Case No.: IPR2023-00208
U.S. Patent No. 11,013,250

JAFCAU

JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Volume 50 No. 21

October 9, 2002

Published by the American Chemical Society http://pubs.acs.org/JAFC

JOURNAL OF
AGRICULTURAL AND FOOD CHEMISTRY

JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY (ISSN 0021-8561) is published biweekly by the American Chemical Society at 1155 16th St., N.W., Washington, DC 20036. Periodicals postage paid at Washington, DC, and additional mailing offices. POSTMASTER: Send address changes to *Journal of Agricultural and Food Chemistry*, Member & Subscriber Services, P.O. Box 3337, Columbus, OH 43210.

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Accepted Papers and Proofs: Direct correspondence to Journal Publications, Columbus, OH. Tel: (614) 447-3665. Fax: (614) 447-3745. E-mail: acsproof@acs.org.

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JOURNAL OF
AGRICULTURAL AND FOOD CHEMISTRY

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JAFCAU 50(21) 5751−6252 (2002) ISSN 0021-8561
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There is no Supporting Information for this issue.

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JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Possible Mechanism for Involvement of Cysteine in Aroma Production in Wine

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Under conditions close to those of wine, that is, low pH, aqueous medium, and low temperatures, this work describes *N*-(2-sulfanylethyl)-2-oxopropanamide (**1**), a new intermediate in the formation of 2-acetylthiazole from methylglyoxal and cysteine. **1** was characterized by MS, derivatization MS, and ^{1}H and ^{13}C NMR and was synthesized from 2-sulfanylethanamine and ethyl pyruvate. A formation pathway for 2-acetylthiazole from methylglyoxal and cysteine is proposed, in which **1** is a new intermediate in Maillard-type reactions in systems under mild conditions.

KEYWORDS: ***N*-(2-Sulfanylethyl)-2-oxopropanamide; Maillard reaction; cysteine; 2-acetylthiazole; wine aroma**

INTRODUCTION

Maillard (*1*) was the first to observe a reaction between sugars and amino acids both at high temperatures and at 37 °C or below. At present, the term "Maillard reaction" describes a group of chemical reactions between amino and carbonyl functions present in food upon high-temperature treatment. According to Potman and Van Wijk (*2*), the Maillard reaction is responsible for the characteristic flavor and colors of many processed food products (baked, fried, or roasted).

Most of the odor products from the Maillard reaction are sulfur-, oxygen-, and nitrogen-containing heterocycles (*3*). Recently, Pripis-Nicolau et al. (*4*) identified some of these products in cysteine/α-dicarbonyl model solutions in mild conditions close to those of wines. Thereafter, we quantified these heterocycles in different wines (*5*). Among these molecules, we were especially interested in the formation of 2-acetylthiazole and 2-acetyl-2-thiazoline in cysteine and methylglyoxal wine-like solutions. 2-Acetylthiazole has been found in ground and canned beef (*6*, *7*), in boiled and baked potatoes (*8*), and in rice bran (*9*). 2-Acetyl-2-thiazoline was reported for the first time as a volatile constituent of beef broth (*10*). The compound was also identified in roast beef (*11*) and in overpasteurized beer (*12*). Later, Hofmann and Schieberle (*13*) described the formation and stability of 2-acetyl-2-thiazoline. These heterocycles are characterized by persistent roasted hazelnut notes, and their odor thresholds are very low (<5 μg/L in water) (*5*). The frequency of the occurrence of 2-acetylthiazole in wine is variable. Pomerol and Saint Emilion are the red wines with the highest mean levels (7 μg/L), whereas among the white wines, Burgundy, Alsace, and Champagne contain on average the highest concentrations (1.4−1.8 μg/L). Among the nitrogen-containing heterocyclic compounds with olfactory impact, 2-acetylthiazole is often encountered in foods. Moreover, it could play a role in wine flavor. Small quantities of 2-acetyl-2-thiazoline have also been detected in wines (*5*).

Maillard compounds with strong odor notes have long been thought to arise from simple amino acid degradation and subsequent interactions. Among these, the Strecker mechanism induces the degradation of cysteine, leading to the formation of the specific aldehyde. Griffith and Hammond (*14*) proposed a reaction pathway for the formation of 2-acetylthiazole from cysteine and methylglyoxal at conditions close to those of wine (25 °C, aqueous medium) with the exception of the pH (8 compared to 3.5 in wine). They suggested the condensation of the amino acid and the dicarbonyl to form 2-acetylthiazolidine, which is then oxidized twice into 2-acetylthiazole.

