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Density functional computational studies on the intermediate stage of the ribose and glycine Maillard reaction: Formation of deoxyosones in aqueous solution

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Abstract

Mechanisms in an aqueous solution of the Maillard reaction are proposed under several pH conditions for the interaction of glycine with cyclic ribose (c-Rib) and open-chain ribose (Rib). According to the Gibbs free energy relationships as well as internal energies values derived from our density functional theory calculations, the c-Rib/Rib + DGly (glycine) are the most favourable reaction pathways for the formation of deoxyosones under basic conditions, where Rib is more reactive than c-Rib. The intermediate stage of the Maillard reaction leads to the formation of deoxyosones.

Keywords: Density functional theory (DFT); Ribose; Glycine; Maillard reaction; Deoxyosones

1. Introduction

Food processing aspects cannot exclude the Maillard reaction (Maillard, 1912). As it is well known, the Maillard reaction (MR) occurs between reducing sugars and compounds with free amino groups (e.g. amines, amino acids, proteins, etc.). This reaction comprises a complex network of mechanisms, which are of particular importance in medicine and food science (Davídek, Velíšek, & Pokorný, 1990; Eskin, 1990; Ledl & Schleicher, 1990; Macrane, Robinson, & Saadler, 1993; Matiacevich & Buera, 2006; Meade, Miller, & Gerrard, 2003; Reber et al., 2002; Seiquer et al., 2006). For example, in medicine these studies are primarily orientated towards health and nutritional aspects (Seiquer et al., 2006). In food science studies related to the MR paths and those that are on the chemistry of MR products (MRPs), focus on materials absorbed from dietary sources or generated in vivo.

While the potential applications of such mechanisms are widespread, there is a lack of studies related to the intermediary stages of MR product formation. Additionally, it is not completely clear which specific biological function is assigned to each individual MR product (Silvan, van de Lagemaat, Olano, & del Castillo, 2006), which can be attributed to difficulties in their purification and identification. Experimental prospects in this area of investigation are thus far unable to provide detailed explanations into whether the mechanisms maintain validity. The quantum chemical results presented herein are crucial to resolve controversies and to shed light on the mechanisms of the Maillard reaction.

In all chemical processes, the study of intermediary compounds can be intertwined with the physical chemistry of the reactants and resulting products. Moreover, it is recognized that most Maillard reactions can be thermodynamically forbidden to proceed and may instead progress to other products or intermediary complexes. Although this

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reaction has been known for quite some time, it is still not clear how effectively the effects of amino acid type, pH dependence, temperature, water content, or interactions with the food matrix can affect the activation of some Maillard reactions.

Experimentally the models of activation employed are focused on thermal activation, while keeping the pH constant and varying the types of reactants (Jing & Kitts, 2002). Alternatively, previous theoretical methods for simulating a complex chemical set of mechanistic channels (such as the Maillard reaction) have been proposed. These theoretical computations include feedback loops, parallel reactions (Patel, Rabone, Russell, Tissen, & Klaffke, 2001), as well as simple and complex reaction kinetics proposed for each stage of the MR synthetic methodologies (Van Boekel, 2001). However, these approaches result in basic mathematical fit procedures, which lack mechanistic insights that may be valuable in industrial and/or medical applications.

In the present study, it is our priority to explore the solution based Maillard mechanism of the interaction between ribose and glycine. Ribose was selected because it is the most abundant sugar, and also since ribose can effectively react with glycine. Due to the stable nature of the resulting products and the abundance of the reactants, these studies have direct relevance to food processing aspects (Blank & Fay, 1996; Cerny & Davidek, 2004; Chen & Ho, 2002; Chen, Xing, Chin, & Ho, 2000; Cuzzoni, Stoppini, Gazzani, & Mazza, 1989; Holum, 1996; Litchfield, Thorpe, & Baynes, 1999; Meynier & Mottram, 1995; Mottram & Leseigneur, 1990; Roger, Matthew, & Elizabeth, 2005; Thorpe & Baynes, 1996).

