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# Formation of 7*H*-Cyclopenta[*b*]pyridin-7-ones as Proline-Specific Maillard Products

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In a series of proline/monosaccharide model experiments 7*H*-cyclopenta[*b*]pyridin-7-ones were formed as Maillard reaction products. Their structures were elucidated by means of MS, IR, and $^1$H NMR spectroscopy and verified by alternative synthetic routes. 1,2,3,4,5,6-Hexahydro-7*H*-cyclopenta[*b*]-pyridin-7-one (**1**) also was found to be a main constituent in wort and beer.

As demonstrated in previous publications model reactions of L-proline and monosaccharides result in complex mixtures of proline-specific compounds (Tressl et al., 1985a–c). Recently we described the formation of 8*H*-cyclopent[*b*]azepin-8-ones by a Strecker-type reaction of proline and cyclic enolones (Tressl et al., 1985d). In this paper we demonstrate the formation of homologous 7*H*-cyclopenta[*b*]pyridin-7-ones by an analogous ring-enlargement reaction of L-azetidinic acid and cyclic enolones. These compounds are also identified in proline model systems with reducing sugars under Maillard reaction conditions. Further investigations predicted 2-acyltetrahydropyridines as possible precursors to form 7*H*-cyclopenta[*b*]pyridin-7-ones in the proline system.

## EXPERIMENTAL SECTION

**Sample Preparation.** *Reaction of L-Proline and Monosaccharides.* Equimolar amounts of L-proline and monosaccharides (0.03 mol of glyceraldehyde, erythrose, arabinose, glucose, and rhamnose, respectively) dissolved in 50 mL of water were autoclaved for 1.5 h at 150–160 °C in a stainless steel laboratory autoclave equipped with a 100-mL duran glass tube and heated by an electric heater with magnetic stirrer. After the mixtures had cooled to room temperature, the pH (5–6) was adjusted to 10–11 by addition of 0.1 N NaOH and the reaction products were extracted three times with freshly distilled diethyl ether. The combined ether extracts were dried over anhydrous sodium sulfate and concentrated to 1 mL. Aliquot amounts of the extracts were investigated by capillary GC/MS and nitrogen-selective detector.

*Reaction of 2-Acetyl-3,4,5,6-tetrahydropyridine and Aldehydes.* Equimolar amounts of 2-acetyl-3,4,5,6-tetrahydropyridine, prepared according to Büchi and Wüest (1971), and aldehydes (acet-, propion-, and pyruvaldehyde, and furfural) were stirred for 2–4 h at room temperature in water at pH 11 adjusted by addition of 0.1 N NaOH. From the acetaldehyde reaction mixture was separated compound **8** by diethyl ether extraction and isolated by liquid–solid chromatography on $Al_2O_3$ with pentane/ether (9:1). Additionally the acet-, propion-, and pyruvaldehyde and the furfural reaction mixtures were autoclaved without further purification for 15 min at 150–160 °C. From these experiments compounds **2**, **4**, **6**, and **7** were isolated by ether extraction and liquid–solid chromatography on $Al_2O_3$ with pentane/ether (9:1) and preparative gas chromatography. The purified compounds were investigated by MS IR, and $^1$H NMR spectroscopy.

*Reaction of L-Azetidinic Acid and Cyclic Enolones.* Equimolar amounts of L-azetidinic acid and cyclic enolones (0.01 mol of 2-hydroxy-2-cyclopententen-1-one, 0.03 mol of cyclotene = 2-hydroxy-3-methyl-2-cyclopenten-1-one, 0.01 mol of ECP = 3-ethyl-2-hydroxy-2-cyclopenten-1-one) dissolved in water were autoclaved for 1.5 h at 160–180 °C and the reaction products extracted as described for the proline/monosaccharide model experiments. From the proline/cyclotene system compounds **3**, **9**, and **11** and from the proline/ECP system compounds **5**, **10**, and **12** were separated by liquid–solid chromatography on $Al_2O_3$ with pentane/ether (9:1). The isolated compounds were investigated by MS, IR, and $^1$H NMR spectroscopy.

**Capillary Gas Chromatography (GC)/Mass Spectrometry (MS).** Capillary gas chromatography/mass spectrometry was carried out by using a 50-m fused silica column (0.32-mm i.d.) coated with Carbowax 20 M + KOH coupled with a Finnigan MAT 4500 quadrupole instrument. Conditions were as follows: temperature program 70–180 °C at 2 °C/min; ionization voltage 70 eV; resolution 1000.