In wine-like solutions, we have found an as yet unknown compound when methylglyoxal and cysteine are presents. On the other hand, the same compound was detected at a higher level than that of 2-acetylthiazole during the degradation of 2-acetyl-2-thiazoline solution. We have used GC, GC-MS, and NMR to unambiguously determine the structure of this new molecule.

MATERIALS AND METHODS

Materials. Cysteine, methylglyoxal, thiazole, 2-acetylthiazole, and 2-acetyl-2-thiazoline were purchased from Sigma Aldrich Chemical Co. Inorganic reagents and solvents were all commercial products of analytical grade. All mixtures were prepared with aqueous ethanolic solution 12% volume with 4 g/L of tartaric acid and adjusted to pH 3.5 with 1 N H_2SO_4 and 1 N NaOH. 2-Acetyl-2-thiazoline solutions were 1 mM, and cysteine/methylglyoxal mixtures were 20 mM for each.

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10.1021/jf025604w CCC: $22.00 © 2002 American Chemical Society
Published on Web 09/11/2002

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Case No.: IPR2023-00208
U.S. Patent No. 11,013,250

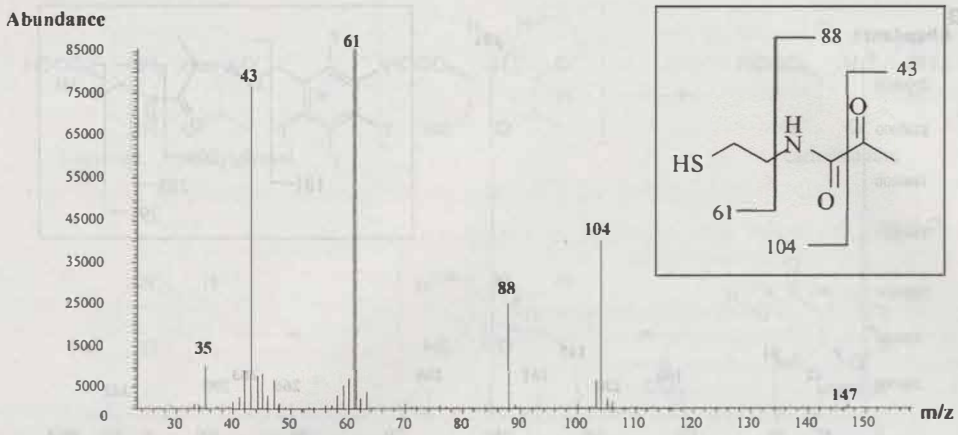

Figure 1. MS (EI) of *N*-(2-sulfanylethyl)-2-oxopropanamide.

Analytical Procedures. Reaction mixtures were analyzed by gas chromatography coupled with various detectors: FID, FPD, NPD, and mass spectrometry or by nose through an olfactometric system. A first gas chromatograph (Hewlett-Packard 5970) was coupled with an NPD, and separation was carried out with an HP5 column (50 m × 0.32 mm, 0.52 μm). A second gas chromatograph (Hewlett-Packard 5970) was coupled with an FID or a sniffing SDS system, and the same column was used. A third gas chromatograph (Hewlett-Packard 6890) was coupled with an FPD, and separations were carried out on an HP5 column (30 m × 0.58 mm, 5 μm) with hydrogen as a carrier gas.

All of the oven temperatures were programmed from 50 to 200 °C at a rate of 2 °C/min, the initial step lasting 1 min. The final isothermal time was 20 min.

GC-MS Analysis. A gas chromatograph (Hewlett-Packard 6890) was coupled with a mass spectrometer (HP 5972; electronic impact, 70 eV; eMV, 2.7 kV). The column was a BP1 (50 m × 0.32 mm, 0.2 μm). The oven temperature was programmed from 50 to 220 °C, the initial step lasting 1 min, at a rate of 2 °C/min to 200 °C and then at a rate of 5 °C/min to 220 °C, and the final step lasting 20 min. The carrier gas was helium (1.5 mL/min). The injector was a split/splitless system (splitless time was 30 s) and the split vent 30 mL/min. Detection was performed in the SCAN mode.

