Quantum dynamics scattering study of AB+CDE reactions: A seven-dimensional treatment for the $\text{H}_2+\text{C}_2\text{H}$ reaction

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Abstract

A time-dependent wave-packet approach is presented for the quantum dynamics study of the AB+CDE reaction system for zero total angular momentum. A seven-degree-of-freedom calculation is employed to study the chemical reaction of H$_2$+C$_2$H $\rightarrow$ H + C$_2$H$_2$ by treating C$_2$H as a linear molecule. Initial state selected reaction probabilities are presented for various initial ro-vibrational states. This study shows that vibrational excitation of H$_2$ enhances the reaction probability, whereas the excitation of C$_2$H has only a small effect on the reactivity. An integral cross section is also reported for the initial ground states of H$_2$ and C$_2$H. The theoretical and experimental results agree with each other very well when the calculated seven dimensional results are adjusted to account for the lower transition state barrier heights found in recent ab initio calculations.

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INTRODUCTION

- Developments of quantum dynamics scattering calculations
  - First quantum dynamics calculation on H+H₂ system\(^a\)
  - First 3D quantum dynamics calculation on H+H₂ in 1976\(^b\)
  - First 6D quantum dynamics calculation on H₂+OH in 1994\(^c\)
- During the past two decades, quantum scattering theories well developed for 3 and 4 atom systems
- Now dynamics calculations compete with experiment in their accuracy
  - H+D₂\(^d\) and F+H₂\(^e\) give the same results as experiments
  - Some properties of H+H₂O, D₂O\(^f\)

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INTRODUCTION

- More than 4 atom systems – quantum dynamics computations still a formidable task.
  - almost all the calculations are reduced dimensional
  - a full dimensional quantum dynamics study for the H+CH$_4^g$
  - no full dimensional quantum dynamics been done on 5 atom systems

- Why study H$_2$+C$_2$H?
  - C$_2$H is one of the most abundant interstellar polyatomic molecules detected$^h$
  - found in Titan and Jupiter's atmospheres$^i$
  - dominant chain carrier to form acetylene
  - hydrocarbon reactions provide disequilibrium species
  - only 4D calculations available for this reaction $^{j,k}$
  - PES of Wang and Bowman$^j$

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THEORETICAL METHODS

- Jacobi coordinates for the reaction AB+CDE

\[ H = -\frac{\hbar^2}{2\mu} \frac{\partial^2}{\partial R^2} + \frac{(\mathbf{J} - \mathbf{j}_{123})^2}{2\mu R^2} + h_{r_1}(r_1) + h_{r_2}(r_2) + h_{r_3}(r_3) + \frac{\mathbf{j}_1^2}{2\mu_1 r_1^2} \]
\[ + \frac{\mathbf{j}_2^2}{2\mu_2 r_2^2} + \frac{\mathbf{j}_3^2}{2\mu_3 r_3^2} + V(R, r_1, r_2, r_3, \theta_1, \theta_2, \theta_3, \phi_1, \phi_2). \]
THEORETICAL METHODS

- 1D vibrational reference Hamiltonians

\[ h_{r_i}(r_i) = -\frac{\hbar^2}{2\mu_i} \frac{\partial^2}{\partial r_i^2} + V_{1D}(r_i), \quad i = 1, 2, 3 \] (2)

- Total angular momentum function of \( \mathbf{j}_{23} = \mathbf{j}_2 + \mathbf{j}_3 \) in BF frame

\[ Y_{j_2j_3}^{j_23\Omega_23}(\hat{r}_2, \hat{r}_3) = \sum_mD_{\Omega_23m}^{j_23}(\chi, \theta_2, \phi_2) \sqrt{\frac{2j_2 + 1}{4\pi}} < j_3m_j_20|j_23m > Y_{j_3m}(\theta_3) \] (3)

- Overall internal angular momentum rotational function of the AB+CDE system, \( \mathbf{j}_{123} = \mathbf{j}_1 + \mathbf{j}_{23} \)

\[ Y_{j_1j_23}^{j_1j_23\Omega_23}(\hat{r}_1, \hat{r}_2, \hat{r}_3) = \sum_{\Omega_23} < j_1K - \Omega_23j_23\Omega_23|j_123K > Y_{j_1K-\Omega_23}(\theta_1, \phi_1) \times Y_{j_2j_3}^{j_23\Omega_23}(\hat{r}_2, \hat{r}_3) \] (4)