Recently, we performed computational studies on the initial stage of the Maillard reaction in aqueous solution of cyclic ribose (c-Rib) and open-chain ribose (Rib) along with glycine (Gly) conformers under different pH conditions (Jalbout, Shipar, & Navarro, 2007). The results revealed that both c-Rib and Rib can participate in the reaction, and that Rib is more reactive than c-Rib. The basic conditions are favourable for the formation of the Amadori rearrangement products (ARPs) in the initial stage as compared with neutral and acidic conditions. We also want to extend our previous study in order to explore how these ARPs formed in the initial stage can consequently perform in the intermediate stage to produce deoxyosones in further reactions (Davídek et al., 1990; Eskin, 1990; Hodge, 1953; Macrane et al., 1993).

The current report will present density functional theory (DFT) computations performed under different

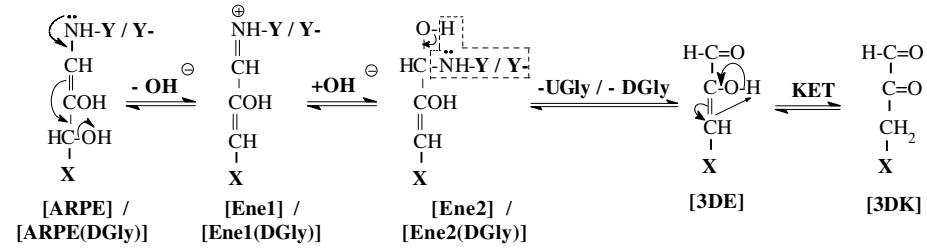

Fig. 1. Proposed mechanisms for the 3-deoxyosone route in the intermediate stage of c-Rib+UGly/PGly/DGly/GlyZ and Rib+UGly/PGly/DGly/GlyZ reactions (the eliminated UGly and DGlyare instantly protonated to PGly and GlyZ, respectively in c-Rib/Rib + PGly and c-Rib/Rib + GlyZ reactions, respectively). Abbreviations: UGly = unionized or unprotonated glycine; PGly = protonated glycine; DGly = deprotonated glycine; GlyZ = glycine zwitterion; ARPE = enol form of the Amadori rearrangement product (1-glycino-pent-2,3,4,5-tetraol-1-ene); ARPE(DGly) = enol form of the Amadori rearrangement product (1-deprotonated glycino-pent-2,3,4,5-ol-1-ene); Ene1 = an ionic adduct of ARPE (1-protonated glycino-pent-2,4,5-triol-1-ene); Ene1(DGly) = an ionic adduct of ARPE(DGly) (1-deprotonated glycino-pent-2,3,4,5-tetraol-1-ene); Ene2 = 1-glycino-pent-1,2,4,5-tetraol-2-ene; Ene2(DGly) = 1-deprotonated glycino-pent-1,2,4,5-tetraol-2-ene; 3DE = enol form of 3-deoxyosone (pent-1-al-2-ene-2,4,5-triol); 3DK = keto form of 3-deoxyosone (pent-1-al-2-one-4,5-diol); KET = keto-enolic tautomerization. X, Y and Y^- refer the –CH (OH)–CH_2OH, –CH_2–CO_2H and –CH_2–CO_2^- groups, respectively.