Derivatizations. Derivatization of sulfanyl groups was carried out by *p*-hydroxymercuribenzoic acid (*p*-HMB) (*15*) at 20 °C for 10 min at pH 10, to form a sulfanyl aryl mercuric derivative. Carbonyl functions were derivatized by reacting with perfluorobenzylhydroxylamine (PFBOA) at 20 °C for 1 h at pH 3 to form an oxime (*16*). Derivatization of α-dicarbonyl functions was done by *o*-diaminobenzene (DAB) at 60 °C for 3 h at pH 3 to form a quinoxaline (*17*).

Nuclear Magnetic Resonance Spectroscopy (NMR). 1D and 2D NMR experiments were performed on a spectrometer equipped with an inverse 5 mm broad-band probe at 400.13 and 100.6 MHz for ^{1}H and ^{13}C, respectively. All spectra were recorded using 2 mg of product dissolved in 0.5 mL of CF_3COOD-acidified (1%) H_2O-d_2 in a 5 mm tube. ^{1}H and ^{13}C chemical shifts were expressed in ppm relative to TMS. ^{1}H and ^{13}C chemical shifts were performed as previously described (*18*). NMR spectra were recorded on a Bruber DPX 400. H_2O-d_2 was used as solvent and TSP as the internal standard.

***N*-(2-Sulfanylethyl)-2-oxopropanamide Synthesis.** A chloroform solution (10 mL of chloroform and 1.2 g of 2-sulfanylethanamine) was stirred with an aqueous solution (10 mL of water and 0.5 g of NaOH). Then the mixture was stirred for 1.5 h at ~58 °C. Next, 1.16 g of ethyl pyruvate in tetrahydrofuran (THF; 10 mL) was dripped into the mixture. The resulting solution was further refluxed for 1.5 h. After the reaction was finished, an aliquot of the oil was dissolved in chloroform for GC-MS analysis.

RESULTS

In cysteine/methylglyoxal wine-like solutions, we have never detected the presence of 2-acetylthiazolidine or any specific aldehyde, but we have found an as yet unknown compound. On the other hand, the same compound was detected at a higher level than that of 2-acetylthiazole during the degradation of 2-acetyl-2-thiazoline solution. Now, we have unambiguously determined the structure of this new molecule.

Table 1. Derivatizations of 1 Chemical Functions

reactive	function	product	result
p-hydroxymercuribenzoic acid	sulfanyl	organometallic complex	+
pentafluorobenzylhydroxylamine	carbonyl	oxime	+
o-diaminobenzene	α-dicarbonyl	quinoxaline	+

Mass Spectrometry. When 2-acetyl-2-thiazoline was dissolved in aqueous alcoholic solution at 1 mM, an unknown compound appeared. By comparison of retention indexes and mass spectra, the unknown compound was sought and observed in cysteine and methylglyoxal model solutions at 20 mM. The GC retention indexes calculated on the HP5 and BP21 columns were 1151 and 1168, respectively. Four experienced researchers in olfactometry attributed the descriptors "roasted" and "rubber" to the odorous zones. Mass spectrometry in the SCAN mode showed fragmentation ions arising from the molecule (**Figure 1**). The ion at *m/z* 43 was characteristic of an acetyl group. The *m/z* ratio of the molecular ion was 147. On the other hand, the specific detectors FPD and NPD showed that the molecule contained nitrogen and sulfur atoms. Because the ion at *m/z* 147 was the molecular ion, the molecule contained an odd number of nitrogen atoms, according to the nitrogen rule. Therefore, the $C_5H_9NSO_2$ formula was proposed.

To determine the chemical functions carried by the molecule, we performed a series of specific derivatizations. The reagents used, the functions observed, and the products formed are presented in **Table 1**. Finally, mass spectrometry of the adducts led us to propose the structure of *N*-(2-sulfanylethyl)-2-oxopropanamide (**1**). This was the case, for example, for the oxime resulting from the derivatization of **1** by PFBOA and for the quinoxaline from derivatization of **1** by DAB. The spectra and fragments are presented in **Figure 2**. In addition to the pentafluorotropylium ion at *m/z* 181, we found ions at *m/z* 295, 283, and 266 in the oxime spectrum that are characteristic of the loss of sulfanylmethyl, 2-sulfanylethenyl, and *N*-(2-sulfanylethyl) radicals. The quinoxaline fragment ions are also characteristic of the loss of sulfanyl, sulfanylmethyl, and 2-sulfanylethenyl radicals, thus confirming the structure of **1**.

