DZ+d optimized geometries are so similar to the SCF/DZ+d geometries, the CISD/DZ+d and CISD+Q/DZ+d relative energies are very similar to the previously reported[18] single point CISD energies at the SCF optimized geometries. The relative energy difference increased with the larger TZ2P basis set; however, higher excitations should decrease the energy difference. Therefore we expect that our CISD+Q/TZ2P energy determination is close to the right answer. Our best ab initio prediction of the relative energies of the two minima is obtained by adding the CISD/DZ+d zero point energies to the TZ2P energies; this yields a relative energy of the trans relative to the dimethyldisilavinylidene of 12.0 kcal/mol.

4. Conclusions

We have predicted that the trans isomer of dimethyldisilyne is a minimum on the CISD/DZ+d potential energy surface and lies only 12.0 kcal/mol above the ground-state dimethyldisilavinylidene isomer. The trans isomer is most likely kinetically stable to isomerization to the dimethyldisilavinylidene structure, however, since the 1,2-methyl shift from one silicon atom to the other is expected to have a reasonably high activation energy. The transition state for this rearrangement should have one methyl group in a bridging position as it migrates between silicon atoms. We attempted to locate the transition state, but, as is often the case with transition state searches, we did not seem to be converging to a stationary point within a reasonable amount of time. This is not surprising as the symmetry of the transition state is necessarily C_1 since the methyl group must rotate, and there are 24 internal degrees of freedom. That such a bridging transition-state isomer should be significantly higher in energy that either the trans or dimethyldisilavinylidene isomers is supported by the instability of the dibridged isomer. In our previous paper,[18] we found the dibridged isomer to be 22.8 and 13.1 kcal/mol (CISD+Q energy and SCF optimized geometry, DZ+PP basis set), respectively, above the vinylidene and trans isomers. Thus it is quite possible that the barrier to rearrangement is large enough for *trans*-$Si_2(CH_3)_2$ to be an isolable species. Since the structures synthesized by West and co-workers[1-3] have a methyl group bonded to each silicon, the likely intermediate is the trans isomer of dimethyldisilyne. Obviously, the definitive synthesis of dimethyldisilyne would be a major accomplishment in organic chemistry.

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AM1 Calculations of Reaction Field Effects on the Tautomeric Equilibria of Nucleic Acid Pyrimidine and Purine Bases and Their 1-Methyl Analogues

Alan R. Katritzky* and Mati Karelson[§]

Contribution from the Department of Chemistry, University of Florida, Gainesville, Florida 32611-2046. *Received April 4, 1990*

Abstract: Semiempirical AM1 quantum-chemical calculations of the principal tautomers of cytosine, thymine, uracil, 1-methylcytosine, 1-methylthymine, 1-methyluracil, adenine, and guanine were carried out for the isolated molecules, and for the same molecules in a polarizable dielectric medium with the relative permittivity of water, using the self-consistent reaction field method. In almost all cases, the same tautomer is predicted as most stable regardless of the method used and environment applied. However, the calculations imply significant quantitative differences in the relative stabilities of the tautomers in different media, which need to be taken account of in the nucleic acid base pairing/mispairing probability estimations based on quantum-chemical data.

Introduction

Tautomeric equilibria of the nucleic acid bases are of great importance and significance. Normal base pairing can only take place between the specific correctly positioned tautomers. However, abnormal pairing can occur between minor tautomers and such abnormal pairing can lead to mutations. Because of the importance of this concept, the tautomerism of the parent nucleic acid bases has been the subject of much investigation within the general framework of heterocyclic tautomerism as a whole: the early work has been summarized in ref 1 and later work, up until about 1975, in ref 2. Kwiatkowski and Pullman reviewed the detailed structures of biological pyrimidines in 1975,[3] as had Pullman and Pullman for the corresponding purines in 1971.[4]

To summarize, it has been conclusively shown that in almost all cases uracil (**13**), thymine (**19**), cytosine (**2**), adenine (**29**), and guanine (**37**) exist predominantly in the structures shown, whether it be in the crystalline state, in aqueous solution, in solutions of nonpolar solvents, or in the gas phase. Although, over the years, many claims to the contrary have appeared (i.e. that these compounds exist, in one phase or another, predominantly in one of the other possible tautomeric forms), all such claims have been disproved (see refs 1 and 2 for detailed rebuttals of several of them). In contrast to this clear picture of which are the dominant tautomeric forms, far less attention has been paid to the *quantitative* tautomeric equilibrium constants between these dominant forms and the next most important form or forms, despite the obvious importance of such quantitative data to considerations of spontaneous mutations. Thus little experimental data are available on the energy differences between the tautomeric forms.