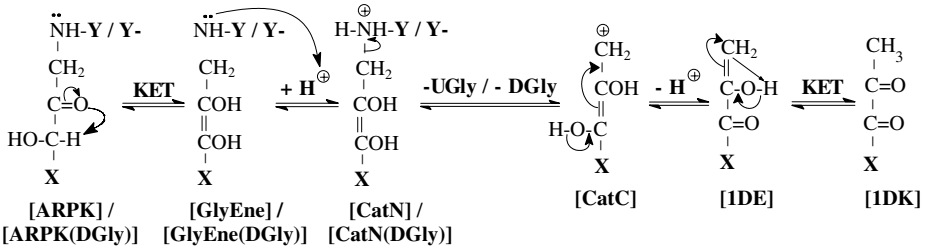

Fig. 2. Proposed mechanisms for the 1-deoxyosone route in the intermediate stage of c-Rib+UGly/PGly/DGly/GlyZ and Rib+UGly/PGly/DGly/GlyZ reactions (the eliminated UGly and DGlyare instantly protonated to PGly and GlyZ, respectively in c-Rib/Rib + PGly and c-Rib/Rib+GlyZ reactions, respectively). Abbreviations: ARPK = keto form of the Amadori rearrangement product (1-glycino-pent-3,4,5-ol-2-one); ARPK(DGly) = keto form of the Amadori rearrangement product (1-deprotonated glycino-pent-3,4,5-ol-2-one); GlyEne = 1-glycino-pent-2,3,4,5-tetraol-2-ene; GlyEne(DGly) = 1-deprtonated glycino-pent-2,3,4,5-tetraol-2-ene; CatN = a nitro-cationic adduct of 1-glycino-pent-2,3,4,5-tetraol-2-ene; CatN(DGly) = a nitro-cationic adduct of 1-deprtonated glycino-pent-2,3,4,5-tetraol-2-ene; CatC = pent-2,3,4,5-tetraol-2-ene-carbonium ion; 1DE = enol form of 1-deoxyosone (pent-1-ene-3-one-2,4,5-triol); 1DK = keto form of 1-deoxyosone (pent-2,3-dione-4,5-diol). For other abbreviations, see the caption of Fig. 1.

pH conditions in aqueous solution on the proposed mechanisms (Figs. 1 and 2) in order to test the possibility of the formation of different compounds. Previous studies were related mainly to the role of the unprotonated amino group, and generally overlooked the function of protonated and deprotonated amino groups in the reaction. This study will be helpful to evaluate the role of protonated glycine, glycine zwitterion and deprotonated glycine in the Maillard reaction involving ribose. Experimental evaluation of the role of these complex species in the Maillard reaction is quite complicated, and therefore, computational methods are used to propose new routes.

2. Methodology

In the standard state, the possibility of the formation of all compounds in the proposed mechanisms (Figs. 1 and 2) was studied in aqueous solution. As all compounds in the proposed mechanisms (Figs. 1 and 2) can have many conformations in solution, it is not practical to consider all of these states during the calculation of energy changes for different steps in a reaction. Therefore, only the lowest energy structures, optimized using a specific method (RB3LYP) were considered and evaluated (Foresman & Frisch, 1996; Frisch & Foresman, 1998). Computations were carried out using the GAUSSIAN 98 suite of codes (Frisch, Trucks, & Schlegel, 2001). The RB3LYP method was coupled to a 6-31G(*d*) polarized basis set (Foresman & Frisch, 1996; Frisch & Foresman, 1998) throughout this work.

During the optimization, all structural parameters (e.g. bond-lengths, bond-angles and dihedral angles) were used as variables and their vibrational frequencies analyzed in order to make sure that the compounds formed were minimum energy structures along the potential energy surface. Due to the fact that many of the intermediates in the proposed mechanisms (Figs. 1 and 2) possess stable cyclic forms, special attention was paid to avoid the possible intramolecular cyclization of the compounds (Jalbout et al., 2007). All RB3LYP/6-31G(d) optimized structures were taken for PCM/RB3LYP/6-31G(d) frequency calculations to achieve the relevant zero point energy (ZPE) and the Gibb's free energy (G^0) in aqueous solution (Foresman & Frisch, 1996; Frisch & Foresman, 1998). By using the PCM/RB3LYP/6-31G(d) on the RB3LYP/6-31G(d) optimized structures, relevant electronic energies in aqueous solution were calculated (Foresman & Frisch, 1996; Frisch & Foresman, 1998). It is important to note that the dielectric constant, $\varepsilon = 78.39$ was used to represent the aqueous solution (Foresman & Frisch, 1996; Frisch & Foresman, 1998) and relevant ZPE were added to the electronic energies to obtain the total electronic energies (E^0). Also, the electronic and free energy changes ($\Delta E^0 = E^0_{\text{Product(s)}} - E^0_{\text{Reactant(s)}}$, and $\Delta G^0 = G^0_{\text{Product(s)}} - G^0_{\text{Reactant(s)}}$, respectively) for different compounds in the proposed mechanisms (Figs. 1 and 2) were calculated by following the total mass balance of the reactions (which are appended as supporting information). Thus, the internal energy changes for the formation of different compounds in the proposed mechanisms were investigated. Relevant dipole moments (μ_{Aq}, in Debye), related to the internal energy of the molecule, of different compounds in aqueous solution were obtained from the electronic energy calculations on the RB3LYP/6-31G(d) optimized structures using the PCM/RB3LYP/6-31G(d) (Foresman & Frisch, 1996; Frisch & Foresman, 1998) method. Finally, the heats of formation (ΔH^0_{f}) of different compounds were obtained by performing AM1 semi-empirical calculations (Foresman & Frisch, 1996; Frisch & Foresman, 1998) on the RB3LYP/6-31G(d) optimized structures to minimize computational expense.

