Ionization and fragmentation of water molecules in ion-H_2O collisions.

Luis Méndez

Universidad Autónoma de Madrid

October 2014

Contents

Motivation

- Primary processes in **IBCT**.
- Production of electrons and ions.
- Atomic data (cross sections) needed in simulations.

Proton – molecule collisions

Primary processes

- **Single Electron Capture (SEC):** $H^+ + M \rightarrow H + M^+$
- **Single Ionization (SI):** $H^+ + M \rightarrow H^+ + M^+ + e^-$
- **Transfer Ionization (TI):** $H^+ + M \rightarrow H + M^{2+} + e^-$
- **Double Ionization (DI):** $H^+ + M \rightarrow H^+ + M^{2+} + 2e^-$

Molecular fragmentation

The cations M^+ and M^{2+} formed in capture and ionization reactions can dissociate;

e.g., the ions:

$$H_2O^+,\ OH^+,\ O^+,\ O^{2+},\ H^+$$

are detected in ion- H_2O collision experiments.

Proton – molecule collisions

Primary processes

- **Single Electron Capture (SEC):** $H^+ + M \rightarrow H + M^+$
- **Single Ionization (SI):** $H^+ + M \rightarrow H^+ + M^+ + e^-$
- **Transfer Ionization (TI):** $H^+ + M \rightarrow H + M^{2+} + e^-$
- **Double Ionization (DI):** $H^+ + M \rightarrow H^+ + M^{2+} + 2e^-$

Molecular fragmentation

The cations M^+ and M^{2+} formed in capture and ionization reactions can dissociate;

e.g., the ions:

$$H_2O^+,\ OH^+,\ O^+,\ O^{2+},\ H^+$$

are detected in ion- H_2O collision experiments.

Eikonal CTMC method

We consider ion-water collisions (see Illescas *et al.*, Phys. Rev. A **83** (2011))

- Franck- Condon approximation.
- The projectile follows **straight-line trajectories**: $\mathbf{R} = \mathbf{b} + \mathbf{v}t$.
- Independent electron approximation.
- Use of a three-centre model potential to describe the electron – H_2O^+ interaction.
- Electronic motion described by a **classical distribution function** $\rho(\mathbf{r}, \mathbf{p}, t)$.
- Orientation-averaged cross sections.

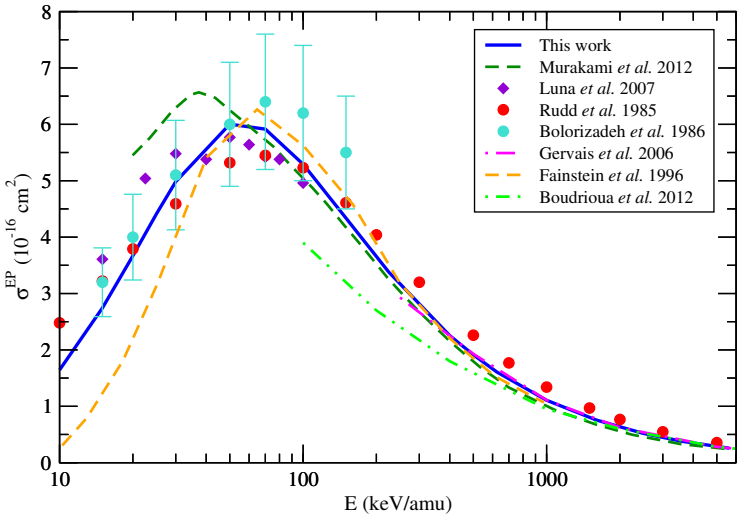
Eikonal CTMC method

We consider ion-water collisions (see Illescas *et al.*, Phys. Rev. A **83** (2011))

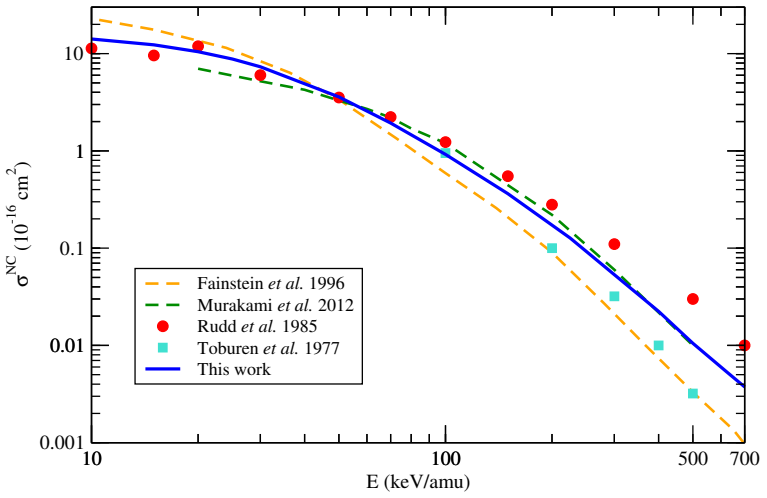
- Franck- Condon approximation.
- The projectile follows **straight-line trajectories**: $\mathbf{R} = \mathbf{b} + \mathbf{v}t$.
- Independent electron approximation.
- Use of a three-centre model potential to describe the electron – H_2O^+ interaction.
- Electronic motion described by a **classical distribution function** $\rho(\mathbf{r}, \mathbf{p}, t)$.
- Orientation-averaged cross sections.

