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Transition State Theory

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Abbreviations

CVT = canonical variational transition state theory; μVT = microcanonical variational transition state theory; TST = transition state theory; VTST = variational TST.

Glossary

Activated complex
Synonym for transition state.
Born–Oppenheimer approximation
The electronically adiabatic separation of electronic and nuclear motion so that the sum of the electronic energy and nuclear repulsion energy serves as a potential energy function for internuclear motion.
Isoinertial coordinates
A coordinate system where all conjugate momenta have the same reduced mass.
Phase space
The combined coordinate system of particle positions and conjugate momenta.
Semiclassical theory
A theory partly based on classical mechanics and partly based on quantum mechanics.

1 INTRODUCTION

Transition state theory (TST) provides a conceptual framework for understanding all chemical reactivity. In addition it provides a powerful computational tool for translating molecular structure and energetics into predictions of chemical reaction rates. In the 1930s to 1960s, transition state theory was often understood (and misunderstood!) in terms of quasiequilibrium concepts that hid its beauty. In the 1970s, the underlying dynamical theory became better appreciated, and the 1980s and 1990s allowed a series of careful validations against more complete dynamical theories that showed that TST not only is elegant and beautiful but also is capable of remarkable quantitative accuracy. Current work is focused on harnessing the quantitative predictive power of TST by interfacing the dynamical theory to modern electronic structure theory for gas-phase energies, and we expect similar progress for condensed-phase reactions when TST is combined with quantitative models for free energies of solvation.

TST is a workhorse of chemical kinetics, serving both as a framework for conceptual understanding and also as a powerful computational device for calculating rate coefficients. In the latter role, one often encounters a variety of generalized TSTs in which the fundamental assumption of transition state is employed, but other elements are added to the calculation as well. In this article, as in much practical work, we will not always retain the word 'generalized' in such cases. It is typically the responsibility of the reader to sort out the elements in such a case, since there is no systematic and generally accepted nomenclature that covers all possible generalizations. Nevertheless most applications of TST are easily categorized as conventional or variational, and as classical or semiclassical. There is no unique fully quantum mechanical version of TST, but practical TST calculations combine the fundamental assumption of transition state theory, which is intrinsically classical, with as many quantum mechanical elements as possible, in order to make quantitative predictions, and indeed the purely classical version of the theory is not very accurate.

The fundamental assumption of transition state theory is the existence of a dynamical bottleneck. Consider a reaction

$$\mathrm{A} + \mathrm{B} \longrightarrow \text{products} \tag{1}$$

with a rate coefficient k defined by

$$-\frac{\mathrm{d}[\mathrm{A}]}{\mathrm{d}t} = k[\mathrm{A}][\mathrm{B}] \tag{2}$$

where t denotes time, and [X] is the concentration of X. Technically, TST replaces k by a one-way flux coefficient corresponding to the rate of passage of phase points (i.e., trajectories) through a hypersurface in phase space that separates reactants from products. The hypersurface is the transition state, and often it is just called the dividing surface. If reactants are in local equilibrium, and all trajectories passing through the dividing surface in the direction of products originated at reactants and will proceed fully to products without ever returning to the dividing surface, then TST is exact in a classical mechanical world. Otherwise it overestimates the rate. Therefore, in variational TST[1] (VTST) one optimizes the location of the dividing surface to minimize the rate. The optimized dividing surface is called the variational transition state or the dynamical bottleneck. In practice, one quantizes the vibrational motions, which involves replacing classical partition functions, which are phase space integrals, by quantal ones, which are sums over states; because of this replacement the upper bound no longer strictly applies. Nevertheless the variational optimization of the dividing surface is still justified on physical grounds. As a final step, one may add a transmission coefficient (κ) to account for tunneling ($\kappa > 1$), for trajectories that recross the transition state ($\kappa < 1$), or both.

2 GAS-PHASE REACTIONS

To appreciate TST fully, it is instructive to consider a sequence of successively more sophisticated formulations. We begin with the quasiequilibrium derivation of transition state theory. Consider reaction (1) with rate constant $k(T)$ defined by equation (2), where T is temperature. Let $\mathrm{AB}^\ddagger$ denote an activated complex in equilibrium with reactants, with the following 'equilibrium constant':

$$K^\ddagger(T) = \frac{[\mathrm{AB}^\ddagger]}{[\mathrm{A}][\mathrm{B}]} \tag{3}$$

This is the first place where one must be careful to avoid oversimplification. In particular, $\mathrm{AB}^\ddagger$ should not be confused with a reaction intermediate which could conceivably be stabilized by collisions. It is associated with an intermediate configuration, part way from reactants to products, but not with an intermediate species. The fuzziness of this distinction can and will be clarified below, but the failure to appreciate this distinction fully is probably the single most important reason for the lack of understanding of TST in its first 30–40 years. In fact there were published papers as late as the 1960s questioning the formulation of the theory and suggesting possible errors of a factor of 2 in the original derivation. Actually the original formulations[2] were correct.

The popular early derivations of TST proceed by writing the rate constant at temperature T as

$$k(T) = \nu(T)K^\ddagger(T) \tag{4}$$

where $\nu(T)$ is a unimolecular frequency of conversion of $\mathrm{AB}^\ddagger$ to products. Equation (4) is usually understood in terms of the quasi-mechanism:

$$\mathrm{A} + \mathrm{B} \overset{K^\ddagger}{\rightleftharpoons} \mathrm{AB}^\ddagger \tag{5}$$

$$\mathrm{AB}^\ddagger \xrightarrow{\nu} \mathrm{C} + \mathrm{D} \tag{6}$$

An expression for ν is 'derived' from statistical thermodynamics in two steps. First, one expresses $K^\ddagger(T)$ in terms of a molar standard-state free energy of activation $\Delta G^{\ddagger,\circ}$, (T) as if it were an ordinary equilibrium constant:

$$K^\ddagger(T) = K^{\ddagger,\circ}(T)\mathrm{e}^{-\Delta G^{\ddagger,\circ}}(T)/RT \tag{7}$$

where R is the gas constant, and

$$K^{\ddagger,\circ}(T) = \frac{[\mathrm{AB}^\ddagger]^\circ}{[\mathrm{A}]^\circ[\mathrm{B}]^\circ} \tag{8}$$

where $[\mathrm{X}]^\circ$ denotes the concentration of X in molecules per unit volume in the standard state. Second, one writes the free energy in terms of partition coefficients of $\mathrm{AB}^\ddagger$, A, and B. Since $\mathrm{AB}^\ddagger$ is an intermediate configuration, not a stable species, one of its degrees of freedom is unbound. Call this degree of freedom the reaction coordinate, s, and assume it is separable. Then, if A has N_A atoms, B has N_B atoms, and $\mathrm{AB}^\ddagger$ has $N_\mathrm{AB}(= N_\mathrm{A} + N_\mathrm{B})$ atoms,

$$\Delta G^{\ddagger,\circ}(T) = \ln \frac{Q_s(T)Q^\ddagger(T)}{K^{\ddagger,\circ}(T)\Phi^\mathrm{R}(T)} \tag{9}$$

where, for a bimolecular reaction,

$$\Phi^\mathrm{R}(T) = \Phi_\mathrm{rel}(T)Q^\mathrm{A}(T)Q^\mathrm{B}(T) \tag{10}$$

