or vaporization were measured using the “vacuum sublimation” drop microcalorimetric method [17]. The microcalorimeter was calibrated in situ for these measurements using the reported enthalpy of sublimation of naphthalene [18] and of vaporization of n-decane [19].

### 2.3. Calvet microcalorimetry

The standard molar enthalpies of sublimation or vaporization were measured using the “vacuum sublimation” drop microcalorimetric method [17]. The microcalorimeter was calibrated in situ for these measurements using the reported enthalpy of sublimation of naphthalene [18] and of vaporization of n-decane [19]. Samples, of about 3 to 5 mg of the crystalline compounds and of 7 to 10 mg of the liquid compound, contained in a thin glass capillary tube sealed at one end, were dropped, at room temperature, into the hot reaction vessel, in a high temperature Calvet microcalorimeter (SETARAM HT 1000D) held at \( T = 366 \) K for chromanone and 3-isochromanone and at \( T = 362 \) K for dihydrocoumarin and then removed from the hot zone by vacuum evaporation. The thermal corrections for the glass capillary tubes were determined in separate experiments and were minimized, as far as possible, by dropping tubes of nearly equal mass into each of the twin calorimeter cells. From six independent experiments for each compound, a mean value was obtained for the observed standard molar enthalpy of sublimation/vaporization, \( \Delta U(T_{15}^o) \), which was then corrected to \( T = 298.15 \) K, \( \Delta U(298.15) \), using the equation:

\[
\Delta U(298.15, \text{K}) = \int_{298.15}^{T} C_{p,m}(g) \, dT,
\]

where \( T \) is the temperature of the hot reaction vessel, \( C_{p,m}(g) \) is the molar heat capacity of the compound in the gas-phase and was obtained from statistical thermodynamics using the vibrational frequencies obtained from the DFT calculations with the B3LYP functional and the 6-31G* basis set.

### Table 1

<table>
<thead>
<tr>
<th>Compound</th>
<th>( T_{\text{cal}}/(\text{K}) )</th>
<th>( \Delta U(T_{\text{cal}})/(\text{kJ} \cdot \text{mol}^{-1}) )</th>
<th>Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromanone</td>
<td>312.28 ± 0.05</td>
<td>16.72 ± 0.20</td>
<td>99.94 ± 0.04</td>
</tr>
<tr>
<td>3-Isochromanone</td>
<td>355.88 ± 0.07</td>
<td>18.27 ± 0.13</td>
<td>99.76 ± 0.43</td>
</tr>
</tbody>
</table>
Chromanone
\[
C_{p,m}(\Omega)/(J \cdot mol^{-1} \cdot K^{-1}) = -0.000363(T/K)^2 \\
+ 0.732/(T/K) - 42.572. \quad (3)
\]

Dihydrocoumarin
\[
C_{p,m}(\Omega)/(J \cdot mol^{-1} \cdot K^{-1}) = -0.000377(T/K)^2 \\
+ 0.745/(T/K) - 45.024. \quad (4)
\]

3-Isocromanone
\[
C_{p,m}(\Omega)/(J \cdot mol^{-1} \cdot K^{-1}) = -0.000362(T/K)^2 \\
+ 0.732/(T/K) - 42.970. \quad (5)
\]

3. Computational details

The geometries of all molecules have been fully optimized using density functional theory (DFT) with the Becke three-parameter hybrid exchange [20] and the Lee–Yang–Parr [21] correlation density functionals (B3LYP) and the Pople’s split-valence 6-31G* extended basis set [22]. The optimum structures so obtained were further certified as true minima by constructing and diagonalizing the corresponding Cartesian Hessian matrix, this procedure providing also the harmonic vibrational frequencies which, after properly scaled by the recommended scaling factor 0.9614 [23] allow reliable calculations of the thermal corrections to the molecular energy. We have further refined the optimum structures by re-optimizing them using the same methodology with the Pople’s split-valence 6-311G* extended basis set [24]. These final optimized structures were then used to perform single point DFT calculations with the cc-pVTZ basis set [25] and also energy calculations based on more accurate correlated computational techniques of the MCCM/3 suite [26,27].

