Tautomerism in Free Base Porphyrins: The Porphyrin Potential Energy Surface

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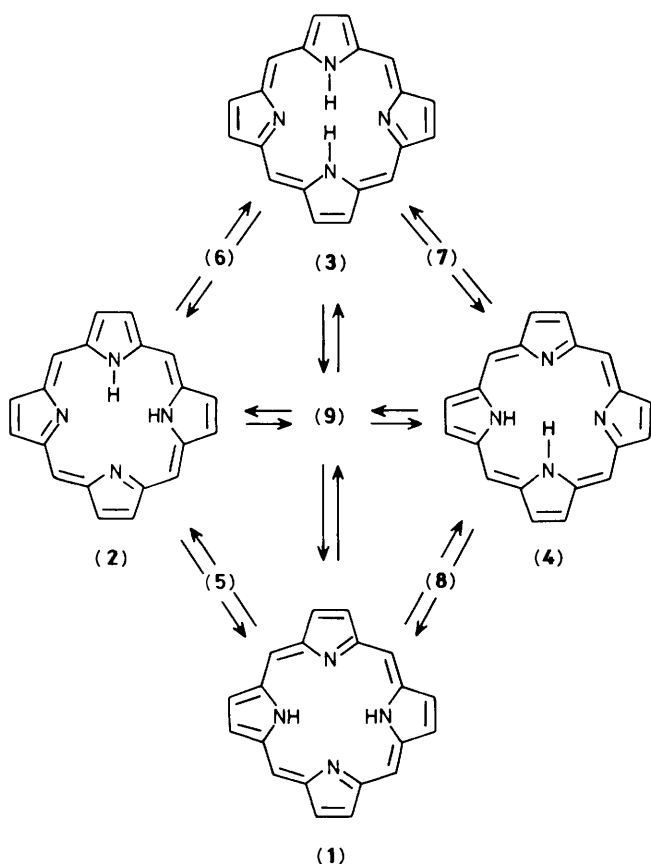AM1 calculations are reported which demonstrate that the classical hydrogen migration in porphyrin occurs via a two-step mechanism, not a synchronous-concerted mechanism as has been previously supposed; the implications of this mechanism on tautomerization dynamics are discussed.

The degenerate tautomerization of free base porphyrin (1) has been the subject of considerable experimental[1—10] and theoretical[11—18] interest. One of the intriguing aspects of this rearrangement is the fast rate of interconversion even at very low (<200 K) temperatures.[1] This high rate is often ascribed to quantum mechanical tunnelling,[1,2,4] but without a good understanding of the potential surface for interconversion between isomers (1) and (3) it is difficult to know how important tunnelling need be, or through what type of barrier it might be occurring. In particular, it would be useful to know if the classical tautomerization proceeds through a concerted or stepwise mechanism. This is a case where a quantum theoretical study could do much to clarify the situation. Theoretical studies of this system have, however, been very limited due to the large size of even the parent porphyrin

molecule. The studies which have been done[11—18] are clearly inadequate for understanding the dynamics of this system because the methods used (e.g. CNDO/2) are relatively poor, and because in all cases the potential energy (PE) surface was not explored in detail. We report a thorough study of the potential surface for interconversion between the tautomers of (1) using the Austin Model 1[19] (AM1) method.

The calculations were carried out using the standard AM1 program and parameters[19] as implemented in the AMPAC computer program.[20] Geometries were optimized with respect to all geometric variables without making any assumptions, and all stationary points were characterized by calculating force constants.[21]

Four minima, structures (1)—(4), were located on the porphyrin PE surface. Structures (1) and (3) are energetically

Scheme 1. AM1 potential surface for tautomerization of free base porphyrin.

Table 1. AM1 calculated heats of formation in kcal mol⁻¹ for all stationary points on the prophyrin potential energy surface.

Structure	Classification	Heat of formation
(1), (3)	Minimum	242.6
(2), (4)	Minimum	249.8
(5)—(8)	Transition State	277.2
(9)	Hilltop	303.4

degenerate tautomers, each being related to the other by C_4 rotation about the molecule's principal axis. Structures (2) and (4), while different in energy from structures (1) and (3), are also a degenerate pair of tautomers, inter-related by C_2 rotation about the molecule's principal axis. While (1) and (3) are tautomers of a well characterized molecule, evidence has only recently been given for the possible existence of a porphyrin structure related to (2) and (4).[22] The potential surface for interconversion of isomers (1)—(4) is outlined in Scheme 1, and the calculated energies of all nine stationary points are given in Table 1.†