$Q_s(T)$ is the 'partition function' of the reaction coordinate; $Q^\ddagger(T)$ is the internal partition function associated with the electronic degrees of freedom of $\mathrm{AB}^\ddagger$ and the $(3N_\mathrm{AB} - 4)$ vibrational-rotational degrees of freedom after removing the reaction coordinate and three coordinates for overall translation; $\Phi_\mathrm{rel}(T)$ is the partition function per unit volume for relative translation of A and B; $Q^\mathrm{A}(T)$ and $Q^\mathrm{B}(T)$ are the internal partition functions of A and B, respectively, associated in each case with their electronic degrees of freedom and their $3N_\mathrm{A} - 3$ or $3N_\mathrm{B} - 3$ vibrational-rotational degrees of freedom; and $\Phi^\mathrm{R}(T)$ is the total partition function per unit volume of reactants, excluding translation of their overall (joint) center of mass. Simple models for the potential along the reaction coordinate lead to various expressions for ν and Q_s but one always finds (in a correct derivation) that

$$\nu Q_s = \frac{k_\mathrm{B}T}{h} \tag{11}$$

where k_B is Boltzmann's constant, and h is Planck's constant. Combining all these considerations one arrives at

$$k(T) = \frac{k_\mathrm{B}T}{h}\frac{Q^\ddagger(T)}{\Phi^\mathrm{R}(T)} \tag{12}$$

Let $V^{\ddagger}$ be the potential energy difference between $AB^{\ddagger}$ and $A + B$. Then it is customary, instead of using a consistent zero of energy for all three partition coefficients, to compute $Q^{\ddagger}(T)$ with the zero of energy at the minimum potential energy of $AB^{\ddagger}$ and $Q^{A}(T)Q^{B}(T)$ with the zero of energy at the minimum potential energy of $A + B$. This changes equation (12) to

$$k(T) = \frac{k_B T}{h} \frac{Q^{\ddagger}(T)}{\Phi^{R}(T)} e^{-V^{\ddagger}/k_B T} \tag{13}$$

Finally one often multiples by a transmission coefficient $\kappa(T)$ that accounts for the fact that not all systems that reach the intermediate $AB^{\ddagger}$ configuration connect to products, leading to $\kappa(T) < 1$, or to account for *tunneling*, leading to $\kappa(T) > 1$. This yields

$$k(T) = \kappa(T) \frac{k_B T}{h} \frac{Q^{\ddagger}(T)}{\Phi^{R}(T)} e^{-V^{\ddagger}/k_B T} \tag{14}$$

The conventional theory is completed by equating $AB^{\ddagger}$ to a saddle point on the potential surface between $A + B$ and $C + D$ and by equating s to the imaginary-frequency normal mode of the *saddle point*. The appropriate saddle point is the highest-energy point on the lowest-energy path from reactants to products.

The conventional treatment raises a number of interesting questions: (i) what is the precise meaning of $AB^{\ddagger}$ being in equilibrium with A and B, even though a reaction is occurring, i.e., C and D are not in equilibrium with A and B? (ii) Does this equilibrium assumption require $AB^{\ddagger}$ to have a lifetime longer than the energy relaxation time of the system? (iii) What is the physical interpretation of assuming separability of the reaction coordinate? (iv) Can one improve on equation (11) by a mathematically more rigorous definition of $AB^{\ddagger}$? (v) Is the saddle point the best configuration to identify with the activated complex? Although this article cannot make the answers to all these questions clear, we do think it is important to emphasize that the answers to these questions are all well known, and that the key to understanding these issues properly is a dynamical reformulation of the theory in terms of the classical mechanical one-way flux of phase points through a hypersurface in phase space. We will illustrate this kind of formulation here so the reader may appreciate the basic idea, but we must refer the reader to more specialized works for a rigorous and complete treatment. An introduction suitable for beginners is provided by Pechukas.[3] Most of the more advanced treatments leading to a complete theoretical framework require considerable sophistication, and the reader must piece together the background for the full argument from several papers. In one case, however, Tucker and one of the authors attempted to provide a reasonably self-contained derivation of the modern transition state theory for a NATO Advanced Study Institute, and the interested reader is referred to that article[4] for a more complete and self-contained treatment than space permits here. Less mathematical introductions are also available.[5,6] As promised, though, we now proceed with an introduction to the dynamical interpretation of transition state theory.

Assume that the $A + B$ system is in the ground electronic state and that the Born–Oppenheimer approximation is valid so that the system motion reduces to $N_A + N_B$ atoms moving on a single potential energy surface. The phase space of the $A + B$ system, excluding overall translation, has $6(N_{AB} - 1)$ degrees of freedom. We identify a reactant region $\mathcal{R}$ of phase space and a product region $\mathcal{P}$, and we consider a $[6(N_{AB} - 1) - 1]$-dimensional hypersurface $\mathcal{D}$ that divides $\mathcal{R}$ from $\mathcal{P}$. (This hypersurface is usually called a 'dividing surface' or a 'generalized transition state.' The conventional transition state is a particular case of this dividing surface that passes through the saddle point.)