- TD wavefunction expanded in terms of the BF rovibrational eigenfunctions

\[ \Psi_{\nu j K}^{JM} = \sum_{n\nu_1\nu_2\nu_3 j_1 j_2 j_3 K} F_{n\nu_1\nu_2\nu_3 j_1 j_2 j_3 K, \nu j K}^{JM}(t) \mu_n^{\nu}(R) \phi_{\nu_1}(r_1) \phi_{\nu_2}(r_2) \phi_{\nu_3}(r_3) \times Y_{j_1j_23j_123}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) \] (5)
THEORETICAL METHODS

- Relationship between the SF rotational basis function $y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}_1', \hat{r}_2', \hat{r}_3')$ and BF rotational function $Y_{j_1j_23j_123K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3)$

$$Y_{j_1j_23j_123K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) = \sum_{L} \sqrt{\frac{2L+1}{2J+1}} <j_{123}KL0|JK> \times y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}_1', \hat{r}_2', \hat{r}_3') \quad (6)$$

- The SF rotational function $y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}_1', \hat{r}_2', \hat{r}_3')$

$$y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}_1', \hat{r}_2', \hat{r}_3') = \sum_{m_jm_1m_2} <j_{123}m_jLM - m_j|JM> \times <j_1m_1j_23m_j - m_1|j_{123}m_j> \times <j_2m_2j_3m_3|j_{23}m_j - m_1> \times y_{j_3}(\hat{r}_3)y_{j_2}(\hat{r}_2)y_{j_1}(\hat{r}_1)y_L(\hat{R}) \quad (7)$$
• Parity operator $\hat{\epsilon}$ on the BF rotational basis function gives

\[
\hat{\epsilon}Y_{j_1j_23j_123K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) = \hat{\epsilon} \sum_{L} \sqrt{\frac{2L + 1}{2J + 1}} < j_{123}KL0|JK > \\
\times y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}'_1, \hat{r}'_2, \hat{r}'_3) \\
= \sum_{L} (-1)^{j_{123}+L+J} < j_{123} - KL0|J - K > \\
\times (-1)^{j_1+j_2+j_3+L} y_{j_1j_23j_123L}^{JM}(\hat{R}', \hat{r}'_1, \hat{r}'_2, \hat{r}'_3) \\
= (-1)^{j_1+j_2+j_3+j_{123}+J} Y_{j_1j_23j_123-K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3)
\]  

(8)

• Parity adapted BF total angular momentum eigenfunction

\[
Y_{j_1j_23j_123K}^{JM\epsilon}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) = \sqrt{\frac{1}{2(1 + \delta_{K0})}} [Y_{j_1j_23j_123K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) \\
+ \epsilon(-1)^{j_1+j_2+j_3+j_{123}+J} Y_{j_1j_23j_123-K}^{JM}(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3)]
\]  

(9)
SEVEN-DIMENSIONAL TREATMENT

- 7D Hamiltonian

\[ H = -\frac{\hbar^2}{2\mu} \frac{\partial^2}{\partial R^2} + \frac{(J - J_{12})^2}{2\mu R^2} + h_{r_1}(r_1) + h_{r_2}(r_2) + h_{r_3}(r_3) + \frac{J_1^2}{2\mu_1 r_1^2} \]

+ \frac{J_2^2}{2\mu_2 r_2^2} + V_{7D}(R, r_1, r_2, r_3, \theta_1, \theta_2, \phi_1) \tag{10} \]

- \( Y^{JM\epsilon}_{j_1 j_2 j_3} K(\hat{R}, \hat{r}_1, \hat{r}_2, \hat{r}_3) \) becomes two angular momentum coupling case

\[ Y^{JM\epsilon}_{j_1 j_2 j_3 K}(\theta_1, \theta_2, \phi_1) = \sqrt{\frac{1}{2(1 + \delta_{K0})}} \left[ Y^{JM}_{j_1 j_2 j_3 K}(\theta_1, \theta_2, \phi_1) + \epsilon(-1)^{j_1+j_2+j_3+J} Y^{JM}_{j_1 j_2 j_3 -K}(\theta_1, \theta_2, \phi_1) \right] \tag{11} \]