By contrast, numerous investigations have taken place of the heats of formation of the various tautomers as calculated by both ab initio and semiempirical molecular orbital methods and several reviews on this topic have been published in recent years.[5-7] A

[§] On sabbatical leave. Permanent address: Laboratory of Chemical Kinetics and Catalysis, Tartu University, Tartu 202400, Estonia.

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Table I. AM1 SCF and SCRF Calculated Relative Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of Cytosine Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
1	1.70	7.74	3.235	3.819
2	(0.0)	(0.0)	6.925	7.400
3	0.65	2.81	7.210	7.745
4	45.81	17.24	13.242	15.889
5	16.21	20.51	4.149	5.158
6	12.10	19.12	2.266	2.688
7	1.45	8.69	2.169	2.635

Table II. AM1 SCF and SCRF Calculated Relative Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of Uracil Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
8	14.88	17.98	2.037	2.402
9	9.32	11.59	2.827	3.364
10	13.95	9.87	5.933	7.262
11	20.58	16.15	6.100	7.320
12	12.56	11.94	4.609	5.358
13	(0.0)	(0.0)	4.288	5.007

Table III. AM1 SCF and SCRF Calculated Relative Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of Thymine Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
14	14.88	17.10	2.241	2.571
15	9.12	11.08	2.506	2.937
16	13.47	9.69	6.051	7.280
17	20.19	17.12	5.790	6.817
18	19.89	13.05	7.496	8.559
19	(0.0)	(0.0)	4.222	5.179

paper by Norinder[8] is directly related to our present work: it gives AM1 calculated relative heats of formation and geometries for the tautomers of cytosine, thymine, uracil, adenine, and guanine tautomers in their isolated forms. There is, as expected, almost complete agreement with our gas-phase calculations.

In the present paper, we follow up our successes in the quantitative calculations of the tautomeric equilibrium constants of various substituted pyridines, both in the gas phase and in aqueous solution,[9] by carrying out similar work on the pyrimidine and purine bases and comparing the results with the limited experimental data available. To take into account the effects of solvent polarity we use the self-consistent reaction field (SCRF) method[10-12] in the framework of semiempirical AM1[13] and MNDO-PM3[14] Hamiltonians. The essence of the SCRF method can be summarized as the use of molecular Hamiltonians in the Hartree–Fock equations, perturbed by the reaction field from the polarizable medium. The reaction field is found iteratively until the intramolecular electronic field is self-consistent (cf. ref 12). The solute molecule is assumed to be embedded into a cavity in the medium: the geometric form of the cavity has been widely discussed (cf. refs 15–20) but our experience has shown that, for

Table IV. AM1 SCF and SCRF Calculated Relative Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of 1-Methylcytosine, 1-Methyluracil, and 1-Methylthymine Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
20	(0.0)	(0.0)	6.041	6.932
21	16.45	18.64	4.561	5.568
22	1.48	6.45	2.384	2.712
23	20.74	16.42	6.565	7.852
24	12.47	12.70	4.497	5.123
25	(0.0)	(0.0)	4.597	5.354
26	20.30	17.05	6.280	7.395
27	12.58	12.37	4.662	5.274
28	(0.0)	(0.0)	4.495	5.130