3. Results and discussion

The ΔE and ΔG values of a reaction indicate the internal energy changes as well as the spontaneity of the reaction, respectively. These computations are done of course, under conditions of constant temperature and pressure. ΔG^0_{Aq} and ΔE^0_{Aq} for the formation of different compounds in the proposed mechanisms (Figs. 1 and 2) in the intermediate stage of c-Rib + Gly and Rib + Gly reactions under different pH conditions in aqueous solution are presented in Table 1. During the calculation of ΔG^0_{Aq}, the c-Rib + Gly and Rib + Gly total free energies in aqueous solution (which can are represented as $G^0_{\text{c-Rib}} + G^0_{\text{UGly/PGly/DGly/GlyZ}}$ and $G^0_{\text{Rib}} + G^0_{\text{UGly/PGly/DGly/GlyZ}}$, respectively (Jalbout et al., 2007) were used as the standard in the $\Delta G^o = G^0_{\text{Product(s)}} - G^0_{\text{Reactant(s)}}$equation. On the other hand, the c-Rib + Gly and Rib + Gly total electronic energies in aqueous solution (that can be described as $E^0_{\text{c-Rib}} + E^0_{\text{UGly/PGly/DGly/GlyZ}}$ and $E^0_{\text{Rib}} + E^0_{\text{UGly/PGly/DGly/GlyZ}}$, respectively (Jalbout et al., 2007)) were used as the standard in the $\Delta E^0 = E^0_{\text{Product(s)}} - E^0_{\text{Reactant(s)}}$ equation for the calculation of ΔE^0_{Aq}. Table 1 also represents the μ_{Aq} and ΔH^0_{f} values of different compounds in the proposed mechanisms (Figs. 1 and 2). Selected RB3LYP/6-31G(d) optimized geometrical parameters of different compounds in the proposed mechanisms (Figs. 1 and 2) are presented in Table 2.

The total mass balance of any reaction is important as it is related to the energy changes. The total mass balance of the reaction under different pH conditions were maintained during the calculation of ΔE^0 and ΔG^0. The main problem in balancing the total mass arises for the protonation ($+H^+$), deprotonation ($-H^+$), and the addition or elimination of OH^- ($+OH^-$ or $-OH^-$). Therefore, the following equations were applied during balancing the total mass (Jalbout et al., 2007):

$$\underset{\text{Hydrogen cation}}{H^+} + \underset{\text{Water}}{H_2O} \rightleftharpoons \underset{\text{Hydronium cation}}{H_3O^+}$$

(protonation and deprotonation)

$$\underset{\text{Hydronium cation}}{H_3O^+} + \underset{\text{Hydroxyl anion}}{OH^-} \rightleftharpoons \underset{\text{Water}}{2H_2O}$$

(addition and elimination of OH^-)

Table 1
ΔG^0_{Aq}, ΔE^0_{Aq}, μ_{Aq} and ΔH^0_f for different compounds presented in Figs. 1 and 2