Let $\mathcal{D}$ be a function of coordinates only, so a point in $\mathcal{D}$ is specified by $[3(N_{AB} - 1) - 1]$ coordinates and $3(N_{AB} - 1)$ momenta. Identify the missing coordinate as the reaction coordinate s (so s becomes a coordinate normal to the hypersurface), and identify the momentum conjugate to s as p_s. Let C denote the $[6(N_{AB} - 1) - 2]$-dimensional hyperface in $\mathcal{D}$ in which $p_s = 0$. Assume that the $\mathcal{R}$ region of phase space is populated according to a Boltzmann equilibrium distribution; then Liouville's theorem of classical statistical mechanics shows it will evolve into a Boltzmann equilibrium distribution at $\mathcal{D}$ and hence also at C. Consider the one-way flux of this equilibrium ensemble of phase points through $\mathcal{D}$ in the $\mathcal{R} \rightarrow \mathcal{P}$ direction. This flux may be calculated quite generally, and using this calculation plus equation (2) yields

$$k(T) = \frac{k_B T}{h} \frac{Q^{GT}(T, s)}{\Phi^{R}(T)} e^{-V_P(s)/k_B T} \tag{15}$$

where $Q^{GT}(T, s)$ is formally identical to a partition coefficient for a system (a 'generalized transition state') with $3N - 4$ degrees of freedom (where the 4 is a sum of 3 for overall translation, which is removed, and 1 for s) that is constrained to have s equal to the value that puts the system in a particular dividing surface. The zero of energy for $Q^{GT}(T, s)$ is the minimum energy of systems in the dividing surface; this minimum energy is $V_P(s)$, where P denotes 'on the (reaction) path'.

The previous paragraph only defined s locally as a coordinate normal to the dividing surface. Now we define a reaction path and we identify the signed progress variable along this path as s with $-\infty$, 0, and $+\infty$ corresponding to reactants, saddle point (the highest energy point on the lowest-energy path), and products, respectively. The dividing surfaces are locally transverse to the path where they intersect it. Then if $s = 0$, equation (15) reduces to equation (13). However, if the rate constant is minimized with respect to the value of s at which the dividing surface intersects the reaction path, we obtain the most popular version of VTST;[7] in particular we obtain canonical VTST, which is called CVT, because a system corresponding to a particular temperature is a canonical ensemble. One might also consider optimizing the orientation of the dividing surface, but experience has shown that good accuracy can usually be obtained without this step provided that the dividing surface is normal to the path of steepest descents in normal-mode coordinates (or any other set of isoinertial coordinates).[7]

When TST is applied to a unimolecular reaction, A → C, it is often called RRKM theory.[8] One simply replaces $\Phi^{R}(T)$ by $Q^{A}(T)$. For unimolecular reactions it is customary to consider the rate constant as a function of total energy E rather than temperature. This is called microcanonical TST since an equilibrium ensemble with a fixed total energy is called a microcanonical ensemble. The microcanonical generalized TST rate is

$$k(E) = \frac{N(E, s)}{h\rho^{R}(E)} \tag{16}$$

for A → C and

$$k(E) = \frac{N(E,s)}{h\phi^{\mathrm{R}}(E)} \tag{17}$$

for A + B → C + D, where $\rho^{\mathrm{R}}(E)$ is the density of states per unit energy of A, $\phi^{\mathrm{R}}(E)$ is the density of states per unit energy and volume of A + B, and $N(E,s)$ is the number of levels α of the generalized transition state at s that have energies $\varepsilon_\alpha(s)$ that are less than E. (Note that each level α is weighted by its degeneracy, but we say 'levels' instead of 'quantum states' to avoid the awkward phrase 'states of the transition state' where the word 'state' would be used with two different meanings in the same sentence.) As for canonical ensembles, the best choice of s is the one that minimizes the rate constant. This yields microcanonical VTST, which is called μVT.

Tunneling is typically important whenever the motion that carries the system through the transition state involves significant motion of protium, deuterium, or tritium atoms (and sometimes, but atypically, when it does not). Tunneling is often approximated by fitting $V_{\mathrm{P}}(s)$ to a parabolic barrier shape, and calculating the tunneling probability as one-dimensional motion along s. This is seldom adequate, but fortunately practical multidimensional tunneling approximations are available; these are based on semiclassical estimates of the amount of wave function decay along various reasonable implicit or explicit tunneling paths.[1,4,9]

In principle one can try to account for recrossing of even the variationally optimized transition state, but such attempts are probably best viewed as beyond the purview of TST itself.

3 CONDENSED-PHASE REACTIONS

Although TST was originally formulated for gas-phase reactions, it has also been widely used to study reactions in condensed phases.[5,10,11] In the gas-phase, reaction rate constants are calculated as an average over an ensemble of individual reaction events in which the reacting species are isolated from other molecules in the gas phase. For bimolecular reactions the reaction events are binary collisions of two molecules. For unimolecular reactions the reaction event is the rearrangment or dissociation of bonds in a single energized molecule, and rate constants for the mechanism of activation of the molecule are not explicitly treated in TST but require extensions, as in practical applications of RRKM theory.[8] Reactions in condensed phases are usually treated by following the same approach: the reacting species (denoted as the solute or solutes) are treated as being distinct from the rest of the extended system (denoted solvent), and the rate constants are calculated as an average over an ensemble of individual reaction events. However, because of the close proximity of other molecules in the condensed phase, the reaction energetics and dynamics are different from what the reactants would experience in isolation. Furthermore, the mechanism of encounter of two molecules in a bimolecular reaction can change dramatically from a well-defined collision in the gas phase to a diffusive encounter followed by multiple impacts in a condensed phase. Bimolecular reactions in condensed phases can be limited by the rate of encounter of the solute molecules (e.g., the relative spatial diffusion of the reactants) or by dynamical processes in the encounter complex (e.g., the bond rearrangment or reaction step). Similarly, the mechanism for activation in a unimolecular reaction changes from energy transfer in binary collisions in the gas phase to energy diffusion from a heat bath in condensed phases.

TST for liquid-phase reactions is concerned with kinetics of the encounter complex or the energized solute and does not account for spatial or energy diffusion. The TST rate constant is often a good approximation to the observed liquid-phase rate constant for bimolecular reactions when the activation barrier for rearrangement in the encounter complex is much larger than any activation barrier for diffusion, or for unimolecular reactions when the coupling of the solvent to the solute is sufficiently strong so that energy flow into the solute is not rate limiting. For reactions in and on solids, TST can be used in some cases to study spatial diffusion (see Section 3.2), but as for the liquid phase, energy diffusion is not treated. TST can of course play a critical role or even the dominant role in more complicated treatments that take account of macroscopic spatial diffusion or microscopic energy diffusion, but it is beyond our scope to consider those aspects here. In this section we consider the approaches used to incorporate the effects of both liquid and solid phases in TST.

