The discovery that RNA molecules can act as enzymes (ribozymes) has prompted great interest in the study of the molecular mechanisms of their catalytic action. A prototype reaction for RNA catalysis is the transphosphorylation and hydrolysis of phosphodiester bonds that form the anionic backbone linkage in DNA and RNA.1–6 These systems have been the focus of theoretical studies in the gas phase,7–10 in solution11–17 (including ab initio studies of the nature of associative and dissociative paths18–20), and in enzymatic environments.21–23 Despite tremendous experimental and theoretical effort, the reaction mechanism for phosphodiester transphosphorylation and hydrolysis is not fully understood.

A powerful experimental technique used to probe the mechanistic details of RNA catalysis is the analysis of “thio effects”3,24 i.e., the change in reaction rate that occurs when oxygen atoms are substituted by sulfur at selected positions. Theoretical studies can provide valuable aid in the mechanistic interpretation of thio effect experiments. Hybrid quantum mechanical/molecular mechanical (QM/MM) methods, pioneered by Warshel,25 are particularly powerful tools.26–28 It would be preferable to employ a high-level ab initio quantum model28–31 in QM/MM studies of RNA catalysis; however, reliable simulations of ribozyme-catalyzed reactions require consideration of a large quantum region and extensive configurational sampling that often necessitates the use of more efficient (e.g., semiempirical) quantum models. The study of transphosphorylation thio effects further requires consideration of d-orbitals for P and S atoms to give reasonable transition states and reaction profiles (Supporting Information and Figure 1). An important step toward a detailed understanding of thio effects in ribozymes is to develop quantum models that are sufficiently accurate and efficient to make feasible application to enzymatic systems and to test these models against nonenzymatic reactions in solution that have been well-characterized by experiment and theoretical work that suggests these reactions proceed through a 

**Scheme 1. In-Line Dianionic Mechanism of Transphosphorylation**

![Scheme 1](image)

...
Table 1. Comparison of Thio Effects for the In-Line Dianionic Mechanism of Transphosphorylation in Solution

<table>
<thead>
<tr>
<th>reaction</th>
<th>$r_{TS_{\infty}}$</th>
<th>$r_{TS}$</th>
<th>P</th>
<th>$r_{lim}$</th>
<th>$r_{lim}$ (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>native</td>
<td>10.5</td>
<td>10.1</td>
<td>15.2</td>
<td>-2.8</td>
<td>1.79</td>
</tr>
<tr>
<td>S: $O_{P1}$</td>
<td>9.6</td>
<td>5.3</td>
<td>18.2</td>
<td>1.3</td>
<td>1.76</td>
</tr>
<tr>
<td>S: $O_{P2}$</td>
<td>9.4</td>
<td>5.5</td>
<td>18.1</td>
<td>1.3</td>
<td>1.75</td>
</tr>
<tr>
<td>S: $O_{P1}\cdot O_{P2}$</td>
<td>10.3</td>
<td>1.6</td>
<td>20.0</td>
<td>2.5</td>
<td>1.74</td>
</tr>
<tr>
<td>S: $O_{2}'$</td>
<td>9.4</td>
<td>7.7</td>
<td>12.3</td>
<td>-6.7</td>
<td>1.78</td>
</tr>
<tr>
<td>S: $O_{2}'$</td>
<td>-</td>
<td>-</td>
<td>34.8</td>
<td>14.3</td>
<td>2.26</td>
</tr>
<tr>
<td>S: $O_{3}'$</td>
<td>7.1</td>
<td>-</td>
<td>-</td>
<td>-27.4</td>
<td>2.41</td>
</tr>
</tbody>
</table>

$^a$ Relative free energies (kcal/mol) with respect to reactants at 300 K along the transition state coordinate for the dianionic in-line attack mechanism of sugar-phosphates and sugar-phosphorothioates in solution. Also depicted are the average values for the average $r_1 = P - X_2$ and $r_2 = P - X_3$ distances at the rate-limiting transition state (see text). $^b$ Data for product was taken from last umbrella sampling point along the reaction coordinate.

Figure 2. Plot of the average values of $r_1$ and $r_2$ for each umbrella sampling window. The rate-limiting transition state is labeled by an ‘X’.

3’-thio substitution under basic conditions results in RNA hydrolysis rates that are 2000-fold increased over the pH range 10–14. The present work suggests the equitorial sulfurs have both stabilizing electronic and destabilizing solvation effects on the rate-limiting transition state. The nonbridging $O_{P1}$ and $O_{P2}$ atoms carry the majority of the dianionic charge and are particularly sensitive to substitution of larger sulfur atoms that result in less favorable solvation. The $O_{2}'$ atom carries much less charge, and substitution by sulfur has an overall stabilizing electronic effect.

The stepwise/concerted nature of the reactions and degree of association/dissociation is illustrated in Figure 2. The reactants and products correspond to the upper left and lower right regions of the plot, respectively. An associative pathway is one that proceeds through the lower left region (initial decrease of $P\longrightarrow X_2$), and a dissociative pathway would proceed through the upper right region (initial increase of $P\longrightarrow X_3$). A concerted path proceeds along the diagonal. All of the transphosphorylation reactions in Figure 2 are stepwise associative in nature, regardless of thio substitution. Thio substitution of the nonbridging phosphoryl oxygens results in an increased degree of association relative to the native reaction. The 2’- and 5’-thio substitutions are also associative, but the rate-limiting step is characterized by the formation/cleavage of the $P-O$ bond rather than the $P-S$ bond.

The results presented here provide an important step toward the development and application of new hybrid QM/MM methods that, combined with experiment, may provide a detailed picture of the molecular mechanisms of RNA catalysis.

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Supporting Information Available: Computational methodology and validation of MNDO Hamiltonian (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References


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