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Hydrogen Tunnelling in the Rearrangements of Carbenes: The Role of Dynamical Calculations†

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Tunnelling controlled chemical reactions are those which preferably proceed through pathways with high but narrow potential energy barriers, via quantum tunnelling, resulting in a product that would be disfavoured classically. These reactions are very sensitive to barrier width, height and temperature and so dynamical theoretical methods are required to describe these processes. Recent experimental work on charge-tagged phenyl pyruvic acid derivatives has found, in contrast to similar systems, no evidence of tunnelling control. Using Semiclassical Transition State Theory, we rationalise these results and find tunnelling is significant in this system.

In recent years, it has been shown that quantum tunnelling can supersede traditional kinetic control of chemical reactions, making some reaction paths with high energy barriers more favourable than alternative pathways with lower barriers[1,2]. This effect has been coined 'tunnelling control'[3]. For theoretical studies, this highlights the importance of considering reaction path width, and dynamical tunnelling calculations, rather than relying on barrier heights alone. A well studied example of this is the family of hydroxycarbenes (R-C-OH)[1,3–7], which form the subject of this work.

Semiclassical Transition State Theory[8,9] (SCTST), and its reduced-dimensional variants[10–12], present a cost-effective method for studying the competition between reaction pathways, whilst accounting for quantum tunnelling effects. Using an absolute minimum of *ab initio* calculations, tunnelling probabilities (and from these, thermal rate constants) are calculated analytically using the WKB (semiclassical) wavefunction combined with vibrational perturbation theory[9]. SCTST has been applied previously to determine the rate constants of a range of chemical reactions including hydrogen abstractions[11,13–16], decomposition of nerve agents[17,18], and important atmospheric processes[19,20]. In this work, we use SCTST in its well-tested one-dimensional form (1D-SCTST), where the reaction mode is considered separable from the other (bound) degrees of freedom. This allows for a method whose computational cost is only slightly larger than that of classical transition state theory, but accounts for tunnelling and anharmonicity in the reaction mode.

Full details of the SCTST method can be found in the a recent review, ref. 12, and the computational details for this work can be found in the supplementary information. Calculations were performed using our in-house *pySCTST* code[21]. In order to allow for a high level of theory in our *ab initio* calculations, here with up to 29 atoms, we keep the number of such calculations to a minimum by using 1D-SCTST.

Recent work[3,6] has identified methylhydroxycarbene as a molecule that decays via a tunnelling controlled pathway, shown in Scheme 1. Experimental work on this molecule at 11 K in an argon matrix shows the only observed product of this decay is the aldehyde, despite the lower barrier required to reach the enol product. This effect has been observed at low temperatures for other substituted carbenes[22], and some theoretical rate calculations confirm these findings[23]. This mechanism has also led to spectroscopic observation of hydrogen tunnelling above room temperature[5].

Our 1D-SCTST calculations for the decay of methylhydroxycarbene, performed at the CCSD(T)/cc-pVTZ // MP2/cc-pVTZ level of theory, are consistent with these experimental findings, as shown in Fig. 1. These predict the aldehyde product dominates at low temperature, with the two pathways being equally fast at 287 K. This is in good agreement with instanton calculations performed in full-dimensions, which predict the crossing point to be 277 K[23]. Classical transition state theory, as expected, incorrectly predicts that the enol product is the dominant product at all

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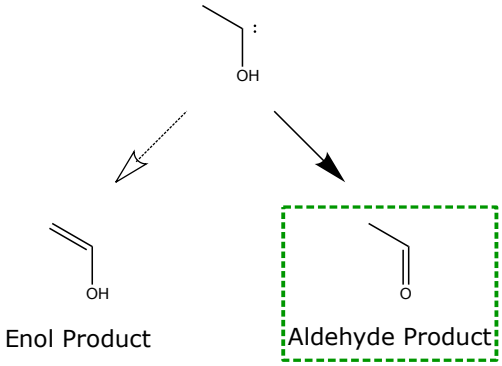


Scheme 1 Methylhydroxycarbene decay is tunnelling controlled at 11 K. The aldehyde product is found, despite the higher energy barrier

temperatures, as it does not account for tunnelling. Calculated barrier heights, frequencies and anharmonic constants for all reactions in this work can be found in Table 1.