NMR Spectra. Figure 3 displays the ^{1}H NMR spectrum of **1**. The signal at 1.70 ppm, which integrates for three protons, is characteristic of an isolated methyl group. Each of the four ddd signals, centered, respectively, at 2.9, 3.1, 3.6, and 3.8 ppm,

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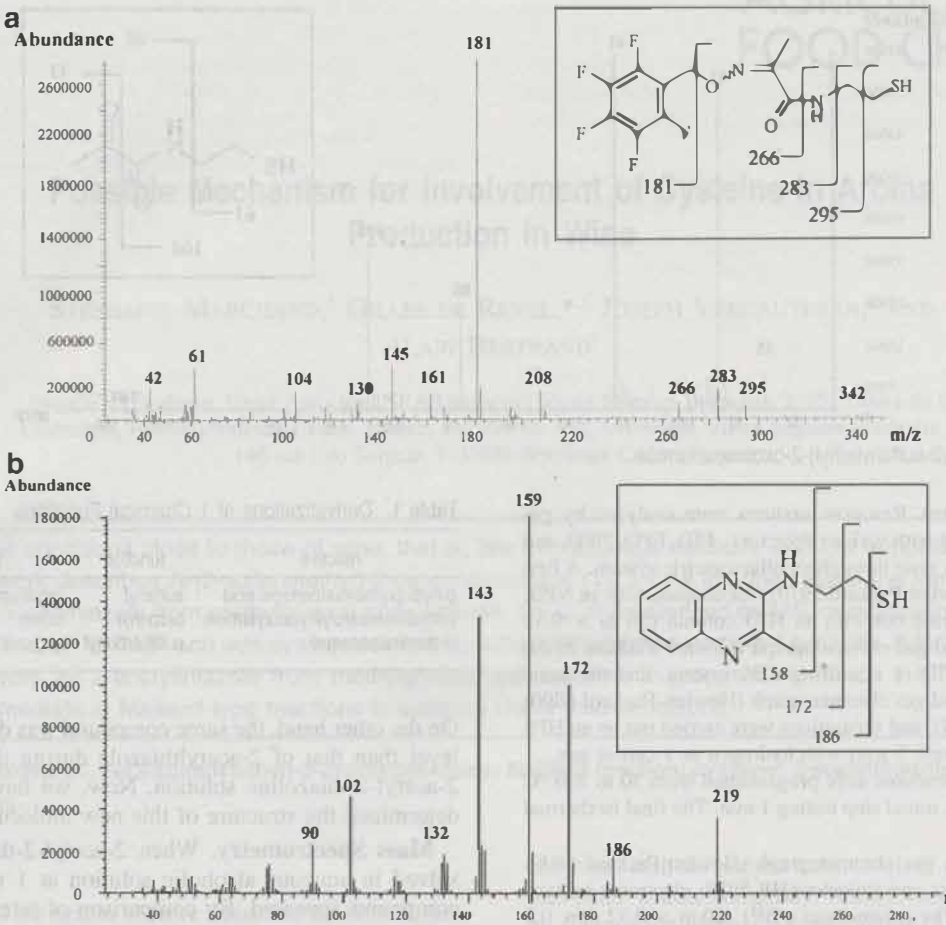

Figure 2. (a) Mass spectrum of PFBOA–[*N*-(2-sulfanylethyl)-2-oxopropanamide] derivative. (b) Mass spectrum of DAB–[*N*-(2-sulfanylethyl)-2-oxopropanamide] derivative.

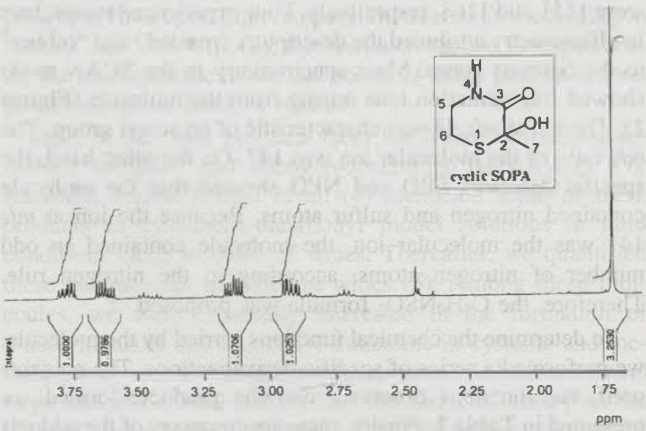

Figure 3. ^{1}H NMR spectrum of *N*-(2-sulfanylethyl)-2-oxopropanamide.