Compounds ↓	ΔG^0_{Aq} (kJ/mol)				ΔE^0_{Aq} (kJ/mol)				μ_{Aq} (Debye)	ΔH^0_f (kJ/mol)
	c-Rib + UGly	Rib + UGly	c-Rib + PGly	Rib + PGly	c-Rib + UGly	Rib + UGly	c-Rib + PGly	Rib + PGly		
ARPE*	56.4	48.7	110.4	102.7	44.4	38.0	99.3	92.9	3.7491	−1136.0
ARPK*	−1.5	−9.2	52.4	44.7	−9.6	−16.0	45.3	38.9	1.4758	−1149.5
Ene1	49.1	41.4	540.0	532.2	28.4	22.0	83.3	76.9	3.2894	−212.6
Ene2	482.7	475.0	973.6	965.9	18.0	11.5	72.9	66.4	5.4236	−1123.0
GlyEne	557.9	550.2	1048.8	1041.1	86.0	79.6	140.9	134.5	1.7508	−1149.6
CatN	56.7	49.0	547.6	539.9	10.7	4.3	65.6	59.2	5.7825	−487.9
CatC	165.3	157.5	137.6	129.9	124.4	118.0	112.8	113.9	2.2892	35.1
3DE	496.9	489.2	469.2	461.5	151.2	157.9	149.5	146.1	2.0509	−661.8
3DK	488.2	480.5	460.6	452.9	138.1	139.3	132.9	133.7	5.8452	−669.4
1DE	489.5	481.8	461.9	454.2	145.2	140.7	142.0	138.5	5.3178	−649.5
1DK	429.9	422.2	402.3	394.6	140.4	137.1	138.8	135.0	1.6873	−690.5
	c-Rib + DGly	Rib + DGly	c-Rib + GlyZ	Rib + GlyZ	c-Rib + DGly	Rib + DGly	c-Rib + GlyZ	Rib + GlyZ		
ARPE(DGly)*	−19.8	−27.5	157.8	150.1	−4.8	−11.2	145.7	139.2	10.9163	−1247.3
ARPK(DGly)*	−52.1	−59.8	125.5	117.8	−32.3	−38.7	118.2	111.8	13.8162	−1251.5
Ene1(DGly)	−109.4	−117.1	68.2	60.5	−3.9	−10.3	100.2	93.7	14.3858	−697.4
Ene2(DGly)	−39.4	−47.1	138.2	130.5	17.2	10.8	121.3	114.8	12.9334	−1299.7
GlyEne(DGly)	−4.8	−12.5	172.8	165.1	53.6	47.2	157.7	151.2	11.4893	−1289.8
CatN(DGly)	−97.1	−104.8	80.5	72.8	−37.9	−44.3	66.2	59.7	12.2834	−988.1
CatC	88.0	80.3	87.6	80.3	104.9	107.7	49.7	43.2	–	–
3DE	−0.81	−8.5	−0.72	−6.9	43.6	37.2	48.9	53.6	–	–
3DK	−9.4	−17.1	−7.7	−16.8	36.2	29.8	43.1	32.3	–	–
1DE	−8.28	−15.9	−8.16	−15.5	34.5	27.5	39.0	35.9	–	–
1DK	−68.0	−80.4	−67.7	−78.1	−22.1	−28.5	−21.8	−28.1	–	–

For abbreviations, see the captions of Figs. 1 and 2.
* Jalbout et al. (2007).

According to the ΔG^0 (Table 1) values, the production of all compounds in the proposed mechanisms for the intermediate stage of c-Rib/Rib + UGly and c-Rib/Rib + PGly reactions (Figs. 1 and 2) is not favourable. The c-Rib+UGly and c-Rib+PGly reactions are less capable in product formation than the Rib+UGly and Rib+PGly reactions (Table 1). This is consistent with the previous computational report on the initial stage of c-Rib/Rib + Gly reactions by which Rib was more reactive than c-Rib(Jalbout et al., 2007). From these calculations, the c-Rib/Rib + UGly reactions suggest to favourably yield ARPK, and not ARPE. However, the c-Rib/Rib + UGly reactions do not favour the production of deoxyosones (3DE, 3DK, 1DE and 1DK) in the intermediate stage (Table 1).

It is therefore assumed that the reactions may follow another mechanism to produce melanoidines through the formation of additional compounds in the intermediate stage. Sufficient information about these systems is not yet available, and therefore, further investigations are required to elucidate this mechanism. Thec-Rib/Rib + PGly reactions will probably not yield ARPE and ARPK in the initial stage (Jalbout et al., 2007) due to unfavourable changes in the free energy. Therefore, it is likely that the production of deoxyosones (3DE, 3DK, 1DE and 1DK) under these conditions is not feasible (Table 1). The presented results are consistent with previous reports stating that the acidic and protonated forms of amino groups (located in amino compounds) are not satisfactory components for successful Maillard reactions to take place (Davídek et al., 1990; Eskin, 1990; Macrane et al., 1993).