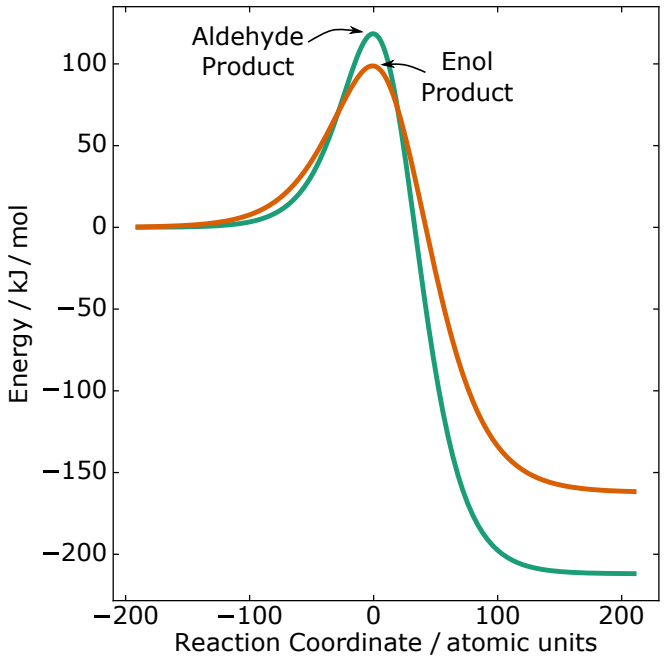
Scheme	Reaction	V_0(kJ/mol)	ω_F ($i$cm^{-1})	x_{FF} (cm^{-1})
1	Aldehyde Pathway	134	1979	-78.1
	Enol Pathway	108	1469	-63.9
2	Aldehyde Pathway	153	2075	-97.2
	Enol Pathway	96	1342	-30.6
2	Enol (Deuterated)	96	1030	-18.3

Table 1 Barrier heights, imaginary frequencies and anharmonic constants for the five reactions studied in this work

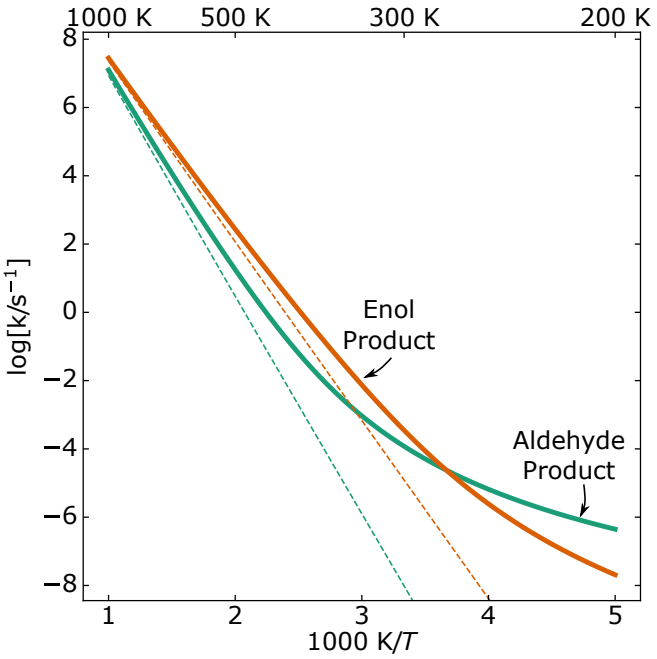
In a recent paper[7], a similar reaction was investigated at higher temperature both experimentally and theoretically, with results contrasting those of methylhydroxycarbene decay. In this study a charge-tagged phenyl pyruvic acid derivative (shown at the top of Scheme 2) was generated, which then loses CO_2 in collision induced dissociation experiments, forming a carbene intermediate at about 320 K. IR spectroscopy (and comparison with theoretically predicted spectra) show that an enol acid is formed, as shown at the bottom left of Scheme 2, and no evidence of the (tunnelling controlled) aldehyde product was detected. This is despite the calculated potential barriers being qualitatively similar to those of the methylhydroxycarbene case. The authors conclude this result implies that the reaction proceeds without tunnelling, and only 'over-the-barrier' reaction trajectories are significant, a result of the carbene being formed initially in an excited state somewhere between the two barrier top energies, allowing for direct over-the-barrier transmission towards the enol (but not the aldehyde) product.