3.1 Reactions in Liquids

The thermodynamic formulation of TST provides a convenient framework for the introduction of solvation effects into the theory. In this formulation, the conventional TST rate constant for the gas-phase reaction is given by:

$$k_{\mathrm{g}}^{\ddagger}(T) = \frac{k_{\mathrm{B}}T}{h}K_{\mathrm{g}}^{\ddagger,\circ}(T)\exp\left[\frac{-\Delta G_{\mathrm{g}}^{\ddagger,\circ}(T)}{RT}\right] \tag{18}$$

where $\Delta G_{\mathrm{g}}^{\ddagger,\circ}(T)$ is the molar free energy of activation for the gas-phase reaction in the standard state, and $K_{\mathrm{g}}^{\ddagger,\circ}(T)$ is the same as in equation (8). Equation (18) includes the entropic effects arising from the bound-state partition function for the modes that are defined by the conventional transition state dividing surface (i.e., those orthogonal to the reaction path at the saddle point). For liquid-phase reactions the solvent 'dresses' the solute, and in this formulation it changes the free energy of activation. The liquid-phase rate constant is then given by:

$$k_{\mathrm{es}}^{\ddagger}(T) = \frac{k_{\mathrm{B}}T}{h}K_{\mathrm{liq}}^{\ddagger,\circ}(T)\exp\left[\frac{-\Delta G_{\mathrm{es}}^{\ddagger,\circ}(T)}{RT}\right] \tag{19}$$

where $\Delta G_{\mathrm{es}}^{\ddagger,\circ}(T)$ is the equilibrium molar solvation free energy of activation for the liquid-phase reaction in the standard state, and we changed the subscript on $K^{\ddagger,\circ}$ to denote that one uses a different standard state in the liquid, e.g., a one-molar ideal solution instead of a one-atmosphere ideal gas. (Note that we assume ideal liquid-phase standard states, and activity coefficients for the reactants and transition state are all set to unity in this expression.) The liquid-phase free energy of activation now includes not only the effects of the internal modes of the solute but also the effects of the solvent. There is ambiguity about what constitutes conventional TST for a liquid-phase reaction. A large (uncountable) number of local equilibrium geometries exist for the solvent, and likewise a large number of transition states exist for the liquid-phase reaction. Therefore, it is impossible to define a conventional transition state as in the gas phase (i.e., in terms of a single saddle point). In the literature, the thermodynamic formulation of TST is usually employed by correcting the free energy of activation for solvent effects at the conventional gas-phase transition state. Consistent with this, we define the conventional transition state dividing surface for the liquid-phase reaction to be the same as for the gas-phase. Thus the dividing surface is expressed only in terms of the solute modes that are orthogonal to the reaction path at the saddle point. Any effect that moves the optimum dividing surface from the conventional (gas-phase) transition state is then labeled a variational effect.

In this model of the solvent dressing the solute, the free energy of activation can be broken down into a contribution from the free energy of activation of the reaction in the gas-phase (i.e., with the solute molecules in isolation), and a contribution from the difference in free energies of solvation of the transition state and reactants:

$$\Delta G_{\mathrm{es}}^{\ddagger,\circ}(T) = \Delta G_{\mathrm{g}}^{\ddagger,\circ}(T) + \Delta G_{\mathrm{S}}^{\ddagger,\circ}(T) - \Delta G_{\mathrm{S}}^{\mathrm{R},\circ}(T) \qquad (20)$$

where $\Delta G_{\mathrm{S}}^{\ddagger,\circ}(T)$ and $\Delta G_{\mathrm{S}}^{\mathrm{R},\circ}(T)$ are the free energies for solvating the gas-phase transition state and reactants, respectively. Figure 1(a) illustrates the effects of solvation on the energetics of a symmetric gas-phase reaction in which the variational transition states for the gas-phase and liquid-phase reactions are at the saddle point. The illustration is for a case where the free energy of solvation of the reactants is more negative than that for the transition state, leading to an increase of the free energy of activation in going to the liquid. This type of behavior is typical of charge transfer reactions, such as $\mathrm{S_N2}$ reactions, in polar solvents where the charge localization in reactants is greater than for the transition state. In other types of reactions, solvation can lower activation barriers by solvating the transition state more effectively than the reactants. This is typical for reactions in which the electrostatic interactions between the solute and the solvent do not dominate. For some such reactions, the major contribution to the solvation free energy is the energy to create the cavity in the solvent to accommodate the solute. This includes both the change in dispersion interactions upon inserting the solute and also the changes in solvent structure. For reactions with transition states that are more compact than reactants, the free energy of cavitation may be lower for the transition state (less positive), and this effect would lower the free energy of activation in the liquid compared with the gas-phase.

The free energies of solvation for the transition state and reactants are obtained from averages over distributions of solvent molecules that are in equilibrium with the solute with the solute frozen at a fixed configuration. Thus the free energy of activation for the reaction in liquid is labeled as an equilibrium solvation (es) free energy. The assumption of equilibration of the solvent to the solute is consistent with the quasiequilibrium assumption of TST, i.e., that the distribution of reacting systems at the transition state is in equilibrium with reactants. (This, in turn, follows from local equilibrium in reactants.) Breakdown of the quasiequilibrium assumption occurs when the fundamental approximation of TST breaks down, that is, when there are classical recrossings of the dividing surface (because, technically, what we require to be in equilibrium with reactants is the distribution of transition state species that originated at reactants and will proceed directly to products without recrossing the transition state[7]). The proximity of solvent molecules in the vicinity of the transition state can induce recrossing.

The surrounding molecules of the solvent change (dress) the effective force field of the solute, and since the solvation free energy changes with changing geometries of the solute, the geometry of the saddle point of the solvent-averaged interaction potential can differ from the gas-phase one. Therefore, dynamical bottlenecks for the liquid-phase reaction can change from the gas-phase ones, and simply obtaining the solvation free energy at the saddle point, as indicated in equation (20) and illustrated in Figure 1(a), may not be adequate.

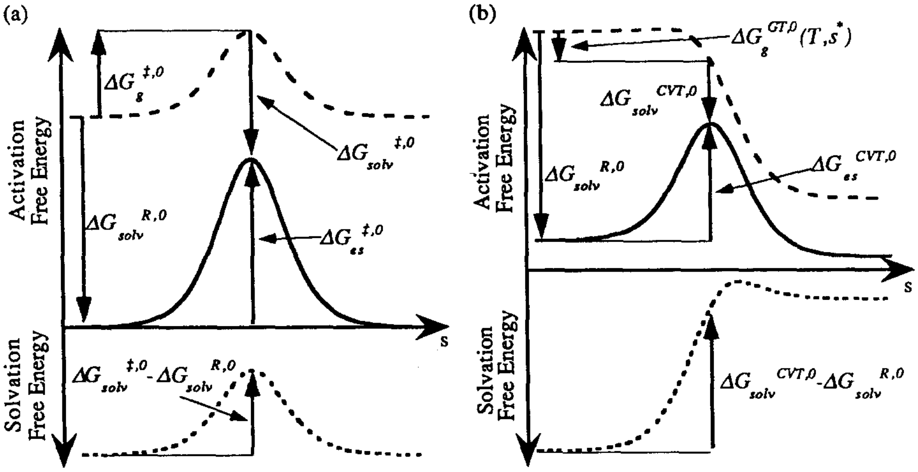


Figure 1 Illustration of equilibrium solvation effects on reaction free energies as a function of the reaction coordinate s: (a) for a symmetric reaction with no variational effects and (b) for a nonsymmetric reaction in which the solvation causes the maximum of the free energy of activation profile to shift. The long-dashed curves are the gas-phase free energy of activation profile, solid curves are the liquid-phase free energy of activation profile, and the short-dashed curves are the solvation free energy of the solute, called ΔG_{S} in the text and ΔG_{solv} in the figure. Free energies depicted in the figures are discussed in the text