**Preparative Gas Chromatography.** Purification by preparative GC was carried out with a Varian Aerograph equipped with a 3-m glass column (2-mm i.d.), coated with 5% SP 2401 DB on 100–200-mesh Supelcoport, temperature program 100–250 °C at 4 °C/min.

**$^1$H NMR and IR Spectroscopy.** $^1$H NMR spectra were recorded at 270 MHz on a Bruker WH 270 NMR spectrometer in $CDCl_3$ solution. Chemical shifts are referenced to tetramethylsilane ($Me_4Si$) as internal standard; coupling constants ($J$) are given in hertz. Infrared spectra were obtained from $CDCl_3$ or $CCl_4$ solutions with a Perkin-

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Elmer Model 275 instrument.

## RESULTS AND DISCUSSION

Pyridines are well-known Maillard products in various foodstuffs and are formed either by degradation of trigonelline (Viani and Horman, 1974) or by the reaction of aldehydes and amino acids via pyridinium salts (Suyama and Adachi, 1986). With L-proline, $\alpha$-dicarbonyls react to 2-acylpyridines by ring-enlargement reaction as formulated by Hodge et al. (1972). From a proline/hydroxyacetone reaction mixture Hunter et al. (1969) isolated 2-acetyl-1,4,5,6-tetrahydropyridine, which possesses a potent crackerlike aroma. From Maillard reaction experiments of proline/monosaccharides we characterized the tautomeric 2-acetyl-3,4,5,6-tetrahydropyridine and homologous 2-propionyl derivatives, which were also identified as aroma compounds in beer (Tressl et al., 1981). On heating monosaccharides with proline under elevated temperature (1.5 h, 150–160 °C) in an autoclave we found homologous derivatives of a new class of compounds that were extracted with ether, separated according to polarity by LSC, and isolated by preparative GC. The purified compounds were investigated by MS, IR, and $^1$H NMR spectroscopy, and the results are summarized in Table I.

From the proline/erythrose experiment we isolated compound **1** in the 10–20-mg range. The IR spectrum indicates a secondary amino group (3380 cm$^{-1}$) and a conjugated carbonyl system (1700, 1655 cm$^{-1}$). The $^1$H NMR spectrum shows five methylene groups, which could be assigned by chemical shift arguments as well as by decoupling experiments. The signals at $\delta$ 1.90, 2.32, and 3.15 belong to a spin system of three adjacent ring methylene groups, whereas the signals at $\delta$ 2.36 and 2.41 are parts of a separate AA'BB' system of neighboring methylene groups. The latter pattern show striking similarity to that observed for the methylene groups of the annellated cyclopentanone moiety in cyclopent[*b*]azepines (Tressl et al., 1985d). The only structure of **1** that conclusively illustrates all the spectroscopic data is 1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one.

Compounds **2–5** were formed in the proline/rhamnose system but also by condensation reaction of 2-acetyl-3,4,5,6,-tetrahydropyridine with acet- and propionaldehyde (**2** and **4**) or by ring-enlargement reaction of azetidinic acid with cyclotene and 3-ethyl-2-hydroxy-2-cyclopenten-1-one (**3** and **5**). They were isolated on the latter routes for the higher yields and the easier separation process. As could be seen from the IR data, the structures of **2–5** are similar to that of compound **1**.

The MS spectra indicate homologous fragments differring in a methyl and an ethyl group, respectively. The positions of the alkyl groups can be proposed from the definite synthetic routes. Therefore, the products generated by condensation reaction are to be substituted in the 5-position, whereas those obtained from azetidinic acid are to be substituted in the 6-position. In each case, because of the resulting nonequivalence of the ring methylene protons and the diastereotopic methylene protons of the ethyl group (**4** and **5**), the alkyl substituents cause much more complex $^1$H NMR spectra as observed for the parent compound **1**. By careful evaluation of the $^1$H NMR data the proposed structures of compounds **2** and **3** as 5- and 6-methyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one and **4** and **5** as 5- and 6-ethyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one were established. Compound **8** was isolated as an intermediate initially generated by reaction of 2-acetyl-3,4,5,6-tetrahydropyridine with acetaldehyde, thus confirming the postulated reaction sequence. On the basis of $^1$H NMR data **8** was identified as 2-acetyl-3-ethylidene-3,4,5,6-tetrahydropyridine.