Conversion of (1) to (3) can proceed either via a two-step mechanism involving intermediates (2) or (4), or a single-step mechanism where both hydrogens move synchronously through stationary point (9). A comparison of the activation energies for these two processes shows that the barrier for the single proton migration is 26 kcal mol⁻¹ (cal = 4.184 J) more favourable than the synchronous process. In addition, examination of the force constants of (9) indicates that it is not a transition state, but a hilltop (second order transition state)

with two imaginary vibrations. In contrast, the stationary points (5)—(8) are all confirmed to be transition states, each possessing one and only one imaginary vibration. The fact that (9) is a hilltop and not a transition state can be understood intuitively by examining Scheme 1. Since conversion of (1) to (3) and (2) to (4) both proceed through the same maximum (9), there must be two vibrational modes for (9) which lead to a decrease, not an increase, in energy. Such a structure cannot by definition be a saddle point (transition state).

These calculations lead to the conclusion that tautomers (1) and (2) interconvert classically, not through a synchronous double proton migration, but by two successive proton migrations. This result should not be surprising in light of the recent suggestion[26] that multi-bond reactions are rarely synchronous. The barrier for the favoured stepwise pathway is still very high, however, and is not consistent with the observation that tautomerization can be 'frozen' on the n.m.r. time scale only by temperatures approaching 200 K. There is also the question of why intermediates (2) and (4), which have protons on adjacent nitrogens, have not been observed even though these calculations predict that they reside in relatively deep energy wells. A likely answer, for which there is considerable experimental evidence,[1,2,4] is tunnelling. A high rate of tunneling would explain why tautomerization is fast even at low temperatures, and why the intermediates (2) and (4) are not observed.

Tunnelling canot occur (i.e. the tunnelling probability is low enough to preclude tunnelling as an important contributor to the overall tautomerism rate) along the two-step pathway because the tunnelling rate is known to be greatly attenuated when the symmetry of the double minimum potential is broken,[27] as is the case here. Hence, we are left with the conclusion that tunnelling must occur through the synchronous pathway. Recall that the synchronous hydrogen migration leads to a hilltop (9) not a true transition state, therefore, from a classical point of view (i.e. transition state theory), stationary point (9) is unimportant in the dynamics of this system. Tunnelling, however, involves the non-classical penetration of a barrier, so the barrier need not be along a classical reaction pathway. Thus, in the present situation tunnelling can only occur at an appreciable rate through the barrier (hilltop) directly separating (1) and (2).[12]

The ground state tunnelling and thermally activated tunnelling (TAT) rates (i.e. tunnelling from vibrationally excited states) were calculated‡ for the synchronous pathway using the method of periodic orbits,[28] which has been shown to give reasonable tunnelling rates.[29] We have also calculated the classical rate for the two-step pathway using transition state theory. It is important to remember that there can be no classical rate associated with the synchronous pathway because the barrier involved is a hilltop, not a proper transition state. Similarly, tunnelling can be neglected for the stepwise pathway because the potential barrier lacks the

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† We have found that the spin-unrestricted[23] (UHF) energies are lower than the RHF energies by about 1 eV. This type of stabilization of the UHF energy is indicative of an electronic state, such as a biradical, in which two electrons are uncoupled and, therefore, highly correlated.[24] In this case it is likely[25] that the unusual stability of the UHF energies are due to the presence of a nearly degenerate HOMO and LUMO in the porphyrin π system. Since the UHF and RHF calculations give qualitatively the same PE surface (i.e. the same minima and stationary points) we will reserve a discussion of the UHF results for a future manuscript.

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‡ The calculated classical and tunnelling rates will be reported at a later date.

necessary symmetry.[27] Although the calculated AM1 barrier heights are probably too high by about 15 kcal mol^{-1},[19] we can draw two qualitative conclusions from these calculations regarding the dynamics of this system: (i) at high temperatures the classical rate constant for the two-step mechanism makes a significant contribution to the overall tautomerization rate of (**1**); (ii) at lower temperatures the tautomerization rate is due almost exclusively to tunnelling through the synchronous hilltop, even though this barrier is higher and would not normally be considered a significant point on the PE surface.

In summary, we find that classical tautomerization in the parent porphyrin does not occur in a synchronous manner, but instead *via* a stepwise mechanism. At low temperatures, however, the primary mechanism for tautomerization is synchronous tunnelling through the hilltop separating (**1**) from (**3**). Similar 'dual' mechanisms may be important in other double hydrogen shifts.[30]

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