$H^+ + H_2O$ collisions. Total cross sections

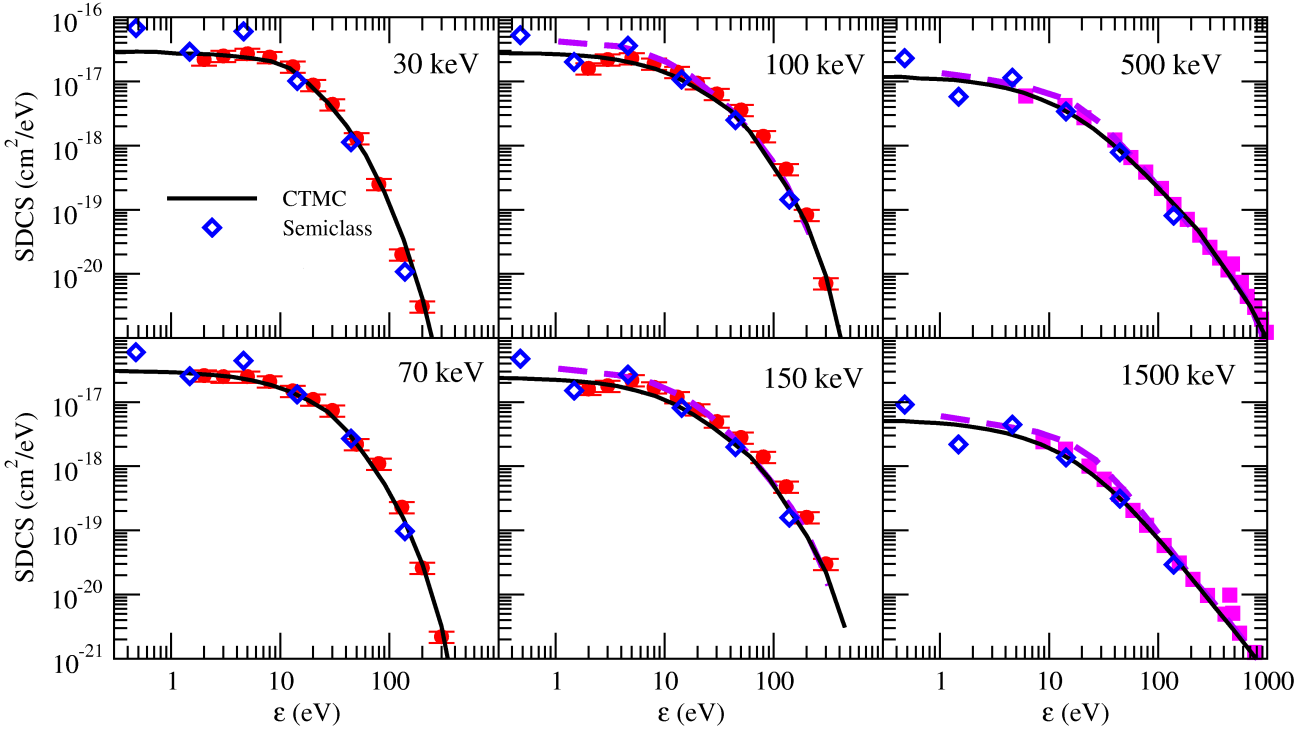
Electron production



Net electron capture



SDCS



- Our calculations: Errea et al. PRA 87, 032709.
- Experiments: Toburen and Wilson, JCP 66, 5202; Rudd et al. PRA, 31, 492.
- Other Calculations: Boudrioua et al. PRA 75, 022720.

Fragmentation cross sections.