Based on the values of ΔG^0 (Table 1), the c-Rib/Rib+DGly reactions should yield the production of all intermediates in the proposed mechanisms (Figs. 1 and 2). The Rib+DGly reaction more readily produces an array of compounds when compared to the c-Rib+DGly reaction. The c-Rib/Rib + DGly reactions were recently reported as the most favourable pathways for producing both ARPE (DGly) and ARPK (DGly) in the initial stage, however, Rib+DGly was more reactive than c-Rib+DGly (Jalbout et al., 2007). Therefore, it is expected that c-Rib/Rib + DGly reactions are most capable in producing deoxyosones (3DE, 3DK, 1DE and 1DK) in the intermediate stage, and Rib+DGly yield deoxyosones to a higher extent than c-Rib+DGly (Table 1).

Congruent with previous statements, we assert that basic conditions facilitate the Maillard reaction to occur spontaneously (Davídek et al., 1990; Eskin, 1990; Macrane et al., 1993). From the calculations, it is evident that the c-Rib/Rib + DGly reactions form the carbonium ion (CatC (pent-2,3,4,5-tetraol-2-ene-carbonium ion)) in the

Table 2
Selected RB3LYP/6-31G(d) geometrical parameters of different compounds presented in Figs. 1 and 2

Compounds↓	Bond lengths (Å)						Bond angles (°)				Dihedral angles (°)	
	C–C	C–O	O–H	C–H	N–C	N–H	C–C–C	H–C–O	C–O–H	C–N–C[e]	C–C–C–C[f]	C–C–N–C[g]
ARPE	1.3461[a], 1.5157	1.3785, 1.4197	0.9764, 0.9749	1.0849, 1.0973	1.4167, 1.4503[d]	1.0154	124	107.8	107.7, 105.2	117.3	−102.7	113.4
ARPE(DGly)	1.3565[a], 1.5196	1.3497, 1.4283	1.05, 0.9733	1.0876, 1.0961	1.4226, 1.4755[d]	1.0203	122.7	106.9	108.9, 104.7	115.6	−96.1	93.9
ARPK	1.5125, 1.5382	1.2245[b], 1.4269	0.9763	1.0989, 1.1113, 1.0966	1.4461, 1.4456[d]	1.0166	116.6	106.7	104.6	115.5	158.7	164.2
ARPK(DGly)	1.4765, 1.5425	1.2389[b], 1.4323	0.9746	1.101, 1.1287, 1.095	1.4528, 1.4762[d]	1.02	117.1	106.4	104.0	111.4	140.7	162.8
Ene1	1.4597, 1.355[a]	1.3777	0.9772	1.1219, 1.1043	1.3124[c], 1.4547[d]	1.0106	125.4	–	109.2	123.3	−178.0	180.0
Ene1(DGly)	1.472, 1.349[a]	1.3747	0.9739	1.1134, 1.104	1.303[c], 1.4331	1.0189	124.0	–	109.0	125.9	−176.8	168.9
Ene2	1.5235, 1.3388[a]	1.4559, 1.3735	0.9746, 0.9809	1.0972, 1.0847	1.4287, 1.4489[d]	1.016	125.8	102.6	106.8, 105.4	117.2	180.0	178.1
Ene2(DGly)	1.528, 1.3467[a]	1.4291, 1.3741	0.9777, 0.9738	1.1343, 1.0998	1.4556, 1.452[d]	1.0076	122.9	104.5	110.3, 108.8	114.4	177.3	176.1
GlyEne	1.5005, 1.3554[a]	1.3828, 1.3819	0.9709, 0.9697	1.1301, 1.1312	1.4528, 1.4329[d]	1.0039	124.0	–	107.4, 106.8	115.5	178.2	137.1
GlyEne(DGly)	1.5033, 1.3571[a]	1.3727, 1.3857	0.9846, 0.9687	1.1273, 1.1322	1.457, 1.4526[d]	1.0082	124.6	–	108.5, 107.1	112.7	178.196	134.7
CatN	1.4873, 1.3621[a]	1.3834, 1.3655	0.972, 0.9736	1.1282, 1.1298	1.5064, 1.4839[d]	1.0325, 1.0274	124.2	–	107.1, 109.2	112.9	180.0	−178.6
CatN(DGly)	1.4949, 1.3565[a]	1.3797, 1.3787	0.9811, 0.9692	1.1256, 1.1347	1.4966, 1.486[d]	1.0363, 1.0179	123.9	–	108.2, 108.0	111.6	176.0	141.9
CatC	1.3585, 1.446[a]	1.3821, 1.3157	0.9748, 0.991	1.1027, 1.1045	–	–	123.8	–	107.9, 113.2	–	−176.8	–
3DE	1.4799, 1.3507[a]	1.2229[b], 1.3554	0.9809	1.1013, 1.0885	–	–	125.4	121.4	105.4	–	0.3	–
3DK	1.5496, 1.5106	1.2049[b], 1.2183[b]	–	1.112, 1.0971, 1.0948	–	–	117.9	122.2	–	–	110.3	–
1DE	1.3435[a], 1.496	1.3579, 1.2205[b]	0.9709	1.0816, 1.087	–	–	123.3	–	108.9	–	15.3	–
1DK	1.5058, 1.5405	1.2164[b], 1.219[b]	–	1.0972, 1.0912, 1.095	–	–	116.5	–	–	–	−168.0	–