Chart I

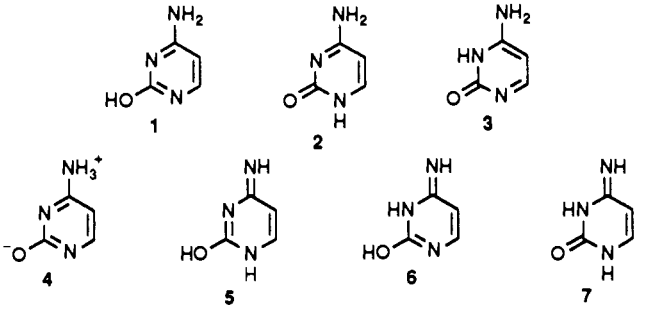

Chart II

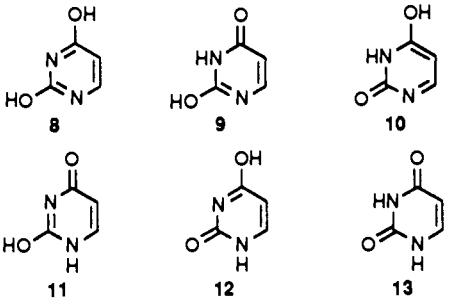

Chart III

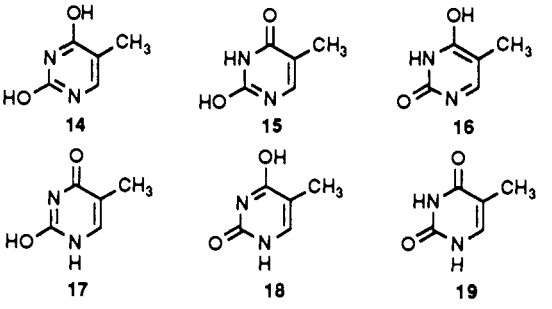

Chart IV

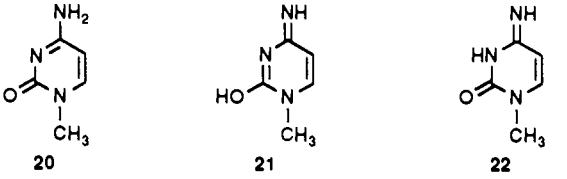

Chart V

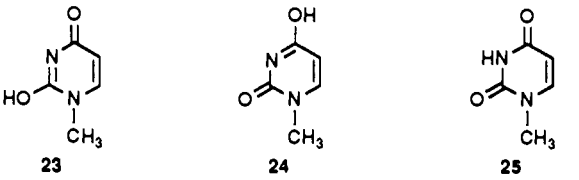

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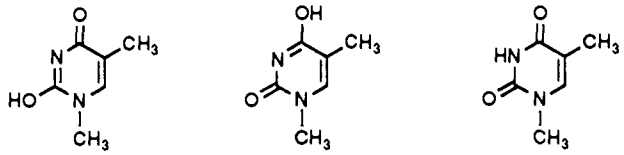
Table V. AM1 SCF and AM1 SCRF Calculated Relative Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of Adenine Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
29	(0.0)	(0.0)	2.180	2.892
30	7.01	2.73	5.999	6.787
31	19.64	9.23	8.827	10.461
32	11.58	9.96	4.543	5.453
33	16.00	14.47	4.049	4.680
34	15.15	13.96	3.779	4.543
35	22.54	15.37	7.905	9.422
36	14.44	14.79	2.048	2.448

Table VI. AM1 SCF and AM1 SCRF Calculated Relatived Heats of Formation $\delta\Delta H_f°$ (kcal/mol) and Dipole Moments (D) of Guanine Tautomers in Different Media

	$\delta\Delta H_f°$		μ	
tautomer	$\epsilon = 1$	$\epsilon = 80$	$\epsilon = 1$	$\epsilon = 80$
37	14.63	7.34	9.533	11.281
38	1.54	5.25	1.726	1.989
39	(0.0)	(0.0)	5.887	6.604
40	7.40	9.55	3.978	4.566
41	3.23	6.26	2.966	3.334
42	27.91	25.09	7.298	9.728
43	17.53	14.78	7.379	8.721
44	6.45	8.91	3.697	4.215
45	6.96	10.42	2.210	2.575
46	10.98	11.27	5.673	6.384
47	23.12	25.69	3.495	4.068
48	34.12	30.74	8.142	9.382
49	18.44	20.57	4.020	4.573
50	16.39	17.30	5.007	5.915

Chart VI



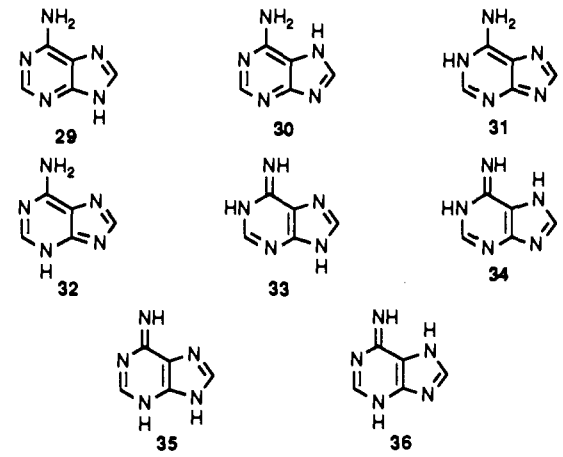
26 **27** **28**

comparatively rigid molecules without long chains, a simple spherical cavity is a satisfactory approximation. In the present work we assumed spherical cavities for the solute molecules with the radii estimated on the basis of molecular bond refractions and atomic van der Waals radii as follows: for cytosine tautomers 3.53 Å, for uracil tautomers 3.45 Å, for thymine tautomers 3.65 Å, for 1-methylcytosine tautomers 3.77 Å, for 1-methyluracil tautomers 3.65 Å, and for 1-methylthymine tautomers 3.83 Å. However, the results are insensitive to changes of 10% in these cavity radii.