Shifts in dynamical bottlenecks due to equilibrium solvation can be accounted for using variational TST. The simplest approximate method to do this is to compute the solvation free energy along the gas-phase reaction coordinate to generate an equilibrium solvation free energy of activation that is a function of the location s of the dividing surface along the reaction path:

$$\Delta G_{\mathrm{es}}^{\mathrm{GT},\circ}(T,s) = \Delta G_{\mathrm{g}}^{\mathrm{GT},\circ}(T,s) + \Delta G_{\mathrm{S}}^{\mathrm{GT},\circ}(T,s) - \Delta G_{\mathrm{S}}^{\mathrm{R},\circ}(T) \quad (21)$$

The optimum location of the dividing surface is where $\Delta G_{\mathrm{es}}^{\mathrm{GT},\circ}(T,s)$ has its maximum, and this is denoted $\Delta G_{\mathrm{es}}^{\mathrm{CVT},\circ}(T)$. The shift of the variational transition state upon solvation is illustrated in Figure 1(b). For this case of an exothermic reaction, the free energy of activation of the gas-phase reaction is negative at the liquid-phase CVT transition state. The solvation of the solute in the region of the transition state is greatly reduced from the solvation of the reactants, thereby leading to a substantial barrier in the liquid-phase reaction where there was a negligible one in the gas-phase.

The simple approach described above assumes that the reaction-path geometries of the solute are not altered appreciably upon solvation. More generally, one could define a multidimensional potential of mean force, $G_{\mathrm{S}}^{\circ}(T,\mathbf{x})$, where $\mathbf{x}$ denotes the collection of solute vibrational coordinates, by

$$G_{\mathrm{S}}^{\circ}(T,\mathbf{x}) = V(\mathbf{x}) + \Delta G_{\mathrm{S}}^{\circ}(T,\mathbf{x}) \quad (22)$$

where $V(\mathbf{x})$ is the solute potential energy function, and $\Delta G_{\mathrm{S}}^{\circ}(T,\mathbf{x})$ is the equilibrium solvation energy. The dimensionality of the free-energy surface is that of the solute. The entire formalism of gas-phase VTST could then be applied, simply replacing $V(\mathbf{x})$ by $G_{\mathrm{S}}^{\circ}(T,\mathbf{x})$. In general one would find that the saddle point of $G_{\mathrm{S}}^{\circ}(T,\mathbf{x})$ does not lie on the gas-phase reaction path.[12] Reoptimization of the saddle point and minimum energy path in the presence of a solvent is much more computationally intensive. To perform the re-optimization requires locating critical geometries and the minimum energy path on the multidimensional potential of mean force, rather than calculating the solvation free energy or potential of mean force as function of a single coordinate.[13]

Whether or not one restricts attention to the gas-phase reaction path, there are several options for calculating $\Delta G_{\mathrm{S}}^{\circ}(T,s)$ or $\Delta G_{\mathrm{S}}^{\circ}(T,\mathbf{x})$. In the simplest approach, the solvation energy is computed for model solute–solvent and solvent-solvent interaction potentials using classical statistical perturbation theory;[14] this assumes that the effects of solvation on the electronic structure and reaction energetics of the solute can be modeled adequately by the solute–solvent interactions of an unpolarized solute. At the next level of complexity, *polarization* of the solute by the solvent as well as the converse can be included using self-consistent reaction field methods, retaining a molecular mechanical solvent[15] or treating the solvent as a three-dimensional dielectric continuum.[16] Either way the interaction of the electronic charge distribution of the solute with the solvent is included directly in the electronic structure calculation. Nonelectrostatic interactions may be based on the solvent-accessible or exposed surface area of the solute.[16] Equilibrium solvation energies are often calculated by performing classical ensemble averages using either Monte Carlo or molecular dynamics methods.[14] When quantum mechanical aspects of equilibrium solvation are important, free energies of activation or potentials of mean force can be calculated quantum mechanically using path integral methods.[17]

Implicit in the equilibrium solvation approach is the assumption that the dividing surface can be defined adequately in terms of just the solute coordinates. Variational transition state theory can account for recrossing effects due to shifts in the location of the equilibrium free energy barriers. In the equilibrium solvation approach the solute molecules evolve in a mean-field potential that neglects dynamical coupling of the solvent and solute coordinates that can also induce recrossings. To go beyond the equilibrium solvation approximation and account for this type of recrossings requires including solvent coordinates in the definition of the transition state dividing surface.[13] Including solvent coordinates in the definition of the dividing surface puts constraints on the averaging over solvent coordinates and therefore implies an ensemble that is different from the ensemble that is in equilibrium with the frozen solute; this effect is sometimes called friction and included in κ.[18–20] This distinction between two types of solvation effects (frictionless effusion over the barrier vs. diffusion with friction) is referred to with different names by different researchers and is variously labeled equilibrium/nonequilibrium, static/dynamic, or adiabatic/nonadiabatic. We use the terms equilibrium and nonequilibrium.

Within a classical mechanical theory, it is possible to carry out the evaluation of the TST rate expression for definitions of the dividing surface that include solvent coordinates.[21,22] Variational *optimization* of the dividing surface within the full space of the system, solute plus solvent coordinates, can mitigate recrossing effects arising from dynamical coupling of the solvent and solute. Full optimization in these extended systems becomes a formidable task, and most often nonequilibrium solvation effects are included by reduced-dimensionality models of the solvent–solute coupling. In these models, the goal is to include collective effects of the solvent that would require including macroscopic numbers of solvent molecules to describe in a molecular system. Examples of these collective effects are nonequilibrium electric polarization in dielectric media and solvent friction.