[a] C=C.
[b] C=O.
[c] N=C.
[d] N–C(Y/Y$^-$).
[e] C–N–C(Y/Y$^-$).
[f] C–C–C–C(X).
[g] C–C–N–C(Y/Y$^-$).

1-deoxyosone route (Fig. 2, Table 1). From this we can assume that in the 1-deoxyosone route the CatN(DGly) species is produced [a nitro-cationic adduct of 1-deprtonated glycino-pent-2,3,4,5-tetraol-2-ene, GlyEne(DGly)] which may eliminate DGly and H^+ simultaneously. This may lead to the formation of 1DE, which can subsequently produce 1DK through keto-enol tautomerization (KET).

In the c-Rib/Rib + DGly reactions, the plausibility for the formation of 3DK and 1DK is more likely than the formation of 3DE and 1DE in the 3- and 1-deoxyosone routes, respectively (Table 1). Production of 3DK via the 3-deoxyosone route is more feasible than the production of 1DE through the 1-deoxyosone route (Table 1). This latter scheme, in the c-Rib/Rib + DGly reactions is assumed to be more favourable than the 3-deoxyosone route. The ΔE^0 (Table 1) values (in the c-Rib/Rib+DGly reactions) show that 1DK is electronically more stable than 1DE, 3DE and 3DK. The 1DK molecular species (which is formed in the Rib+DGly reaction) is electronically more stable than that of the c-Rib+DGly reaction. 1DK has the lowest μ_{Aq} among the different compounds formed in the intermediate stage of c-Rib/Rib+Gly (UGly, PGly, DGly and GlyZ) reactions (Table 1). GlyEne (1-glycino-pent-2,3,4,5-tetraol-2-ene) has the second lowest and GlyEne(DGly) [1-deprtonated glycino-pent-2,3,4,5-tetraol-2-ene] has the fourth highest μ_{Aq} (Table 1). Ene1 (DGly)[1-deprotonated glycino-pent-2,3,4,5-tetraol-1-ene] has the highest and Ene1(1-protonated glycino-pent-2,4,5-triol-1-ene) has the fifth lowest μ_{Aq} amongst various intermediates of the intermediate stage (Table 1).

The highest ΔH_f^0 is found for CatC, whereas the lowest is for Ene2 (DGly)[1-deprotonated glycino-pent-1,2,4,5-tetraol-2-ene], and Ene2 (1-glycino-pent-1,2,4,5-tetraol-2-ene) possesses the seventh lowest ΔH_f^0 (Table 1). Adequate experimental data on these species is still insufficient, and therefore, additional studies are necessary to obtain proper information. The present investigations are targeted towards the understanding of these complex mechanisms.