In the proline/glucose and proline/glyceraldehyde experiments, component **6** is formed as a major product but separation by preparative GC failed because of its unexpected lability. Therefore, **6** was prepared by reaction of 2-acetyl-3,4,5,6-tetrahydropyridine with pyruvaldehyde and separated under mild conditions by LSC. Even the pure compound **6** dissolved in diethyl ether and kept at −20 °C decomposed during 3 days. Thus, the spectral data had to be taken from the freshly prepared component. The $^1$H NMR spectrum indicates three neighboring methylene groups ($\delta$ 1.86, 2.98, and 3.17) that we assign to a tetrahydropyridine moiety, two singlets of a methyl ($\delta$ 2.24), and a methylene group ($\delta$ 2.38). These elements could be also estabished by $^{13}$C NMR, but a more detailed investigation was prevented by the remarkable regress in concentration of the original compound during spectral recording. Therefore, a definite interpretation of the data has to be taken with care. An 2-acetyl-3-ylidene structure, comparable to that of compound **8**, can be ruled out for the absence of an olefinic proton. A bicyclic cyclopenta[*b*]pyridine structure cannot be assumed without reservation. The IR spectrum indicates a further olefinic absorption band (1550 cm$^{-1}$) beneath those (1705, 1660 cm$^{-1}$) expected for an $\alpha,\beta$-unsaturated carbonyl group. The broad absorption at 3350 cm$^{-1}$ point at a secondary amino group and/or an enolic cyclopenta[*b*]pyridinone structure can be proposed. Compound **6**, therefore, was tentatively identified as 5-(1-hydroxyethylidene)-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one.

From the furfural/2-acetyl-3,4,5,6-tetrahydropyridine experiment we isolated the component **7**, the $^1$H NMR spectrum of which confirms the furyl moiety with its typical pattern. The other signals are comparable to those of the 5-alkyl-substituted homologues. MS and the $^1$H NMR spectrum are in full agreement with the structure of 5-(2-furyl)-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]-pyridin-7-one.

Compounds **9–12** were unexpected reaction products of the cyclotene and 3-ethyl-2-hydroxy-2-cyclopenten-1-one/azetidinic acid experiments. Though the acid has a secondary amine structure, it seems to act as a transamination reagent during Strecker degradation. The imine **9** and its corresponding dicyclopentapyrazine **11** recently were isolated and identified from a cyclotene/ammonia/hydrogen sulfide model browing system. On the basis of spectral data we identified compound **10** as 3-ethyl-2-hydroxy-2-cyclopentenimine and compound **12** as 1,5- or 1,7-diethyl-1,2,3,5,6,7-hexahydrodicyclopentapyrazine. From capillary GC/MS we detected four isomers (cis and trans isomers of 1,5- and 1,7-substituted derivatives) of compounds **11** and **12**, respectively.

**Formation of 7*H*-Cyclopenta[*b*]pyridin-7-one in Model Experiments.** 7*H*-Cyclopenta[*b*]pyridin-7-ones are formed in the ppm range in the proline/monosaccharide model experiments. The results are summarized in Table II. As recently described, compound **1** may be formed from an iminium ion intermediate of the 3-deoxyosone of erythrose by ring enlargement, dehydration, and Michael addition (Tressl et al., 1985a).

From glucose, **1** can be formed by fragmentation of the sugar–amine compound, which leads to $C_2$ and $C_3$ fragments, as well as erythrose and glyceraldehyde. Whereas erythrose leads to compound **1**, glyceraldehyde and proline probably react via a series of iminium intermediates (**A–C**, Figure 1). The initially formed **A** undergoes dehydration and decarboxylation to **B**. The condensation reaction of both **A** and **B** leads to the iminium intermediate **C**, which

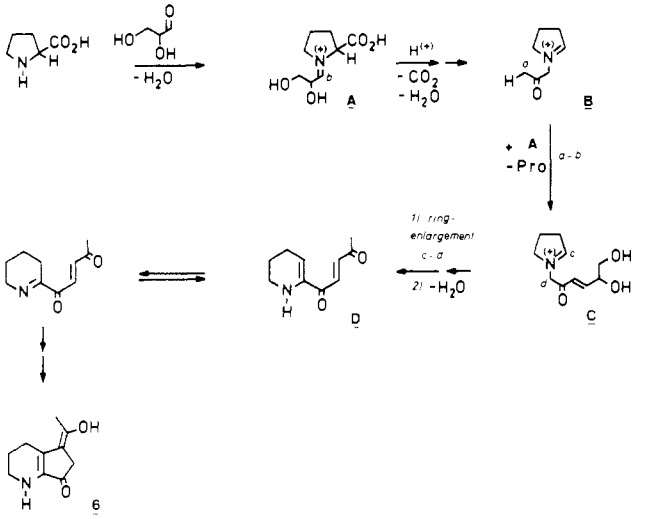


**Figure 1.** Formation of compound **6** from L-proline and glyceraldehyde.

is transformed by a ring-enlargement reaction and dehydration into the tetrahydropyridine **D**. Finally, intramolecular cyclization by Michael addition leads to compound **6**, the dominant product in this model system. The methyl-substituted derivatives **2** and **5** are primarily generated in the rhamnose experiment, indicating that aldol and retro-aldol reactions are predominant. The mechanisms may be comparable to that described in Figure 1.