- 7D initial wave-packet

\[ \Psi_{n_0 \nu_0 j_0 K_0}(t = 0) = \Phi_k(R) \phi_{\nu_1 j_1 0}(r_1) \phi_{\nu_2 j_2 0}(r_2, r_3) Y^{JM\epsilon}_{j_1 j_2 j_3 j_0 K_0} \tag{12} \]

- \( \phi_{\nu_2 j_2 0}(r_2, r_3) \) is the eigenfunction of the two dimensional vibrational Hamiltonian

\[ H = h_{r_2}(r_2) + h_{r_3}(r_3) + V_{2D}(R = \infty, r_1, r_2, r_3, \theta_1, \theta_2, \theta_3 = 0, \phi_1, \phi_2) \tag{13} \]
SEVEN-DIMENSIONAL TREATMENT

- Split-operator method to propagate the wave packet

\[ \psi^{JM\epsilon}(\mathbf{R}, \mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, t + \Delta) = e^{-iH_0\Delta/2} e^{-i\mathcal{U}\Delta} e^{-iH_0\Delta/2} \psi^{JM\epsilon}(\mathbf{R}, \mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, t) \]  

(14)

- Reference Hamiltonian \( H_0 \) defined as

\[ H_0 = -\frac{\hbar^2}{2\mu} \frac{\partial^2}{\partial R^2} + h_{r_1}(r_1) + h_{r_2}(r_2) + h_{r_3}(r_3) \]  

(15)

- Effective potential operator

\[ U = \frac{(\mathbf{J} - \mathbf{j}_{12})^2}{2\mu R^2} + \frac{\mathbf{j}_1^2}{2\mu_1 r_1^2} + \frac{\mathbf{j}_2^2}{2\mu_2 r_2^2} + V_{TD}(R, r_1, r_2, r_3, \theta_1, \theta_2, \phi_1) \]  

(16)
RESULTS AND DISCUSSION

- Initial state reaction probabilities for $\text{H}_2(\nu_1, j_1=0) + \text{C}_2\text{H}(\nu_2=\nu_3=0, j_2=0)$ → $\text{H} + \text{C}_2\text{H}_2$ as a function of kinetic energy for $J=0$
RESULTS AND DISCUSSION

- Initial state reaction probabilities for $\text{H}_2(\nu_1=0, j_1=0) + \text{C}_2\text{H}(\nu_2, \nu_3, j_2=0) \rightarrow \text{H} + \text{C}_2\text{H}_2$ as a function of kinetic energy for $J=0$
RESULTS AND DISCUSSION

- Initial state reaction probabilities for \( \text{H}_2(\nu_1=0, j_1) + \text{C}_2\text{H}(\nu_2=\nu_3=0, j_2=0) \rightarrow \text{H} + \text{C}_2\text{H}_2 \) as a function of kinetic energy for \( J=0 \)
RESULTS AND DISCUSSION

- Initial state reaction probabilities for $H_2(\nu_1=0, j_1=0) + C_2H(\nu_2=\nu_3=0, j_2) \rightarrow H + C_2H_2$ as a function of kinetic energy for $J=0$
RESULTS AND DISCUSSION

- Integral cross section for the collision of ground state $H_2(\nu_1=0, j_1=0)$ with $C_2H(\nu_2=\nu_3=0, j_2=0)$ as a function of kinetic energy.
RESULTS AND DISCUSSION

• Comparison between present 7D results $k_7D$, rescaled 7D results $k_7D \times e^{2.08/kT}$ and $k_7D \times e^{2.24/kT}$ using barrier height differences between Wang and Bowman's PES and ab initio results, and various experimental results.

\[ k \propto \text{exp}(2.24/kT) \]

\[ k \propto \text{exp}(2.08/kT) \]

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CONCLUSIONS and FUTURE WORK

• Conclusions
  
  – vibrational excitation of H₂ molecule enhances the reaction probabilities; while the vibrational excitation of C₂H doesn't change the reactivity much
  
  – ground rotational state of H₂ gives the largest probability; \( j_2 = 1 \) initial rotational state of C₂H gives the largest probability
  
  – Both the 7D quantum calculation results and the \textit{ab initio} studies indicate the current barrier height of Wang and Bowman's PES is too large

• Future work
  
  – Extend the current 7D calculation to full-9D calculation
  
  – Extend the AB+CDE calculation to A+BCDE calculation