Results and Discussion

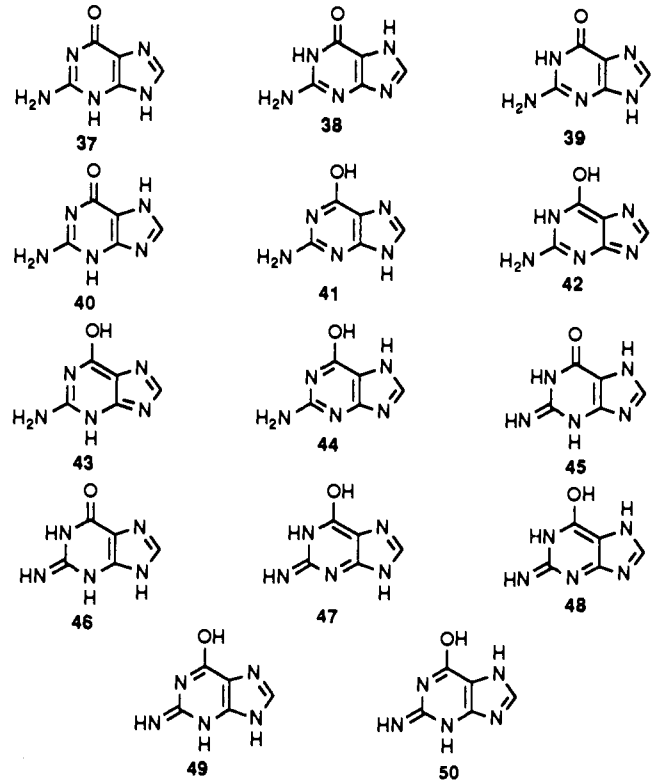
The AM1 calculated relative heats of formation, dipole moments, and ionization potentials are given in Tables I–VI for the individual tautomeric forms as presented in Charts I–VIII. Only those tautomers with complete cyclic conjugation are considered. Our tentative calculations of all zwitterions, and of those neutral tautomers including $-CH_2-$ groups in the ring skeleton, indicate that such species are at least 20 kcal/mol destabilized in comparison with the most stable tautomers of the respective compounds, both as regards the isolated molecules and those in the polarizable dielectric medium. Therefore the contributions of such nonconjugated forms are negligible regardless of the medium, and thus they can be eliminated in model mutagenic DNA mispairing calculations. The corresponding results using the MNDO-PM3 method are given in the supplementary material (Tables A–D). Planarity of the heavy-atom skeletons has been enforced; within this constraint, full geometry optimization was carried out for every tautomer in both media. The calculated geometries in the form of the *Z* matrices are given in the supplementary material.

Chart VII



29 **30** **31** **32** **33** **34** **35** **36**

Chart VIII



37 **38** **39** **40** **41** **42** **43** **44** **45** **46** **47** **48** **49** **50**

Cytosine and 1-Methylcytosine. The AM1 calculations of heats of formation (Table I) clearly show as the most stable form the 1*H*-oxo-amino form **2**, both for the gas phase and for aqueous solution. It has been shown recently that a substantial amount of hydroxy-amino form **1** may be present in the case of isolated molecules. These experiments, based on the IR calculated force constant comparisons with spectral frequencies obtained in Ar or N_2 matrices[7,21-26] or on the moments of inertia calculated from

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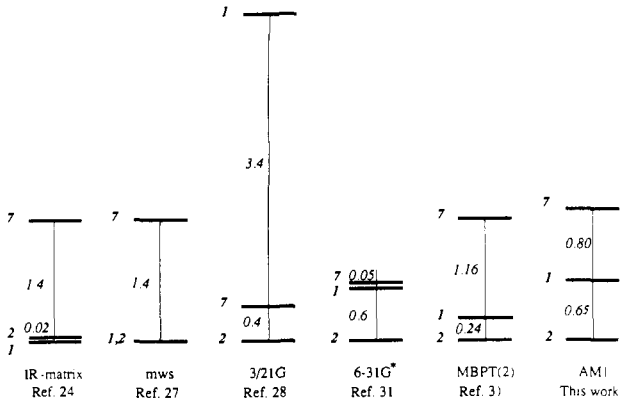

Figure 1. The relative stability (kcal/mol) of cytosine tautomers in the gas phase of the inert gas matrices as estimated experimentally or calculated with different quantum-chemical methods.