The intramolecular cyclization by Michael addition postulated above can also be realized by interchange of the donor and acceptor centers setting up the new carbon–carbon bond. Thus, starting from 2-acetyl-3,4,5,6-tetrahydropyridine and aldehydes active Michael systems are generated that easily undergo intramolecular addition, forming a new CC bond between C-5 and C-6 of the resulting bicyclic system. This reaction route was used to synthesize compounds **2**, **4**, and **6**–**8** as demonstrated in Figure 2.

In analogy to the formation of cyclopent[*b*]azepinones from proline and hydroxycyclopentenones, the corresponding reaction of azetidinic acid leads to cyclopenta[*b*]pyridinones. Figure 3 may explain the formation of the 6-methyl and 6-ethyl derivatives **3** and **5** via decarboxylation, ring-enlargement reaction, and dehydration. The so called Strecker amine of azetidinic acid intermedially formed by reaction of the initially generated iminium ion with hydroxyl ions will be easily transformed into 3-aminopropionaldehyde. Starting from this aldehyde, the cyclopentenolones can be transformed into imines **9** and **10** and the corresponding dicyclopentapyrazines **11** and **12**, as outlined in Figure 4.

**Compound 1 in Wort and Beer.** In a series of experiments we recently characterized compound **1** to be a main constituent in wort and beer, depending on the process temperature, time, and evaporation rate (Hug et al., 1983). Under more extreme wort boiling conditions (80 min, 120 °C) the concentrations of **1** and other proline-specific Maillard products increase 10- to 20-fold, with the effect of reaching the detection thresholds of some odorous constituents. The very strong cooky and bready odor qualities of 2-acetyl-3,4,5,6- and -1,4,5,6-tetrahydropyridine are responsible for the undesired flavor character of overpasteurized beers. Under elevated temperatures retro-aldol reactions also lead to an increase of reactive carbonyl compounds such as pyruvaldehyde and other aldehydes, which are common volatiles in wort and beer. As demonstrated in the present paper these aldehydes

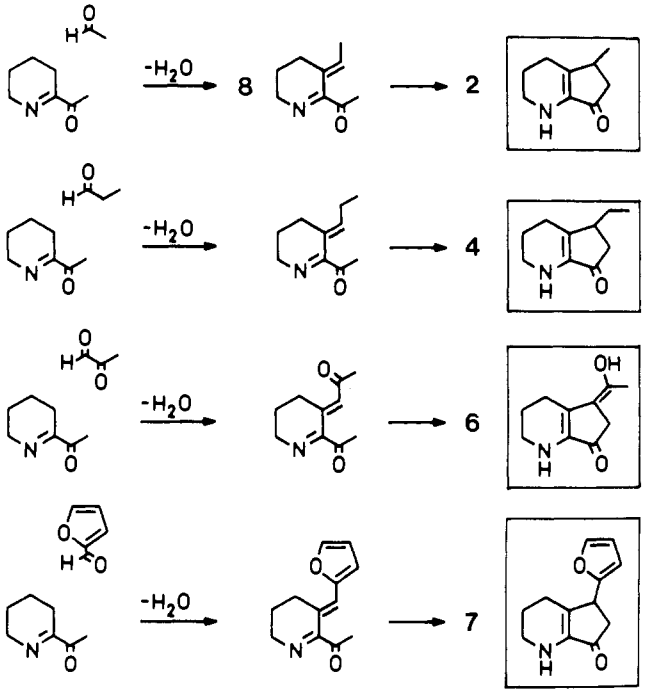


**Figure 2.** Formation of 3-substituted 7*H*-cyclopenta[*b*]-pyridin-7-ones from aldol condensation of 2-acetyl-3,4,5,6-tetrahydropyridine with aldehydes.