Based on our ΔG^0 (Table 1) calculations, the c-Rib/Rib + GlyZ reactions are the second most favourable mechanistic pathway for the formation of deoxyosones (3DE, 3DK, 1DE and 1DK). Also, the Rib+GlyZ reaction is more favourable than the c-Rib+GlyZ reaction. The c-Rib/Rib + GlyZ reactions were reported to be unfeasible for the formation of ARPs [ARPE (DGly) and ARPK (DGly)] in the initial stage (Jalbout et al., 2007). Therefore, we do not expect the production of deoxyosones under these conditions. The calculated values are not in agreement with the previous reports, which suggest that, the acidic or protonated forms of amino groups of amino compounds disrupt the browning reaction (Davídek et al., 1990; Eskin, 1990; Macrane et al., 1993). The reactions are also unfeasible for the formation of Ene1(DGly), Ene2(DGly), GlyEne(DGly), CatN(DGly) and CatC (Table 1). Therefore, it is possible that the reactions under these conditions should follow some other mechanism (such as the 4- and/or 6-deoxyosone routes) in order to produce deoxyosones (Harrold, 1991).

Interestingly, the possibility of the formation of deoxyosones in c-Rib/Rib + GlyZ reactions is quite similar to that of the c-Rib/Rib + DGly reactions (Table 1). In comparison with the c-Rib/Rib + DGly reactions, the probability of the formation of 3DK and 1DK in c-Rib/Rib + GlyZ reactions is more plausible than the formation of 3DE and 1DE, respectively (Table 1). From the calculated ΔE^0 (Table 1) values, 1DK is electronically more stable than 1DE, 3DE and 3DK. We can also deduce that 1DK (formed in Rib+GlyZ reaction) is electronically more stable than that of the c-Rib+GlyZ reaction.

However, sufficient experimental data are not yet available, and therefore, the production of deoxyosones in the c-Rib/Rib + GlyZ reactions remains a scientific enigma. Experimental evaluation and detection of the related intermediates is difficult as they readily undergo further reactions, and the final products in Maillard reaction have a tendency to produce complex mixtures. Deoxyosones will easily undergo further reactions to produce melanoidines (Davídek et al., 1990; Eskin, 1990; Macrane et al., 1993), which can prevent adequate isolation of particular compounds. Therefore, detection of these species in the reaction will be complicated. Also, the experimental distinction of the enol and keto forms of different compounds, such as deoxyosones, is not an easy task. The present results should be helpful in performing experimental studies to resolve proper mechanisms for related reaction in foods and other systems, such as in the human body. Additionally, it would be of practical interest to obtain information on the error of our ΔE^0 and ΔG^0 values for different compounds caused by using conformations other than the global minima. In order to fulfill this intention, extensive theoretical studies on the potential energy surfaces of different compounds in the reaction are required. However, computational results can generally be varied between 10% and 15% when compared to experimental values (Hehre, Radom, Schleyer, & Pople, 1986; Young, 2001). Therefore, while we believe that the values computed are relatively accurate, some error should be expected.

4. Conclusions

The evaluation and experimental detection of relevant intermediates in the Maillard reaction are extremely difficult, which permit theoretical studies to provide insights into their mechanisms of formation. According to the Gibbs free energy values derived from our DFT study in the proposed mechanisms for the intermediate stage, the c-Rib/Rib + DGly reactions are the most favourable reactions for the formation of deoxyosones under basic conditions. Also, Rib is more reactive than c-Rib to produce deoxyosones, which is due to the increased stability of the latter compound. From analysis of the electronic energies, 1DK is found to be the most stable product resulting from the c-Rib + DGly (−22.1 kJ/mol) and the Rib + DGly reactions (−28.5 kJ/mol).

The computational results presented should be instructive for further theoretical and experimental investigations to unravel the mechanisms of Maillard reaction. Adequate experimental data are not yet available, and therefore, extensive exertions are necessary to establish proper mechanism of the reaction, leading to information about proper controlling techniques of Maillard reactions in different systems. The c-Rib/Rib + UGly and c-Rib/Rib + PGly reactions for production of all compounds will probably not proceed, but other stable intermediates may be formed.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foodchem.2007.04.061.

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