the microwave spectra,[27] give almost the same stability for forms **1** and **2** (cf. Figure 1). Ab initio calculations are in favor of the 1*H*-oxo-amino form **2**. For instance, the small split basis set (3-21G) calculations prefer this form over form **1** by 3.8 kcal/mol[28,29] whereas the large basis set calculations (6-31G*//3-21G) give the energy difference as 0.6 kcal/mol.[30,31] It also has been suggested that electron correlation may play an important role in the tautomerism of cytosine. The corresponding calculations using second-order Møller–Plesset perturbation (MP2) theory or second-order many-body perturbation theory (MBPT(2)) again predict the 1*H*-oxo-amino form **2** of cytosine as the most stable tautomer by 0.24 kcal/mol over form **1** (cf. ref 31). The small basis set ab initio calculations give the 1*H*-oxo-amino form **7** as the second most stable tautomer (only 0.39 kcal/mol or 0.61 kcal/mol less stable than **2**, using 3-21G or 6-31G*//3-21G basis sets, respectively[30]). However, taking into account some correlation energy in the framework of MBPT(2) theory enhances this difference to 1.4 kcal/mol, and the hydroxyamino form **1** is now predicted to be favored in comparison with the 1*H*-oxo-imino form **7**.[31a] Recent calculations[31b] on the cytosine tautomers using fourth-order many-body perturbational theory with coupled cluster expansion (MBPT(4)–CCSD + T(CCSD)) and taking into account semiempirically estimated zero-point vibration corrections (ZPV) to the energies of tautomeric species even gives hydroxyamino form **1** as the most stable tautomer of cytosine as its isolated form, favored by 1 kcal/mol over tautomer **2** and by 1.5 kcal/mol over tautomer **7**. Notably, the PM3 method gives the same qualitative order of stabilities. However, even the highly sophisticated ab initio calculation mentioned cannot be considered as the final exact theoretical prediction of the relative stabilities of cytosine tautomers because of the neglect of the effects of heat capacity and entropy on the equilibrium. The semiempirical AM1 and PM3 methods implicitly include the heat capacity and also electron correlation effects through the parametrization of molecular integrals on the basis of experimental standard heats of formation and other properties of chemical compounds (cf. refs 13 and 14). Obviously, the slight discrepancy between the different experimental and theoretical estimations of relative stabilities of

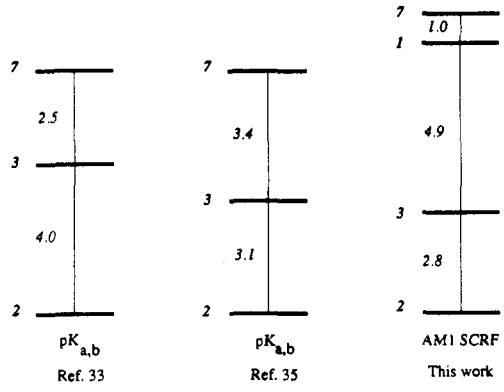

Figure 2. The experimental and theoretical (AM1 SCRF) relative stabilities (kcal/mol) of cytosine tautomers in aqueous solution.

cytosine tautomers in their isolated form is not conclusively accounted for, but notably, the PM3 calculation gives the same order of tautomer stabilities, and the AM1 numerical data are close to those of experimentally measured $\delta\Delta H_f^\circ$ values (cf. Table I, and Figure 1). Thus they seem to be reliable methods for the prediction of the relative stabilities of heterocyclic tautomers as previously shown by us for simpler molecules.[9,32]