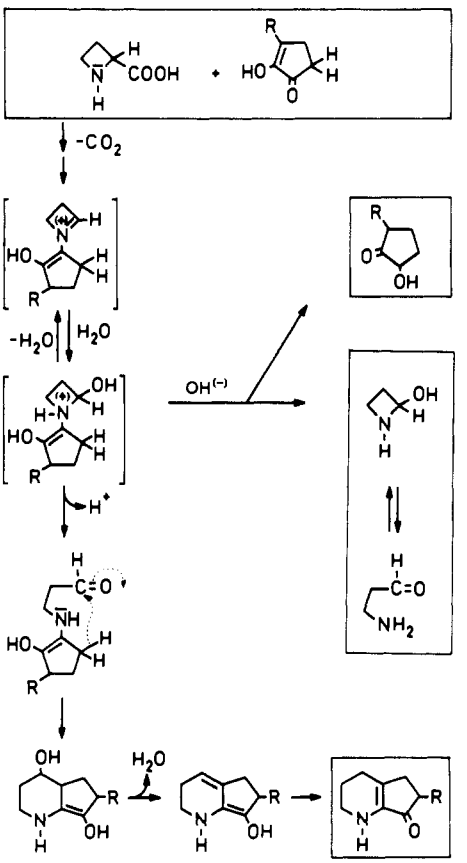


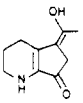
**Figure 3.** Formation of 7*H*-cyclopenta[*b*]pyridin-7-ones and 3-aminopropionaldehyde in azetidinic acid/cyclic enolone model experiments.

react with 2-acetyl-3,4,5,6-tetrahydropyridine to active Michael systems (8 and comparable compounds), which easily undergo intramolecular condensation to form hexahydrocyclopenta[*b*]pyridinones (see Figure 2). Polyreactive aldehydes may polymerize to higher molecular systems not detectable by conventional analytical methods.