When dynamical effects of solvent molecules in close proximity to the solute are important (such as in solvent caging), these local solvent molecules can be explicitly included in the definition of the solute, although inclusion of even a few solvent molecules rapidly makes the calculations unwieldy owing to the problem of multiple transition states differing in the solvent coordinates. Treatment of long-range collective solvent effects can often be modeled by effective solvent coordinates. A popular model in the literature describes solvent frictional effects by a collection of harmonic oscillators that are linearly coupled to the solute. In the limit of a continuum of oscillators, the classical dynamics for this model are equivalent to the generalized Langevin equation for solute dynamics.[23] When the solute is treated as a single coordinate (the reaction coordinate) that is coupled to the harmonic bath, application of conventional TST (but allowing the dividing surface at the saddle point to include dependence on the solvent coordinates) yields the Kramers and Grote–Hynes theories.[18,20,24]

Figure 2 illustrates the model of a single effective solvent coordinate for the simple case of a single harmonic oscillator coupled to an Eckart potential. The equilibrium solvation path for this model is obtained by finding the minimum in the potential with respect to the solvent coordinate at each location

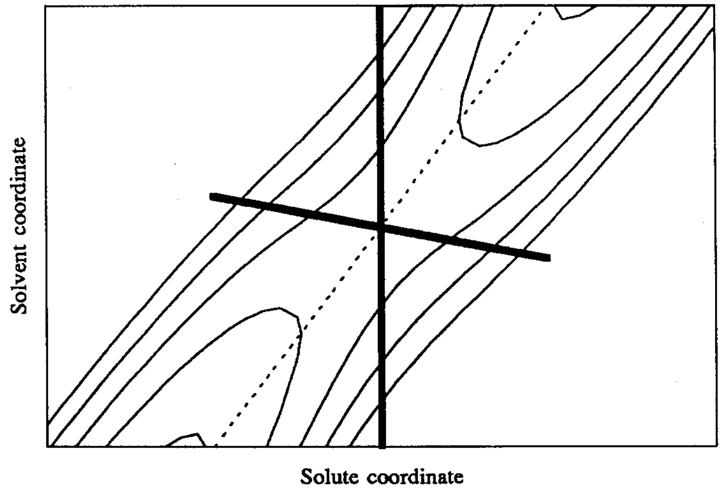


Figure 2 Illustration of nonequilibrium solvation for the simple reaction model of a Eckart potential barrier representing the solute coupled linearly to a single harmonic oscillator representing the solvent. The thin curves are equipotential contours as a function of solute coordinate and solvent coordinate. The dashed line is the equilibrium solvation path for this model. The thick lines are the conventional transition state dividing surfaces for the gas-phase reaction (vertical line that is defined in terms of the solute coordinate only) and for the solution-phase (line that makes a 28° angle with the abscissa)

of the solute coordinate. The equilibrium solvation path and thereby the solution-phase conventional TST dividing surface in the coupled system include substanstial solvent character, whereas the gas-phase conventional TST dividing surface is defined in terms of just the solute coordinate (the heavy vertical line). It is easy to imagine that the solution-phase dividing surface will be recrossed less than the gas-phase one. In fact, for the pictured model, the classical rate constant is lowered by about a factor of 3 by the variational process that includes the solvent coordinates in the dividing surface.

It is easiest to see how to include the solvent effects discussed above when the solvent and solute-solvent coupling are treated using classical mechanics. A classical treatment of the solvent is generally justified based on the argument that most solvents of interest are composed of sufficiently massive particles and characterized by low-frequency modes that are treated adequately by classical mechanics. However, accurate treatment of reaction rates often requires accounting for important quantum mechanical effects such as the rapid polarization of solvent electronic motions, zero-point energies of solute and solvent vibrations, and tunneling, particularly for reactions involving light atoms such as hydrogen. Including quantum mechanical effects in extended systems is a challenge and requires adopting highly approximate approaches.

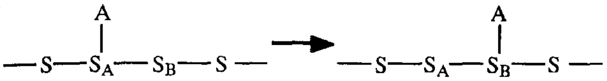
At the crudest level, the free energy of activation for the gas-phase reaction is computed including quantization of bound modes and the solvation free energies are computed thermodynamically. Quantum mechanical tunneling is sometimes included as if it is the same as for the gas phase, but this is often inappropriate since the shape of the barrier to reaction may be completely altered by solvation effects; furthermore, solute-solvent coupling may be quantitatively important for the tunneling probability. This approach also neglects the effect of solvation on molecular vibrations in the solute. Furthermore, the separation of the total system into a solute that is treated quantum mechanically and the solvent that is treated classically precludes including solvent coordinates in the transition state dividing surface. The approach of treating the solvent classically while treating the solute quantum mechanically represents an approximation whose validity is poorly understood for reactions in liquids.

For gas-phase reactions, tunneling contributions are often accurately predicted by calculating the extent of tunneling through the ground-state vibrationally adiabatic barrier when reaction-path curvature coupling is included between the reaction coordinate and vibrational motion.[9] The question arises of what is the best effective potential for calculating tunneling corrections for liquid-phase reactions. A solvent-averaged mean-field potential that is related to the potential of mean force is an appropriate choice.[25] This neglects reaction-path curvature coupling between the solute and solvent modes. These effects can be included in an approximate manner by the nonequilibrium solvation models described above.[13]

3.2 Reactions in and on Solids

The solid phase presents some fundamental differences from liquid and gas phases. First, the effect the solid has on the electronic structure of a sorbate can be profound (e.g., H_2 chemidissociation on metals). Thus new processes may be energetically accessible in solid-state systems that are not important in liquid or gas phases. Second, dynamical processes in solid-state systems can be significantly different from those in liquid or gas phases. The average environment that a solute molecule encounters in gas and liquid phases is translationally invariant. This is not true for the solid with well-defined lattice sites; e.g., the average environment a solute molecule sees near a lattice site is very different from that near an interstitial site. Therefore, diffusion of sorbates in or on a solid can often be treated as isolated jumps between well-defined sorption sites, and the diffusion constant can be approximated from the rate constants for isolated jumps.