Here we aim to compliment these experiments with additional theoretical findings, and present an alternative conclusion, whereby the experimental findings are entirely consistent with a quantum tunnelling picture from a thermalised carbene. Since both pathways involve the transfer of a light hydrogen atom, it also seems very likely *a priori* that tunnelling is significant.

We performed 1D-SCTST calculations to determine the relative rates of enol and aldehyde products, from the carbene species.

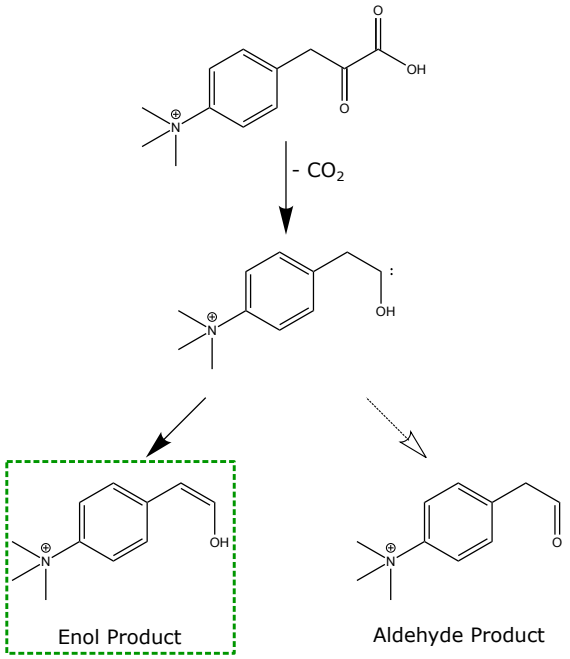


(a) Reaction Barriers



(b) Arrhenius Plot. TST results shown as dotted lines.