**Table I. 7*H*-Hexahydrocyclopenta[*b*]pyridin-7-ones and Byproducts Characterized in Proline/Sugar Model Experiments**

| no. | $I_{KI}$ | component | spectroscopic data: IR, $cm^{-1}$; MS, *m/e* (rel intens); $^1H$ NMR, $\delta$ |
|---|---|---|---|
| 1 | 2128 | 1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3380 (m), 1700 (s), 1655 (s), 1485 (m), 1290 (m), 1260 (m), 1210 (m), 1180 (m), 1130 (m), 1030 (m)<br>MS: 137 ($M^+$, 100), 136 (34), 109 (33), 108 (57), 106 (4), 95 (6), 94 (49), 81 (66), 80 (27), 79 (10), 68 (17), 67 (25), 65 (6), 54 (19), 53 (31), 52 (17), 41 (30)<br>$^1H$ NMR: 1.90 (sym mc, 2 H, 3-H), 2.32 (t, 2 H, $J$ = 6.4 Hz, 4-H), 2.36, 2.41 (each m, 2 H, 5-H, 6-H, AA'BB'), 3.15 (sym mc, 2 H, 2-H), 3.50 (br s, 1 H, NH) |
| 2 | 2120 | 5-methyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3380 (m), 1700 (s), 1650 (s), 1485 (m), 1340 (m), 1295 (m)<br>MS: 151 ($M^+$, 39), 150 (4), 136 (100), 123 (5), 122 (6), 109 (5), 108 (38), 95 (7), 94 (8), 81 (12), 80 (13), 79 (8), 67 (3), 65 (9), 54 (11), 53 (19), 52 (19), 41 (13)<br>$^1H$ NMR: 1.14 (d, 3 H, $J$ = 7.4 Hz, $CH_3$), 1.95 (m, 3 H, 3-H, 3'-H, 6-H), 2.19 (dt, 1 H, $J$ = 19 Hz, 6 Hz, 4-H), 2.42 (dt, 1 H, $J$ = 19 Hz, 6 Hz, 4'-H), 2.62 (dd, 1 H, $J$ = 18 Hz, 6.4 Hz, 6'-H), 2.72 (mc, 1 H, 5-H), 3.14 (AB part of $ABX_2$, 2 H, $J_{22'}$ = 11.5 Hz, $J_{23}$ = 5 Hz, 2-H, 5'-H), 3.59 (br s, 1 H, NH) |
| 3 | 2084 | 6-methyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3380 (m), 1700 (s), 1659 (s), 1485 (m), 1460 (m), 1445 (m), 1340 (m), 1295 (s), 1260 (m), 1210 (m), 1130 (s)<br>MS: 151 ($M^+$, 100), 150 (28), 136 (17), 123 (18), 122 (55), 109 (13), 108 (75), 95 (26), 94 (43), 81 (45), 80 (26), 79 (11), 68 (16), 67 (27), 65 (9), 54 (11), 53 (19), 52 (10), 41 (13)<br>$^1H$ NMR: 1.18 (d, 3 H, $J$ = 7.5 Hz, $CH_3$), 1.95 (sym mc, 2 H, 3-H), 2.01 (ddt, 1 H, $J$ = 17.5 Hz, 2 Hz, 2 Hz, 5-H), 2.32 (br t, 2 H, $J$ = 6.3 Hz, 4-H), 2.40 (br quint, 1 H, $J \approx 7$ Hz, 6-H), 2.69 (ddt, 1 H, $J$ = 17.5 Hz, 6.3 Hz, 1.9 Hz, 5'-H), 3.16 (mc, 2 H, 2-H), 3.45 (br s, 1 H, NH) |
| 4 | 2228 | 5-ethyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3380 (m), 1700 (s), 1650 (s), 1485 (m), 1460 (m), 1380 (m), 1340 (m), 1295 (m), 1210 (m), 1170 (m), 1135 (m)<br>MS: 165 ($M^+$, 18), 150 (1), 136 (100), 120 (2), 108 (32), 106 (5), 94 (2), 93 (3), 81 (3), 80 (9), 79 (4), 67 (3), 65 (3), 53 (8)<br>$^1H$ NMR: 0.89 (t, 3 H, $J$ = 7.2 Hz, $CH_3$), 1.25 (m, 1 H, $CHHCH_3$), 1.76 (m, 1 H, $CHHCH_3$), 1.91 (m, 2 H, 3-H), 2.02 (dd, 1 H, $J$ = 18.3 Hz, 1.25 Hz, 6-H), 2.20 2.40 (AB, each dt, 1 H, $J$ = 18.7 Hz, 6 Hz, 4-H, 4'-H), 2.51 (dd, 1 H, $J$ = 18.3 Hz, 6.2 Hz, 6'-H), 2.63 (m, 1 H, 5-H), 3.15 (sym mc, 2 H, 2-H), 3.50 (br s, 1 H, NH) |
| 5 | 2151 | 6-ethyl-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3380 (m), 1700 (s), 1655 (s), 1485 (m), 1460 (m), 1380 (m), 1340 (m), 1290 (s), 1210 (m), 1130 (s)<br>MS: 165 ($M^+$, 100), 164 (22), 150 (21), 137 (72), 136 (61), 122 (60), 109 (25), 108 (55), 96 (12), 95 (25), 94 (32), 81 (40), 80 (23), 68 (25), 67 (30), 53 (28), 41 (32)<br>$^1H$ NMR: 0.94 (t, 3 H, $J$ = 7.5 Hz, $CH_3$), 1.20–1.45 (m, 1 H, $CHHCH_3$), 1.84 (mc, 1 H, $CHHCH_3$), 1.92 (sym mc, 2 H, 3-H), 2.10 (ddt, 1 H, $J$ = 17.5 Hz, 1.9 Hz, 5-H), 2.22–2.41 (m, 3 H, 4-H, 6-H), 2.59 (ddt, 1 H, $J$ = 17.5 Hz, 6.2 Hz, 1.9 Hz, 5'-H), 3.15 (br t, 2 H, $J$ = 5.5 Hz, 2-H), 3.47 (br s, 1 H, NH) |