is integrated for one proton and corresponds to the four protons of an ethane chain. However, such diastereotopic protons can be explained only by a cyclic structure. Indeed, the ^{13}C NMR spectrum shows four peaks between 25 and 76 ppm and only one signal at low field attributed to the lactam carbonyl. One-bond and long-range ^{1}H−^{13}C reverse heteronuclear chemical shift correlations (HMQC and HMBC) made it possible to unambiguously assign all the resonances (**Table 2**): the carbon of the methyl group is responsible for the peak at 26.9 ppm; the carbons of the two methylenic groups are responsible for the peaks at 24.9 and 43.5 ppm; the peak at 76.8 ppm is due to the hemi-thioketal carbon atom; finally, the quaternary carbonyl group is responsible for the peak at 172.3 ppm. Therefore, this downfield signal is in favor of a cyclic structure for **1** (only one carbonyl and a quaternary carbon alcohol).

Table 2. Assignment of ^{1}H and ^{13}C NMR Signals

C no.	δ ^{13}C	δ ^{1}H (multiplicity)	HMBC
2	76.8 (C)		H-1, H-5
3	172.3 (C)		
5	43.5 (CH_2)	3.6 (ddd) 3.8 (ddd)	H-1
6	24.9 (CH_2)	2.9 (ddd) 3.1 (ddd)	H-2
7	26.8 (CH_2)	1.7 (s)	H-5

Chemical synthesis of **1** was performed, and the reaction products were analyzed by GC-MS. Retention times and fragmentation spectra were compared with those of **1**, thus confirming the structure.

DISCUSSION

Heterocyclic compounds, especially sulfur ones, may play a major role in the aroma of many processed products (*19*). The pathways for such heterocycle formations have been proposed as part of the Maillard reaction (*14*, *20*). The first step is Strecker degradation. It often involves the formation of a Schiff base, leading to the degradation of the amino acids to their corresponding aldehydes (*21*−*23*). Simultaneously, hydrogen sulfide reacts with the breakdown products of sugars (*24*, *25*). Because these reactions are often run at basic or neutral pH and at quite high temperature (>100 °C), they are efficient and rapid. Although our wine conditions are quite different, the reaction products are close to Maillard reaction adducts.

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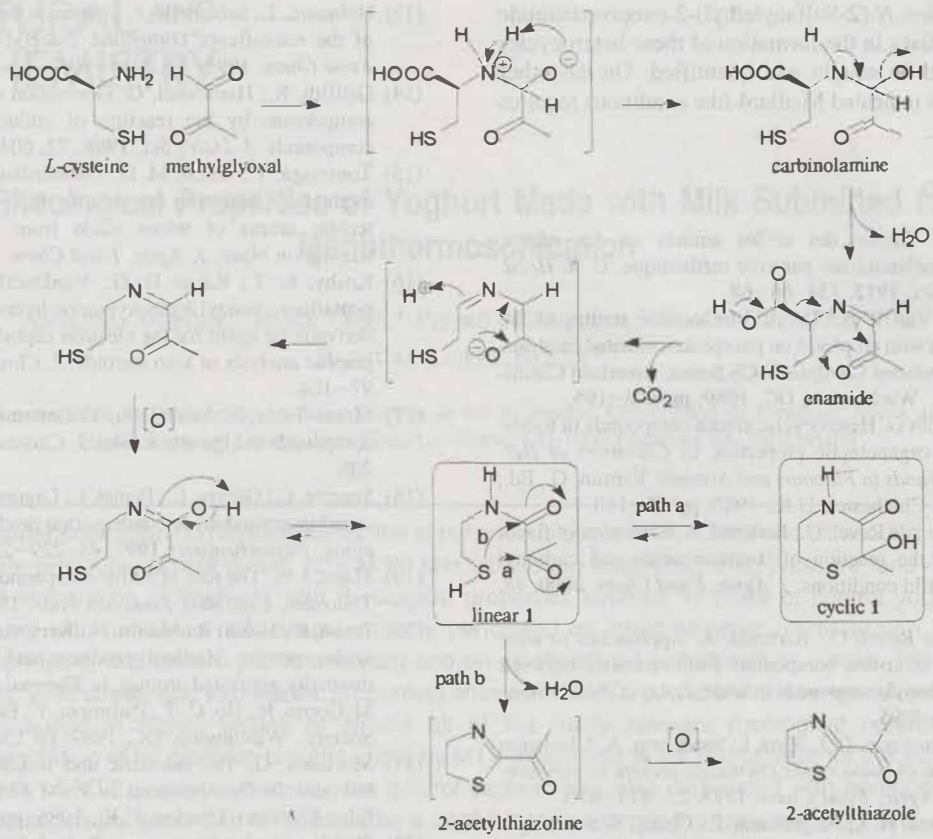

Figure 4. Proposed pathway leading from cysteine and methylglyoxal to 2-acetylthiazole through the new intermediate *N*-(2-sulfanylethyl)-2-oxopropanamide.