The first applications of TST to solid-phase processes were for diffusion of sorbates on and in surfaces using quantum mechanical[26] and classical[27] formulations for the theory. Reviews of these approaches[28] and of more modern TST approaches[29] to surface diffusion are available. Activated diffusion is treated as a unimolecular rearrangement reaction:



$$-\mathrm{S}-\overset{\mathrm{A}}{\underset{|}{\mathrm{S_A}}}-\mathrm{S_B}-\mathrm{S}- \longrightarrow -\mathrm{S}-\mathrm{S_A}-\overset{\mathrm{A}}{\underset{|}{\mathrm{S_B}}}-\mathrm{S}-$$

where A is the sorbate and S denotes a site in or on the solid. In the simplest approximation the solid is treated as being rigid, with the atoms fixed at their lattice positions. In this case the solid acts as a substrate that changes the energetics, and in the language used for liquid-phase reactions, the mean-field (equilibrium) effect of vibrations of the solid (phonons) on the reaction energetics of the solute and the dynamical influence of phonons are neglected. In this case diffusion can be treated using TST in which the sorbate moves in the field of the solid and the conventional TST rate constant for the jump is given by:

$$k^{\ddagger}_{\text{diff}}(T) = \frac{k_B T}{h}\frac{Q^{\ddagger}(T)}{Q^{R}(T)}\exp\left[\frac{-E^{\ddagger}}{k_B T}\right] \tag{23}$$

where, for a sorbate with N atoms, Q^R is the $3N$-dimensional partition function for reactants, $Q^{\ddagger}$ is the $(3N-1)$-dimensional partition function for the transition state (the average is carried out in the $(3N-1)$-dimensional space of the dividing surface), and $E^{\ddagger}$ is the classical barrier height for the diffusion process. Diffusion rates can be obtained by solving the kinetic equations for all the possible hops that can occur. In principle, even for simple solids with just one type of site (e.g., surface diffusion on a 100 surface of a face-centered cubic metal) there will be many types of hops corresponding to movement of the sorbate to different nearby sites. TST approximates the total flux out of a site, but it cannot say whether the adsorbate has moved to the nearest or a farther site. The rate constant for a single hop is approximated by the total flux, and all multiple hops are neglected. With this approximation and for simple cases (e.g., diffusion with just one type of site and jump rate) the diffusion coefficient can be expressed in closed form in terms of the hopping rates,[30] for example

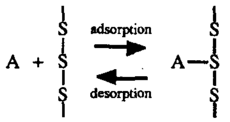
$$D(T) = \frac{a^2}{2\gamma}k_{\text{diff}}(T) \tag{24}$$

where a is the hop length and γ is the dimensionality of the system ($\gamma = 2$ for surface diffusion and $\gamma = 3$ for bulk diffusion).

The approximation of treating the solid as rigid breaks down when the solute molecules (or sorbates) cause relaxation or reconstruction of the solid or when sorbate vibrational modes mix appreciably with the phonon modes of the solid. To include the effects of relaxation of the solid on energetics of the process, the single-hop diffusion can be treated as motion along a one-dimensional reaction coordinate while allowing all other coordinates in the system to relax adiabatically. The rate constant takes on the simple form of an attempt frequency obtained from the one-dimensional model and a Boltzmann factor that is a function of the energy difference between the saddle point and reactants. This approach neglects important changes in frequencies along the reaction coordinate. Vineyard[27] proposed that the attempt frequency be giving from a classical harmonic TST prescription, that is, using an expression similar to equation (23) in which the partition functions include contributions from phonon modes of the solid and are approximated by a classical harmonic prescription.

To go beyond these simple approximations, the solid can be treated as a cluster in which the atoms are allowed to move. To avoid spurious edge effects in the finite-size cluster, either the cluster can be embedded in a large rigid slab of the solid (the embedded cluster model[31]) or periodic boundary conditions can be applied. The moving cluster is treated as a polyatomic molecule in the field of the extended (rigid or periodic) solid system. Once the reaction system is defined to resemble a polyatomic system, VTST can be used similarly to the way it is applied to gas-phase reactions, including the incorporation of important quantum mechanical effects. In the language of liquid-phase reaction rate theory, this approach explicitly includes equilibrium and nonequilibrium effects of the condensed phase for cluster sizes that are large enough to converge the computed rate constant.

Approaches similar to those used for diffusion can also be use to treat adsorption, desorption, and surface reactions. In TST the adsorption process is treated as a bimolecular reaction of a gas-phase molecule with a surface site, and desorption is treated as a unimolecular dissociation:



where A is the sorbate, and one or more S denotes the surface. The areal rate[32] of disappearance of A from the gas phase (the number of A molecules per surface area per time) is equal to the product of the adsorption rate constant k_{abs}, the gas-phase concentration of A in molecules per volume, and the concentration of surface sites in sites per area gives the rate constant in units of volume per site per second. The conventional TST rate constant takes the form:

$$k^{\ddagger}_{\text{abs}}(T) = \frac{k_B(T)}{h}\frac{\overline{Q}^{\ddagger}(T)}{\Phi^{A}(T)\overline{Q}^{S}(T)}\exp\left[\frac{-E^{\ddagger}}{k_B T}\right] \tag{25}$$

where $\overline{Q}^{\ddagger}(T)$ and $\overline{Q}^{S}(T)$ are the partition function per unit area for the transition state and for a surface site, and $E^{\ddagger}$ is the barrier height for the adsorption process. Note that in $\overline{Q}^{\ddagger}$ and $\overline{Q}^{S}$ motion in the plane parallel to the surface is constrained to be in the unit cell of a surface site and is normalized by the surface area. Alternatively, $\overline{Q}^{S}$ and $\overline{Q}^{\ddagger}$ can be defined without the normalization to the area of a surface site (for a rigid surface Q^S equals unity in this case), but the evaluation of the transition state partition function is still accomplished within the unit cell of a surface site.

Mechanisms of solid-phase reactions can be further complicated by the need to include the relative population of the sites. For example, rates of surface adsorption, desorption, and diffusion are generally strong functions of the surface coverage (the number of adsorbates per site on the surface).[33] Most applications of TST to reactions in solid phases consider the infinite dilution case in which the population of occupied sites is infinitesimal. For nonzero populations of occupied sites, the rate constants for processes with unoccupied sites are then assumed to be the same as in the infinite dilution case, and rate constants for processes at occupied sites are assumed to be zero. This approach neglects the effect that nearby sorbates can have on reaction energetics and dynamics. TST can be used to study the effects of nearby sorbates on the rates of processes, but this increases the number of elementary steps that need to be considered; once the kinetic parameters are determined the overall rate can be evaluated using a master equation approach.[34]

A special complication occurs for reactions involving bulk metals, where the *Born–Oppenheimer approximation* breaks down. Nevertheless, one can justify the use of an effective potential function by taking account of the *Pauli Exclusion Principle*.[35]

4 CASE STUDIES

The reaction $H + H'H'' \rightarrow HH' + H''$ and isotopic analogs such as $D + H_2 \rightarrow HD + D$ have played critical roles in the development of the theory chemical kinetics. Recent advances in quantum scattering theory have allowed one to test the assumptions of TST in unprecedented ways, and again the $H + H_2$ and $D + H_2$ reactions provide the prototype cases.