| 6 | 2535 | 5-(1-hydroxyethylidene)-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | IR: 3350 (m), 1705 (m), 1660 (s), 1550 (s), 1430 (m), 1360 (m), 1330 (m), 1300 (m), 1250 (m), 1120 (m), 1015 (m)<br>MS: 179 ($M^+$, 100), 178 (18), 164 (15), 150 (5), 136 (70), 122 (4), 108 (34), 94 (17), 81 (16), 80 (10), 79 (15), 67 (15), 65 (15), 53 (18), 52 (18), 43 (75), 41 (19)<br>$^1H$ NMR: 1.86 (br quint, 2 H, $j$ = 6.5 Hz, 3-H), 2.24 (s, 3 H, $—COCH_3$ or $=COHCH_3$), 2.38 (s, 2 3 H, 6-H), 2.98 (t, 2 H, $J$ = 6.5 Hz, 4-H), 3.17 (m, 2 H, 2-H), possibly also a broad signal at $\delta$ 2.8 |
| 7 | | 5-(2-furyl)-1,2,3,4,5,6-hexahydro-7*H*-cyclopenta[*b*]pyridin-7-one | MS: 203 ($M^+$, 98), 202 (28), 175 (100), 174 (37), 160 (33), 147 (70), 146 (48), 132 (24), 118 (20), 105 (19), 91 (24), 87 (43), 81 (63), 77 (31), 65 (31), 53 (30), 51 (30), 41 (26), 39 (43)<br>$^1H$ NMR: 1.90 (m, 2 H, H-3), 2.24 (br t, 2 H, $J \approx 6$ Hz, H-4), 2.50 (ddt, 1 H, $J$ = 19 Hz, 2 Hz, ca. 1 Hz, H-6), 2.80 (ddt, 1 H, $J$ = 19 Hz, 6.8 Hz, 1 Hz, H-6'), 3.18 (br t, 2 H, $J$ = 5.4 Hz, H-2), 3.65 (br s, 1 H, NH), 3.98 (ddt, 1 H, $J$ = 6.8 Hz, 2 Hz, ca. 2 Hz, H-5), 6.08 (br d, 1 H, $J$ = 3.6 Hz, furan H-3), 6.31 (dd, 1 H, $J$ = 3.6 Hz, 2.2 Hz, furan H-4), 7.33 (br d, 1 H, $J$ = 2.2 Hz, furan H-5) |
| 8 | | 2-acetyl-3-ethylidene-3,4,5,6-tetrahydropyridine | MS: 151 ($M^+$, 47), 150 (10), 136 (100), 123 (7), 122 (4), 109 (25), 108 (60), 94 (26), 91 (20), 81 (47), 80 (40), 67 (18), 53 (37), 43 (65), 41 (28)<br>$^1H$ NMR: 1.70 (br quint, 2 H, $J$ = 6 Hz, 5-H), 1.75 (d, 3 H, $J$ = 7.1 Hz, $CH_3$, 2.38 (br t, 2 H, $J$ = 6 Hz, 4-H), 2.43 (s, 3 H, $COCH_3$), 3.71 (t, 2 H, $J$ = 5.4 Hz, 6-H), 6.19 (qt, 1 H, $J$ = 7.1 Hz, 1.4 Hz, =CH) |
| 9 | | 2-hydroxy-3-methyl-2-cyclopentenimine | IR: 3460 (m), 3370 (m), 1700 (s), 1660 (s), 1590 (s), 1400 (s), 1360 (m), 1205 (m), 1120 (s)<br>MS: 111 ($M^+$, 100), 110 (10), 96 (10), 83 (20), 82 (70), 68 (32), 55 (45), 54 (32), 42 (29), 41 (29)<br>$^1H$ NMR: 1.94 (br s, 3 H, $CH_3$), 2.38, 2.42 (AA'BB', sym mc, 4 H, 4-H, 5-H), 3.40 (br s, 2 H, OH, NH) |
| 10 | | 3-ethyl-2-hydroxy-2-cyclopentenimine | IR: 3470 (m), 3370 (m), 1700 (s), 1660 (s), 1590 (s), 1395 (m)<br>MS: 125 ($M^+$, 85), 110 (100), 96 (36), 82 (79), 69 (30), 68 (29), 55 (27), 54 (31), 41 (38)<br>$^1H$ NMR: 1.06 (t, 3 H, $J$ = 7.5 Hz, $CH_3$), 2.27 (q, 2 H, $J$ = 7.5 Hz, $CH_2CH_3$), 2.30, 2.36 (AA'BB', sym mc, 4 H, 4-H, 5-H), 3.40 (br s, 2 H, OH, NH) |
| 11 | | 1,5- or 1,7-dimethyl-1,2,3,5,6,7-hexahydrodicyclopentapyrazine (3:1 mixture of isomers) | IR: 1710 (m), 1455 (s), 1370 (s), 1290 (m), 1160 (s)<br>MS: 188 ($M^+$, 25), 173 (100), 158 (8), 157 (8), 145 (2), 131 (1), 117 (1), 104 (1), 92 (2), 79 (10), 77 (8), 65 (23), 53 (5)<br>$^1H$ NMR: 1.35, 1.36 (each d, 6 H (ca. 1:3), $J$ = 6.9 Hz, $CH_3$), 1.74 (mc, 2 H, 2/6-H), 2.43 (mc, 2 H, 2'/6'-H), 2.96 (mc, 4 H, 3/5-H, 3/7-H), 3.21 (br quint, 2 H, $J$ = 6.9 Hz, 1/7-H, 1/5-H) |
| 12 | | 1,5- or 1,7-diethyl-1,2,3,5,6,7-hexahydrodicyclopentapyrazine (mixture of three isomers) | IR: 1700 (m), 1460 (m), 1370 (m), 1260 (m), 1170 (m)<br>MS: 216 ($M^+$, 15), 201 (1), 188 (100), 187 (26), 171 (3), 159 (31), 157 (10), 133 (3), 118 (1), 104 (1), 91 (4), 77 (6), 65 (31), 53 (5), 41 (9)<br>$^1H$ NMR: 1.02 (t, 6 H, $J \approx 7$ Hz, $CH_2CH_3$), 1.53 (mc, 2 H, $CHHCH_3$), 1.81 (mc, 2 H, 2/6-H), 2.02 (mc, 2 H, $CHHCH_3$), 2.37 (mc, 2 H, 2'/6'-H), 2.97 (mc, 4 H, 3/5-H, 3/7-H), 3.04 (mc, 2 H, 1/7-H, 1/5-H) (major isomer) |