Fig. 1 Tunnelling control in the decay of methylhydroxycarbene

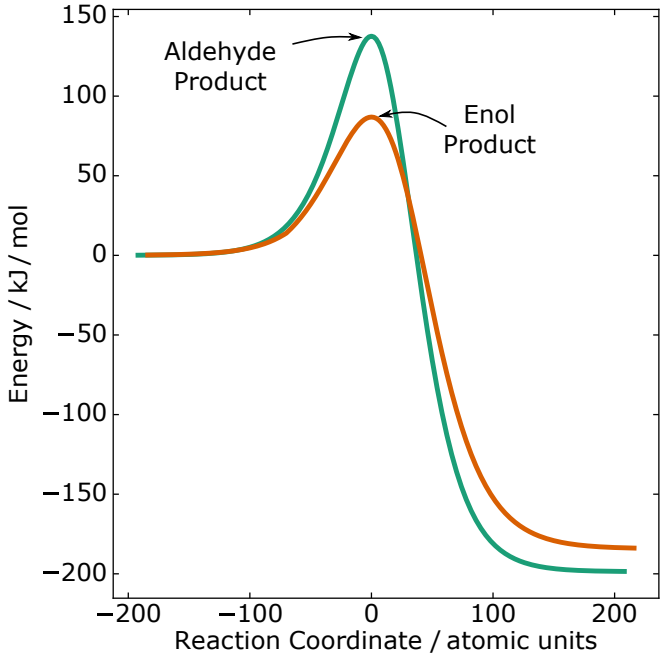


Scheme 2 The kinetic control (enol) product is found

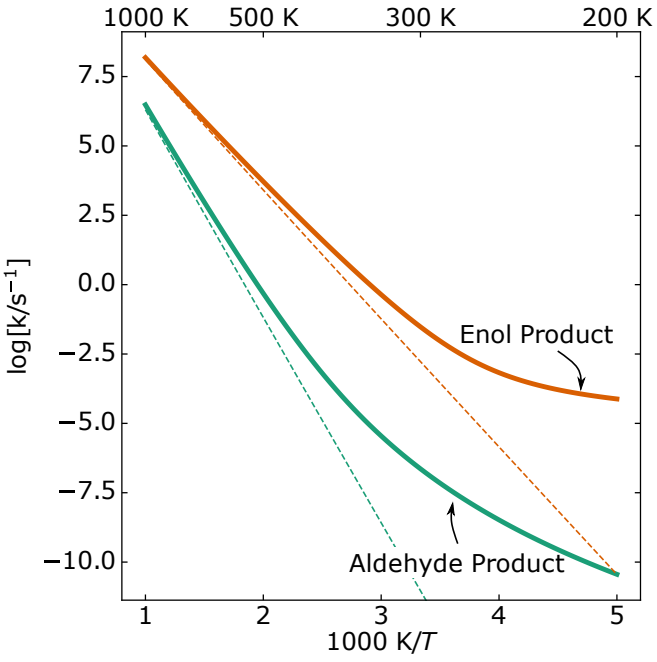
SCTST in full dimensions, whilst likely to be more accurate, is prohibitively expensive for this system, with 29 atoms. The results of our SCTST calculations, performed at the M06-2X/cc-pVTZ level of theory[24] are shown in Fig. 2. This functional has been used previously in SCTST calculations with larger molecules[17] and is known to be accurate for kinetics and main group chemistry[24]. Our calculated barrier heights for the enol- and aldehyde- pathways are 152 and 96 kJ/mol respectively, slightly larger than those calculated using B3LYP (131 and 88 kJ/mol, respectively) by the original authors[7].

Our results suggest that, in contrast to the case of methylhydroxycarbene, the aldehyde reaction barrier is not sufficiently narrow to allow for tunnelling control, even at very low temperatures. At the temperatures at which the experiments were performed, the enol-product formation is more than 10,000 times faster than the aldehyde decay, as shown in Fig. 2 (b), so our results are consistent with the experimental results. The disparity with the methylhydroxycarbene results is the much larger difference in barrier height between the two pathways (a difference of 57 kJ/mol compared to a difference of 26 kJ/mol), and the much higher temperature at which the experiments have been performed. It is clear, however, that tunnelling does contribute significantly to the reaction, even through the kinetic (enol) pathway. Moreover, excited carbenes are not necessary to explain the experimental results. Fig. 3 shows that tunnelling speeds up the reaction by a factor of 10 at 320 K for the enol-product pathway.

A key experimental indicator of tunnelling is a large kinetic isotope effect. This can be investigated by determining the rates when the hydrogen atom involved is substituted for deuterium. Fig. 4 (a) shows this has a significant impact on the rate of the



(a) Reaction Barriers



(b) Arrhenius Plot. TST results shown as dotted lines.

Fig. 2 Kinetic control dominates in the decay of charge-tagged Phenyl Pyruvic Acid Derivative, but tunnelling is significant.

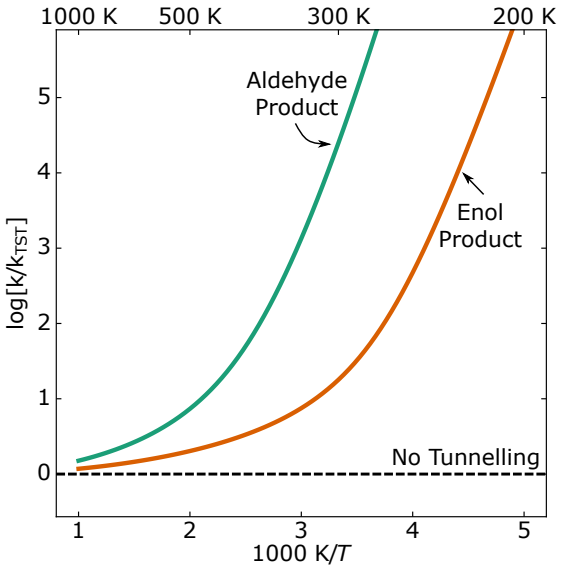


Fig. 3 The tunnelling speed-up factor of each pathway in the decay of the charge-tagged Phenyl Pyruvic Acid Derivative (Scheme 2). The enol pathway has a tunnelling speed up of a factor of 11.7 at 320 K.

enol path, with a predicted kinetic isotope effect at 320 K of :