All the geometry optimizations vibrational analysis and single point calculations have been performed using the UK version of program GAMESS [28,29]. The MCCM/3 series of calculations have been performed using the MLGauss program version 2.0 [30], which rely on the Gaussian 03 series of programs [31]. NBO analysis of the wave functions has been made by using the NBOS5.0 module [41] inside the Gaussian 03 code.

4. Experimental results

The temperature of fusion of the crystalline compounds was measured using a differential scanning calorimeter. The results (observed in each case at the onset temperature of the calorimetric peak), T_{ fus }, are presented in table 1 together with the enthalpies of fusion, at the temperatures of fusion, \( \Delta h_{fus}^\theta(T_{ fus }) \), and the purity of the purified samples. Those values represent the mean values of six independent experiments on fresh samples and the uncertainties are twice the standard deviation of the mean.

Results for a typical combustion experiment of the three isomers are given in table 2. The values of the massic energy of combustion, \( \Delta H^\theta_m \), refer to the combustion reaction:

\[
\text{C}_6\text{H}_6\text{O}_2(\ell) + 10\text{O}_2(\ell) \rightarrow 9\text{CO}_2(\ell) + 4\text{H}_2\text{O}(\ell). \quad (6)
\]

The individual results of all combustion experiments, together with the mean value and associated standard deviation, are given for each compound in table 3. Table 4 lists the derived standard molar entropies and enthalpies of combustion and the standard molar enthalpies of formation for the compounds in the condensed phase, at \( T = 298.15 \) K. In accordance with normal thermochemical practice, [32] the uncertainties assigned to the standard molar enthalpies of combustion are, in each case, twice the overall standard deviation of the mean and include the uncertainties in calibration and in the values of auxiliary quantities. To derive \( \Delta H^\theta_m(\text{cr},l) \) from \( \Delta H^\theta_m(\text{cr},l) \), the following standard molar enthalpies of formation, at \( T = 298.15 \) K, were used for \( \text{H}_2\text{O}(l) \), \(-285.830 \pm 0.042 \) kJ mol\(^{-1} \) [33]; \( \text{CO}_2(\ell) \) and \(-393.51 \pm 0.13 \) kJ mol\(^{-1} \) [33].

Measurements of the standard molar enthalpy of vaporization for dihydrocoumarin and of the standard molar enthalpy of sublimation for the crystalline compounds are given in table 5 with uncertainties of twice the standard deviation of the mean.

The derived standard molar enthalpies of formation, in both condensed and gaseous phases, at \( T = 298.15 \) K, are summarized in table 6.

5. Computational results and discussion

Each of the three isomeric chromanones has an optimum geometry consisting of a planar benzenic ring and a heterocyclic ring largely distorted from planarity. Planarity of the last ring is inhibited either by the angular strain within the sp\(^3\) hybridized carbon atoms as well as the repulsion between contiguous –CH\(_2– \) groups. The hydrogen atoms of these fragments are, in fact, observed to be almost perfectly mutually staggered conformations for the chromanone and dihydrocoumarin isomers.

Total energies, identified by the subscripts B3LYP/6-311G**, B3LYP/cc-pVTZ, MC-UFF/3 and MC-QCISD/3 as well as thermal corrections, TCE/6-31G**, are reported in table 6 for the studied compounds.