Table II

| | Gly | Ery | Ara | Glu | Rham |
|---|---|---|---|---|---|
|  | 45 | 350 | 25 | 150 | 40 |
|  | 7 | 1 | 30 | 10 | 80 |
|  | 4 | | | 4 | 20 |
|  | | | | | 40 |
|  | | | | 4 | 5 |
|  | 500 | | | 50 | |

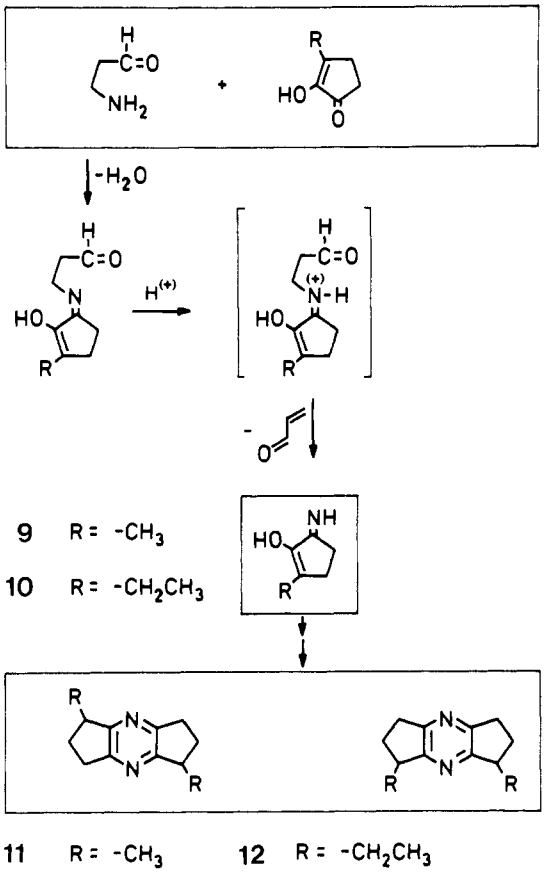



**Figure 4.** Secondary reaction of 3-aminopropionaldehyde and cyclic enolone to cyclopentenimines **9** and **11** and hexahydrodicyclopentapyrazines **10** and **12**.

These reactions may be responsible for the relatively moderate increase of 2-acetyltetrahydropyridines in wort and beer, even under elevated temperatures. It also is an example for transforming reactive, odorous intermediates into inactive derivatives with negligible odor and taste qualities.

**Registry No.** **1**, 104704-30-5; **2**, 104704-29-2; **3**, 104704-38-3; **4**, 104704-37-2; **5**, 118355-69-4; **6**, 118355-70-7; **7**, 118355-71-8; **8**, 118355-72-9; **9**, 61133-60-6; **10**, 90554-84-0; *cis*-1,5-dimethyl-11, 72438-08-5; *trans*-1,5-dimethyl-11, 72438-09-6; *cis*-1,7-dimethyl-11, 72438-07-4; *trans*-1,7-dimethyl-11, 72438-06-3; *cis*-1,5-diethyl-17, 118355-74-1; *trans*-1,5-diethyl-12, 118355-75-2; *cis*-1,7-diethyl-12, 118355-76-3; *trans*-1,7-diethyl-12, 118355-77-4; L-proline, 147-85-3; glyceraldehyde, 367-47-5; erythrose, 1758-51-6; arabinose, 147-81-9; glucose, 50-99-7; rhamnose, 10485-94-6; 2-acetyl-3,4,5,6-tetrahydropyridine, 27300-27-2; acetaldehyde, 75-07-0; propionaldehyde, 123-38-6; pyruvaldehyde, 78-98-8; furfural, 98-01-1; L-azetidinic acid, 2133-34-8; 2-hydroxy-2-cyclopenten-1-one, 10493-98-8; 2-hydroxy-3-methyl-2-cyclopenten-1-one, 80-71-7; 3-ethyl-2-hydroxy-2-cyclopenten-1-one, 21835-01-8.

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