In aqueous solution, according to the AM1 calculations, the 1*H*-oxo-amino form **2** is more stable by 7.7 kcal/mol over the hydroxy-amino form **1**, by 2.8 kcal/mol over the alternative oxo-amino form **3**, and by 8.7 kcal/mol over the oxo-imino form **7** (cf. Figure 2). Experimentally, pK_a measurements indicate a pK_T value of 2.9 for the equilibrium between forms **2** and **3** in aqueous solution at 20 °C;[33] this corresponds to 4 kcal/mol. Furthermore, the equilibrium constant between form **3** and form **7** was shown[33] to be approximately 60 corresponding to 2.5 kcal/mol. Reference 34 indicates that the equilibrium between form **2** and form **7** corresponds to a pK_T of approximately 5 in aqueous solution corresponding to approximately 7 kcal/mol. The data of temperature-jump UV-spectroscopy measurements in aqueous solutions have been interpreted[35] as the 1*H*-amino-oxo form **2** being more stable by 3.1 kcal/mol than the 3*H*-oxo-amino form **3** and more stable by 6.5 kcal/mol than 1*H*-oxo-imino form **7**. Consequently, within the limits of experimental uncertainty, the AM1 calculational results are in fair agreement with measured relative stabilities of cytosine tautomers in solution (cf. Figure 2). The calculated dipole moment for the most stable tautomer of isolated cytosine by both AM1 and PM3 methods (6.9 and 6.8 D, respectively, cf. Tables I and V) is in good agreement with experimental data (7.0 D[36]) and with ab initio predictions (7.2 D[29]). Significantly, the dipole moments are sensitive to the change of dielectric medium (cf. Tables I–VIII) to extents which are unique for each compound. Thus the SCRF method accounts for specifically the first- and second-order solvent polarization effects around the solute molecule. This procedure clarifies the effects of solvent on tautomeric equilibrium which is important from both the theoretical and the applied point of view.

For 1-methylcytosine, the oxo-amino tautomer **20** is predicted as the most stable form by both PM3 and AM1 methods both in the gas phase and in solution. In the gas phase, AM1 gives an energy close to that of **20** for the 3*H*-oxo-imino form **22**, whereas in solution the energies of **20** and **22** are substantially different (cf. Table IV). This example illustrates the differential effects of a polar medium on the relative stabilities of tautomers.

Uracil and Thymine and the Corresponding 1-Methyl Analogues. Results of AM1 and PM3 calculations of the individual tautomers of uracil and of thymine are shown in Tables II and III. Similar

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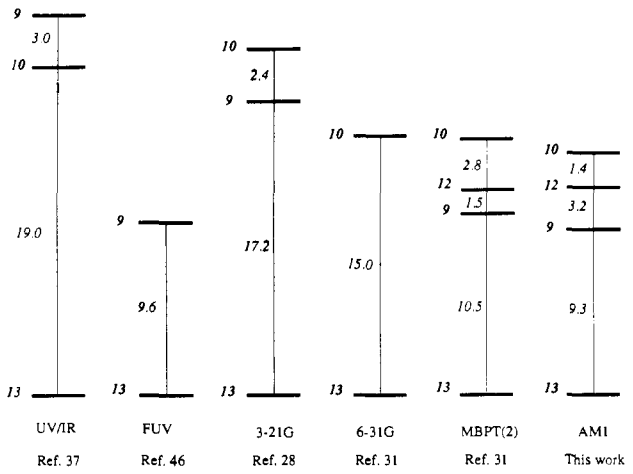

Figure 3. The relative stability (kcal/mol) of uracil tautomers in the gas phase or in the inert gas matrices as estimated experimentally or calculated with different quantum-chemical methods.

results for 1-methyluracil and 1-methylthymine are presented in Table IV. In accordance with the experimental data,[2,37-44] the dioxo forms **13** and **19** are clearly the most stable for both thymine and uracil both in the gas phase ($\epsilon = 1$) and in aqueous solution ($\epsilon = 80$). In all four cases, the AM1 calculated $\Delta H_f°$ for the next most stable tautomer is more than 9 kcal/mol higher. The next most stable tautomeric forms, i.e. **9** and **15** for the gas phase and **10** and **16** for aqueous solution, are not of great influence because they cannot occur in the nucleic acids, where the bases are fixed in a 1*H*-mode.

Among the three forms of each base which can exist in the nucleic acids, i.e. **11–13** and **17–19**, the 4-hydroxy forms **12** and **18** are the next most stable both in the gas phase and in aqueous solution. Qualitatively the same predictions are obtained with use of the PM3 method, whereas MNDO calculations give the wrong order of stabilities for both bases (cf ref 45).

Recent experimental evidence from the fluorescence excitation and dispersed fluorescence techniques indicates the existence of uracil tautomer **9** as a minor component with $\delta\Delta H_f° = 9.6$ kcal/mol[47] (cf. Figure 3) in the gas phase[46] (the earlier experimental estimate[37] $\delta\Delta H_f° = 22 + 10$ kcal/mol is clearly too uncertain): the AM1 and PM3 energies are in remarkably good agreement with the experimental estimation. Ab initio DZP basis set MBPT(2) calculated values, 12.0 kcal/mol for the relative stability of dioxo form **13** over the 1*H*-oxo-hydroxy form **12** and 10.5 kcal/mol for its stability over the 3*H*-oxo-hydroxy form **9**, have been published recently.[7b] The agreement between AM1 and MBPT(2) results is remarkably good (cf. Figure 3).