In order to estimate the enthalpies of formation of the systems from the calculated energies, we used the following set of
homodesmic reactions involving auxiliary systems whose thermochemical properties are well established experimentally [34–37]. The optimum geometries, the energies and the thermal corrections for all the auxiliary molecules have also been obtained using the same procedures as described above.
The estimated values of molar enthalpies of formation in the gaseous phase obtained by DFT calculations and MCCM/3 methods for the compounds are presented in Table 7, for all reactions used. We can observe from that table a good agreement between our computational estimates and the experimental data, with almost no significant difference between the DFT and the most accurate correlated MC-UT/3 and MC-QCISD/3 results. This is perhaps an indication of the adequacy of the chosen homodesmotic reactions. Differences between the two sets of calculations become apparent when we consider the estimates of the enthalpies of formation...
obtained from atomization reactions. Even though we get acceptable results from the MC-UT/3 and MC-QCISD/3 energies, with deviations not exceeding 12.5 kJ mol⁻¹, the estimates obtained from the more reliable B3LYP energies become clearly unacceptable, since the associated errors can exceed 50 kJ mol⁻¹ for the B3LYP-ccPVTZ results and are even worst for the B3LYP-6-311G* ones. The experimentally observed stability ordering is well described by all our calculations which correctly predict dihydrocoumarin to be the most stable isomer, followed by 3-isochromanone (about 12 kJ mol⁻¹ less stable) and by chromanone (about 44 kJ mol⁻¹ more unstable). Thus, we recognize that those isomers which are more stabilized involve the O=C=O fragment. This behaviour is likely to be understood from the interactions involving electron delocalization of the lone electronic pairs of the oxygen atoms. We can quantitatively probe such interactions through an analysis of the wave functions in the framework of Natural Bond Orbital (NBO) theory [38–41], according to which, the electronic population should be distributed over a set of localized one-centre ("lone-pair") and two-centre ("bond") orbitals. This localized description closely mimics a classical Lewis type picture of the electronic system, while delocalization effects are evidenced by small occupancies of the set of anti-bonding orbitals. The stabilizing effect of such delocalization interactions can be quantitatively obtained as second-order perturbative estimates of the corresponding bonding–anti-bonding interactions. By doing so, we were able to identify the leading donor–acceptor interactions which are responsible for the different stabilities of the chromanone isomers as being those involving the π lone-electronic pair of the ring oxygen and the anti-bonding π*(C=O), which contributes with a stabilization energy of about 36 kcal mol⁻¹ and 43 kcal mol⁻¹, respectively for dihydrocoumarin and for 3-isochromanone, and the π lone-electronic pair of the carbonyl oxygen and the anti-bonding σ*(C=O) involving the carbon atom of the same group and the other oxygen atom, contributing with 36 kcal mol⁻¹ and 34 kcal mol⁻¹, respectively for dihydrocoumarin and for 3-isochromanone. Note that neither of the above interactions is allowed in chromanone. The other important interaction justifying differences in stability involve electronic delocalization from the π lone-electronic pair of the ring oxygen to the closer anti-bonding π*(C=C) of the benzene ring. This interaction, which is absent in 3-isochromanone, contributes a stabilization of about 22 kcal mol⁻¹ and 28 kcal mol⁻¹, respectively for dihydrocoumarin and chromanone.

6. Conclusions

In this paper, we have reported experimental measurements of the standard molar energies of combustion of chromanone, dihydrocoumarin, and 3-isochromanone in oxygen at T = 298.15 K, obtained by combustion calorimetry, which, together with the corresponding standard molar enthalpies of sublimation and vaporization, obtained from Calvet microcalorimetry, provided the experimental estimates of their standard molar enthalpies of formation in the gaseous phase. Calculations conducted at the DFT/B3LYP and at more accurate correlated levels also provided reliable estimates of the thermochemical parameters of the title species. The differences in accuracy between both sets of computational results become evident when we consider (non-isodemic) atomization reactions instead of the more restrictive homodesmotic reactions. Indeed, in spite of both sets of calculations being equally appropriate in describing the energetics of the latter reactions, only the correlated calculations relying on the procedures of the MCMC/3 [26,27] suite provided acceptable descriptions of the energetics of atomization reactions.

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