Equation (17) for the rate constant in a microcanonical ensemble makes the startling prediction that the reaction rate increases by discrete amounts as the energy of the system is increased and the number of discrete levels of the quantized transition state that are energetically accessible increases. If this is true one should see steps in $k(E)$ as a function of total energy E. In quantum mechanics these steps are smeared out.[36] This smearing is an intrinsic feature of quantum mechanics and is similar to the intrinsic delocalization of a quantum mechanical harmonic oscillator as compared with a classical harmonic oscillator at rest in its lowest energy state, and it is also associated with an intrinsic width in coordinate space for the wave packets of systems passing through the transition state. (This width in turn accounts for tunneling, by which a system is quantum mechanically delocalized from the reactant side of a barrier to its product side.) The smearing in energy (‘uncertainty’ in energy) of the quantized levels of the transition state may be estimated from the lifetime of these levels (which is the amount of time added to a system’s transit time from reactants to products because of the fact that it is slowed down by converting its energy of motion along the reaction coordinate into the quantized electronic–vibrational–rotational energy requirement of the transition state level). Accurate quantum dynamical calculations[37] on the $H + H_2$ reaction have now shown that the low-lying vibrational levels of the transition state have lifetimes on the order of 5–30 ps, resulting in widths of 60–240 cm^{-1}, which are small enough compared with the average vibrational spacings of $\sim$800 cm^{-1} for low-lying levels that the levels are indeed resolvable. Experimental work lags theory in resolving the transition state spectrum, but efforts are under way to study the quantized transition state effect in photodissociation reactions.

Accurate quantum mechanical calculations[38] on the $D + H_2$ reaction allow one to test the quantitative predictive ability of variational transition state theory with multidimensional tunneling contributions. Such VTST calculations[39] agree with accurate quantum dynamics with an average error of only 13% for all temperatures in the range 167 to 1500 K. Furthermore, because this is the reaction where the potential energy surface[40] is most quantitatively known, we can compare to experiment as well, and the totally *ab initio* prediction based on VTST with multidimensional semiclassical tunneling contributions agrees with experiment with an average error of 20% for 200–1500 K.

The gas-phase reaction $F^-(D_2O) + CH_3Cl \rightarrow Cl^- + CH_3F + D_2O$ provides another illuminating test case for TST. Why is this reaction 54% faster than the corresponding reaction involving H_2O instead of D_2O? TST can provide a quantitative answer, and in the process it shows how using TST to interpret experimental kinetic isotope effects can be a source of great insight. It turns out that the effect is dominated by the contribution to the free energy of activation from the O–D and O–H stretches of the D_2O and H_2O in their hydrogen-bonding modes.[41] Hydrogen bonding lowers the frequency of this mode from 3834 cm^{-1} in H_2O to 2261 cm^{-1} in $F(H_2O)^-$ but to only 3124 cm^{-1} in the transition state, where the hydrogen bond is weaker because of delocalization of 20% of the charge from F^- to CH_3Cl in the transition state. The need to supply an extra 863 cm^{-1} to this mode at the transition state slows down the reaction. For the D_2O case, the frequencies are reduced by $\sim\sqrt{2}$ so one needs to supply only 618 cm^{-1} and the reaction is slowed down less by this mode. The kinetic isotope effect provides a quantitative measure of the extent to which the hydrogen bond is weakened at the transition state. There is no other way to get this information, and no theory other than TST to interpret it.

Finally, we consider a condensed phase example, namely $^{35}Cl^- + CH_3{}^{37}Cl \rightarrow CH_3{}^{35}Cl + {}^{37}Cl^-$ in aqueous solution. Why does this reaction have a 26 kcal mol^{-1} activation energy in solution, when in the gas-phase the barrier to interconversion has a lower energy than reactants? The answer is that the equilibrium free energy of solvation of the transition state is 33 kcal mol^{-1} less negative than the free energy of solvation of reactants.[42,43] Nonequilibrium effects are smaller but have been variously estimated to lower the reaction rates a further 4–57%.[44–46]

5 CONCLUDING REMARKS

TST has served as a useful general interpretative tool for relating reaction rate constants to molecular structure and the features of potential energy surfaces ever since it was placed in its modern form by Eyring[47] in 1935. Two modern extensions, namely the variational optimization of the transition state and the inclusion of multidimensional tunneling effects by semiclassical approximations, allow the theory to provide highly accurate gas-phase rate constants limited more by the uncertainties in the potential energy surface than by the dynamical assumptions underlying the extended TST calculation. Much current research on gas-phase TST is concentrated on improving the reaction path calculation, including anharmonicity, and making the interface with electronic structure theory more convenient and economical. The latter is particularly important for allowing higher levels of electronic structure theory and hence improving the predictive value of the theory.

Condensed-phase TST provides a model for quantitatively estimating reaction rates in solution, but condensed-phase rate processes require new considerations since one must introduce at the outset a statistical mechanical treatment of an essentially infinite number of bath modes of the solvent for liquid-phase reactions or of the phonons and other extended modes for solid-state reactions or reactions at a fluid–solid interface. Considerable current research is focused on the definition of effective solvent coordinates and on determining to what extent the bath modes may be considered equilibrated with the solute or the part of the extended system where reaction actually occurs.

A recent overview of progress ~~is~~ in developing TST as a quantitative tool for gas-phase bimolecular, gas-phase unimolecular, and condensed-phase reactions was presented in the centennial issue of *Journal of Physical Chemistry*.[48]

In addition to its use as a quantitative tool for actual calculations, TST serves an important role in providing a conceptual framework for qualitative discussions. Concepts such as early and late transition states, separation of the energy and entropy of activation, and predicting the effect of substituents or solvent changes on organic reaction rates by comparing their effect at the dynamical bottleneck to their effect on reactants all owe their exceptional predictive power to the existence and validity of an underlying quantitative theory which provides their underpinning. Because of the exciting new possibilities for evolving computational chemistry from an exploratory tool to a quantitative predictive tool, we anticipate that TST will play an even greater role in chemical kinetics in the next 60 years than it did in its first 60.

6 RELATED ARTICLES

Rates of Chemical Reactions; Reaction Path Following; Reaction Path Hamiltonian and its Use for Investigating Reaction Mechanisms; Reactive Scattering of Polyatomic Molecules; Solvation: Modeling; Statistical Adiabatic Channel Models; Unimolecular Reaction Dynamics.

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