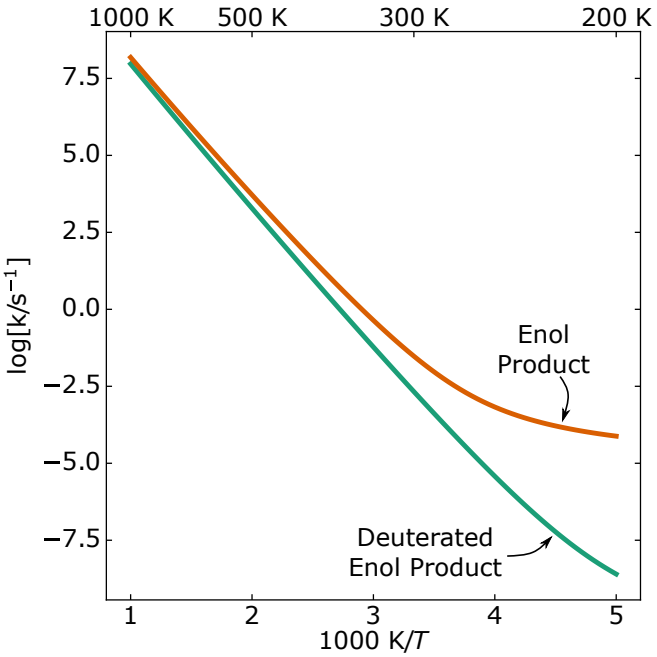
$$\mathrm{KIE} = \frac{k(\mathrm{H})}{k(\mathrm{D})} = 9.1 \tag{1}$$

which is owing to two factors; the slight increase in barrier height due to changes in ZPEs of the reactant and transition state (a classical effect), and the increased mass of the tunnelling atom, making tunnelling much less favourable (a quantum effect). The contributions of these two effects are illustrated in Fig. 4 (b). The enol pathway remains the dominant pathway under these conditions.

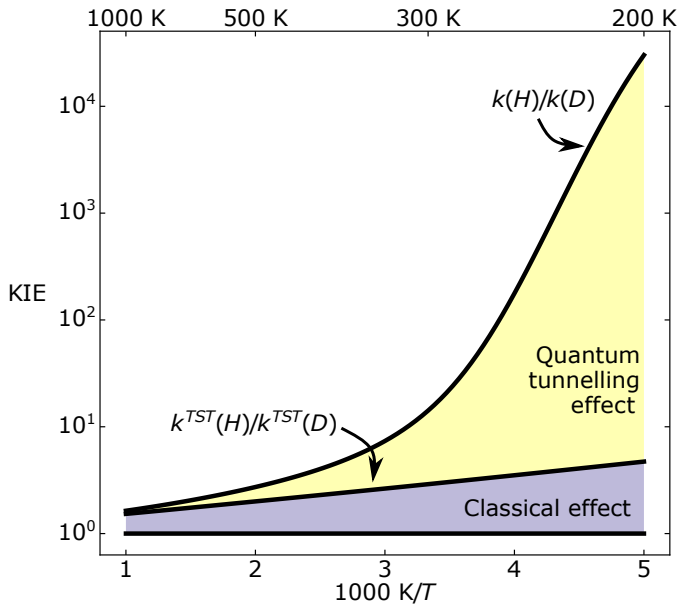
The key conclusion of this work is that the absence of tunnelling control does not imply the absence of tunnelling. We have found tunnelling is a significant factor in the decay of phenyl pyruvic acid derivative carbenes, despite the wider, lower barrier being preferred. Moreover, no excited state carbenes need be invoked in order to explain the experimental results. This is in contrast to the conclusions drawn in ref. 7. Since tunnelling control is highly sensitive to temperature and barrier height and width, it is not sufficient to look at just barrier heights, nor barrier shapes, but rather dynamical calculations are needed to determine their behaviour, which may change qualitatively with temperature. SCTST is a convenient method to study this and similar systems, and may prove a powerful tool in understanding similar organic systems.

Conflicts of interest

There are no conflicts to declare



(a) Arrhenius Plot



(b) Relative Rates

Fig. 4 A strong kinetic isotope effect is predicted for the enol product pathway in the decay of the charge-tagged Phenyl Pyruvic Acid Derivative (Scheme 2).

Acknowledgements

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