The AM1 and PM3 calculated dipole moments for the most stable tautomer (Tables II and III) are in excellent agreement with the experimental data obtained in the gas phase (4.16 and 4.13 D for uracil and thymine, respectively[47]), which makes it possible to correctly predict the solvent reaction field effect in the framework of the SCRF model.

The AM1 and PM3 SCF and SCRF calculations of 1-methyluracil and 1-methylthymine tautomers also show the dominance of dioxo forms **25** and **28** both in the gas phase and in solution (cf. Table IV). Apparently the only quantitative experimental solution data to compare with these results are those provided by one of the present authors,[33,48] nearly 30 years ago when he reported pK_T values of 3.3–4.0 for 1-methyluracil and 1.3–3.3 for 5-bromouracil in aqueous solution at room temperature. These values correspond to 4.0–5.5 kcal/mol and are uncertain due to the fact that uracil does not behave as a Hammett base and does not follow the Hammett acidity function.[49] The substantially higher, calculated values of $\delta\Delta H_f°$ may require new interpretations of the acidity function behavior (cf. ref 49).

Adenine. The AM1 calculational results for the adenine tautomers are given in Table V. The AM1 method predicts the 9*H*-amino form **29** as the most stable. The next most stable 7*H*-amino tautomer **30**, which is 7 kcal/mol less stable as regards the isolated forms, is substantially stabilized by a high dielectric medium (to within 2.7 kcal/mol), making adenine susceptible to mutagenically important tautomeric changes in solution. (The PM3 method[14] also predicts tautomer **30** as the next stable form, it being only 2.02 kcal/mol less stable than tautomer **1** in solution.) Experimental evidence indicates that this minor tautomeric form **30** exists in substantial amounts in solution (the estimated free energy change is $\Delta G_T = 0.8$ kcal/mol for adenine and $\Delta G_T = 2.8$ kcal/mol for 1-methyladenine[50]).

Chemical modification of adenine nucleotides may in principle be important for induced mutagenicity, thus Italian authors[51] have stated that the protonation of 1-methyl substitution of adenine specifically lowers the energies of imino tautomers of adenine. For adenine itself the imino forms are of negligible importance both in the gas phase and in solution as confirmed by the calculational results of the present work. However, 1-methyladenine gives a quite different type of compound, and protonated species cannot be directly compared with the neutral compounds. In this work we are studying only the influence of the prototropic tautomerism on the possible base mispairing in nucleic acids.

Guanine. The AM1 results of guanine tautomer calculations are presented in Table VI. The most stable tautomer is predicted to be the amino-oxo form **39** by the AM1 and also by the PM3 calculations. This is also observed experimentally.[2] According to the PM3 results, the next most stable tautomers **38** and **41** have almost the same energy (being respectively 0.92 and 0.99 kcal/mol less stable than **41**, both as the isolated molecule and in solution (cf. Table VI)). Recently Russian authors[52] observed the presence of amino-oxo form **38** in a mixture of water and ethylene glycol (1:1 v/v) at 77 K using fluorescence absorption and excitation spectroscopy. The hydroxy-amino form **41** of guanine has been detected in inert gas matrices from IR spectral measurements.[7a,53] Ab initio calculations using a small split basis set (3-21G) predict the amino-oxo form **39** to be 5 kcal/mol more stable than **13**.[29] However, calculations using the 6-31G*//3-21G basis set give this energy difference as 1.7 kcal/mol whereas the use of second-order many-body perturbational theory with a large basis set (MBPT(2)/6-31G*//3-21G) further reduces this difference to 0.7 kcal/mol.[31a] Despite the slight discrepancy in the experimental observations, the overall agreement with sophisticated ab initio calculations indicates that the AM1 and PM3 methods are satisfactory for the predictions of the relative stabilities of guanine tautomers in their isolated forms.

In the highly polarizable dielectric medium, the stability of amino-oxo tautomer **11** in comparison with the next most stable tautomers is predicted to increase significantly over that in the

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gas phase (cf. Table VI). Indeed, only form **11** is experimentally detectable in aqueous solutions of guanine.[1]

Conclusions

The results presented in this paper confirm our earlier observations about the validity of the AM1 SCRF method[9,32] for the quantitative prediction of relative stabilities of heterocycle tautomers in solution.

In a few cases, where the comparison is available, the predictions by AM1 are correct also for gas-phase tautomerization energies of nucleic acid bases. AM1 gives also a good representation of the charge distribution in molecules in terms of calculated dipole moments, enabling us to correctly account for the specific solvent polarity effects on the tautomer energies in the framework of the self-consistent reaction field model. Therefore, this method is promising for the study of base pairing and mispairing processes in DNA, which has great importance in the investigation of mutation frequency. Such an investigation is now in progress.