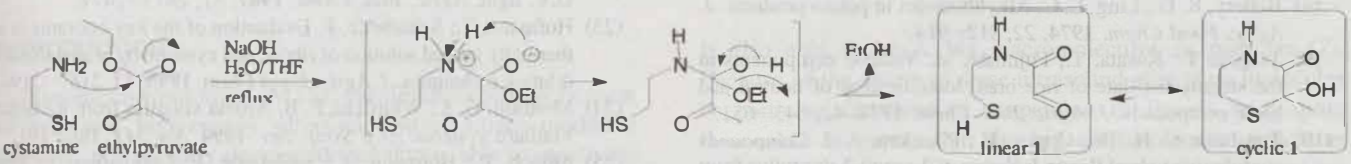

Figure 5. Chemical correlation of *N*-(2-sulfanylethyl)-2-oxopropanamide by direct synthesis.

We were unable to isolate a Schiff base, but we did isolate **1**, a possible intermediary between, on the one hand, cysteine and methylglyoxal, and, on the other hand, the thiazole-type heterocycles. **Figure 4** suggests the formation pathway of 2-acetylthiazole from cysteine and methylglyoxal in aqueous and acidic conditions (wine-type conditions). The pathway starts by the formation of a carbinol amine, which is dehydrated under acidic conditions to form an imine. The conjugation between the imine and the carbonyl functions (enamide) is the driving force that best explains the loss of the carboxyl group. The resulting decarboxylated enamide undergoes an oxidation reaction that ends up as a stable keto-amide. The oxidation step can occur in many ways, because it is not a major phenomenon but only the transformation of a tiny amount of the starting material. For instance, it could be the result of a dismutation with the starting aldehyde (present in a large excess) or with dioxygen dissolved in the solvents. Another pathway could be the cyclization of the imino-ketone to give 2-acetylthiazolidine, which is rapidly oxidized into 2-acetyl-2-thiazoline, and then the hydrolysis of 2-acetyl-2-thiazoline leading to **1**. This would involve the loss of conjugation between unsaturated bonds (imine and carbonyl). Moreover, 2-acetylthiazolidine has never been detected in solutions, so the pathway involving oxidation of the imino-ketone seems to be the most plausible. Further investigations on this point are required. The linear form of **1** gains in stability by the formation of a six-membered cycle after the nucleophilic attack of the sulfur on the ketone group (path a). To prove that **1** really is a compound resulting from two sequential events (first, a decarboxylation, and, second, an oxidation step), we tried to synthesize it directly from chemicals not bearing the carboxyl group (cystamine, rather than cysteine) and at the right number of oxidation (ethyl pyruvate instead of methylglyoxal). In such a case, the isolated compound was mainly the cyclic form of **1** (**Figure 5**) even though yields were relatively low, due to the concurrent reactivity of the amine with the ketone of pyruvate.

Alternatively, the linear form of **1** may close either directly or after reopening of the cyclic one, due to the attack of the sulfur on the carboxamide (path b, **Figure 4**), thereby leading to the even more stable five-membered ring (2-acetylthiazoline). Once formed, this thiazoline undergoes an easy oxidation step (in the same conditions as above) and yields the acetylthiazole, a compound that is formed naturally, even if resulting from many events, due to the low energy of this aromatic ring.

Whatever its conformation, **1** may be considered to be involved in the formation of sulfur- and nitrogen-containing heterocycles under "wine conditions". This compound could play the role of the Schiff base in a mechanism comparable to Strecker degradation but at low temperature, with acid pH and in an aqueous medium.

These data throw light on the involvement of **1** in the reaction mechanisms leading to the formation of very odorous hetero-

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cycles such as thiazoles. *N*-(2-Sulfanylethyl)-2-oxopropanamide could be an intermediary in the formation of these heterocycles in wines, so it could be sought and quantified. On the other hand, its possible role in heated Maillard-like conditions requires further investigation.

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Received for review April 20, 2002. Revised manuscript received July 26, 2002. Accepted August 4, 2002. This work was supported by CIVB (Comite Interprofessionnel des Vins de Bordeaux).

JF025604W