Registry No. Cytosine, 71-30-7; thymine, 65-71-4; uracil, 66-22-8; 1-methylcytosine, 1122-47-0; 1-methylthymine, 4160-72-9; 1-methyluracil, 615-77-0; adenine, 73-24-5; guanine, 73-40-5.

Supplementary Material Available: Tables of AM1 and MNDO/PM3 Z matrices for cytosine, uracil, thymine, 1-methylcytosine, 1-methyluracil, and 1-methylthymine tautomers, adenine, and guanine and listings of PM3 SCF and SCRF calculated relative heats of formation and dipole moments of cytosine, uracil, thymine, 1-methylcytosine, 1-methyluracil, and 1-methylthymine tautomers in different media (65 pages). Ordering information is given on any current masthead page.

Chemiluminescent Decomposition of 1,2-Dioxetanes: An MC-SCF/MP2 Study with VB Analysis

Mar Reguero,[1b] Fernando Bernardi,[1a] Andrea Bottoni,[1a] Massimo Olivucci,[1b] and Michael A. Robb*[,1b]

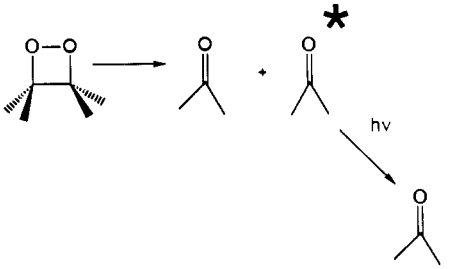
Contribution from the Dipartimento di Chimica "G. Ciamician" dell'Universita di Bologna, Via Selmi 2, 40126 Bologna, Italy, and the Department of Chemistry, King's College, London, Strand, London WC2R 2LS, U.K. *Received July 6, 1990*

Abstract: MC-SCF (at the 4-31G level) geometry optimizations and analytical hessian (frequencies) for ground-state (S_0) and excited state (T_1 and S_1) surfaces that are necessary in the description of the mechanism of the chemiluminescent decomposition of 1,2-dioxetane are reported. The energetics have been confirmed by multi-reference MP2 computations at selected critical points. The origin of the S_0/T_1 surface intersection and the different barrier heights in S_0/T_1 fragmentation are rationalized using a rigorous VB model. The computed results suggest a novel mechanism where the rate-determining step occurs on the excited T_1 surface. The computed activation energy is 25.3 kcal mol^{-1} at the MC-SCF/MP2/6-31G* level (21.3 kcal mol^{-1} with zero-point correction from 4-31G level MC-SCF) which is in acceptable agreement with the experimental activation energy of 22.1 ± 0.3 kcal mol^{-1}. Our computed value of $\Delta S^{\ddagger}$ is 5 cal mol^{-1} K^{-1} in agreement with the experimental result which is small or negative depending upon solvent. Our results suggest that the thermal S_0 ring opening of dioxetane to produce a biradical can occur almost without activation energy. The S_0–T_1 *avoided* crossing is shown to occur along an O–O bond rupture coordinate in the region just before the biradical minimum and is controlled by strong spin–orbit coupling. After passage (via C–C stretching) through a second *real* T_1–S_0 crossing immediately after the biradical minimum the rate-determining step involves a transition state for C–C fragmentation on the T_1 surface to produce triplet and ground-state formaldehyde.

Introduction

The chemiluminescence of 1,2-dioxetantes (Scheme I) is an electronically forbidden *nonadiabatic* (i.e. a change from one potential energy surface to another) reaction.[2] As a result of much experimental work, very accurate energetics and rate data are available;[3,4] however, the precise nature of the mechanism remains the subject of some controversy.[5] In this paper we shall show that theoretical computations can now provide a rationalization of the experimental data and a more detailed discussion of the mechanism.

Scheme I



Such reactions are difficult to study theoretically because not only must one treat synchronous and biradical paths on the ground-state surface with balanced accuracy but also one must treat the excited state and the ground state with equal accuracy since a surface crossing is involved. Further, in addition to the location of minima and transition structures on ground and excited states, one is interested in characterizing the regions where the ground- and excited-state surfaces intersect.

Let us begin with a summary of the mechanistic possibilities for these reactions. First, let us consider only the ground-state thermal decomposition of a 1,2-dioxetane to produce 2 mol of

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