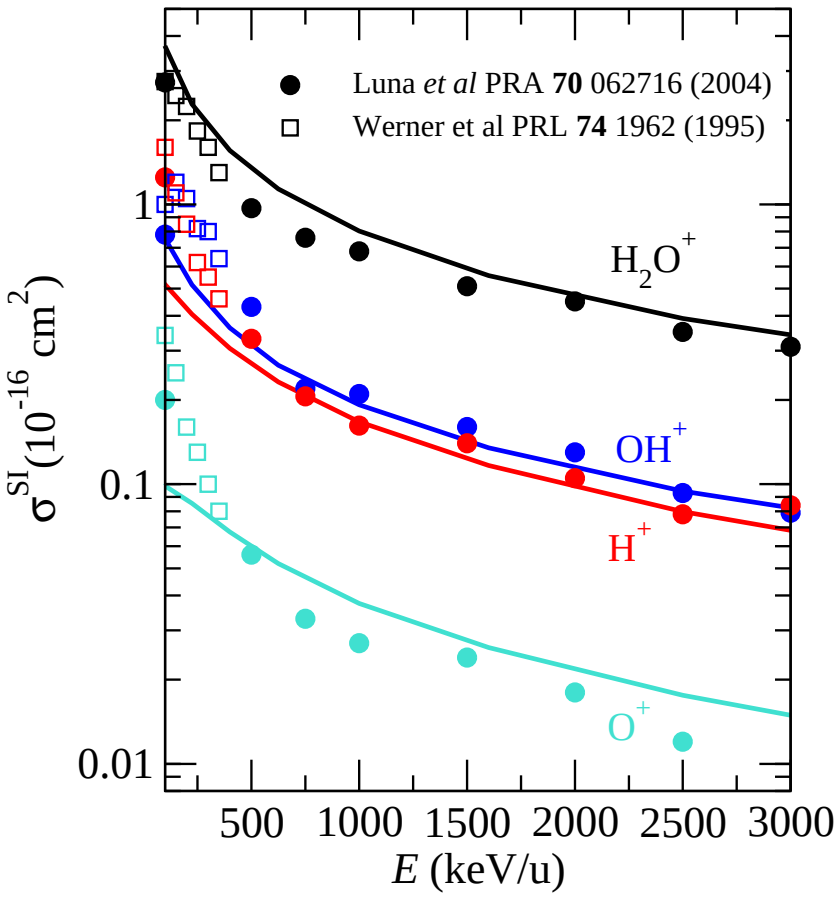
Tan et al. CP 29, 299

$$\sigma^{H_2O^+} = 1.0\ \sigma(1b_1) + 1.0\ \sigma(3a_1) + 0.08\ \sigma(1b_2)$$

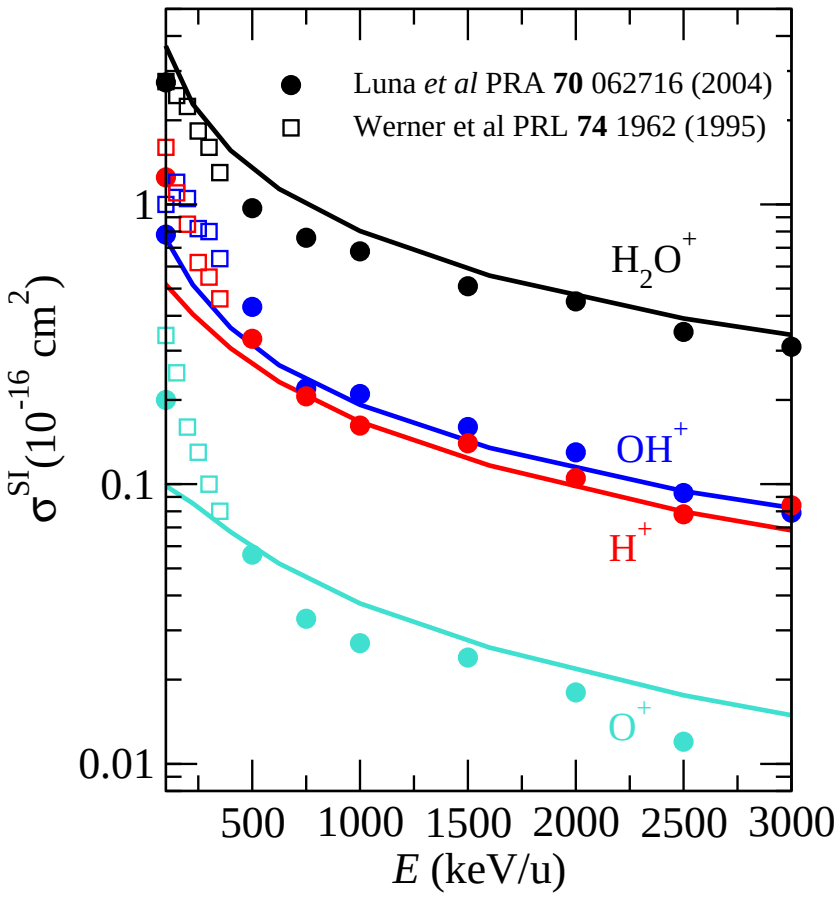
$$\sigma^{OH^+} = 0.7\ \sigma(1b_2)$$

$$\sigma^{H^+} = 0.22\ \sigma(1b_2) + 0.74\ \sigma(2a_1)$$

$$\sigma^{O^+} = 0.26\ \sigma(2a_1)$$

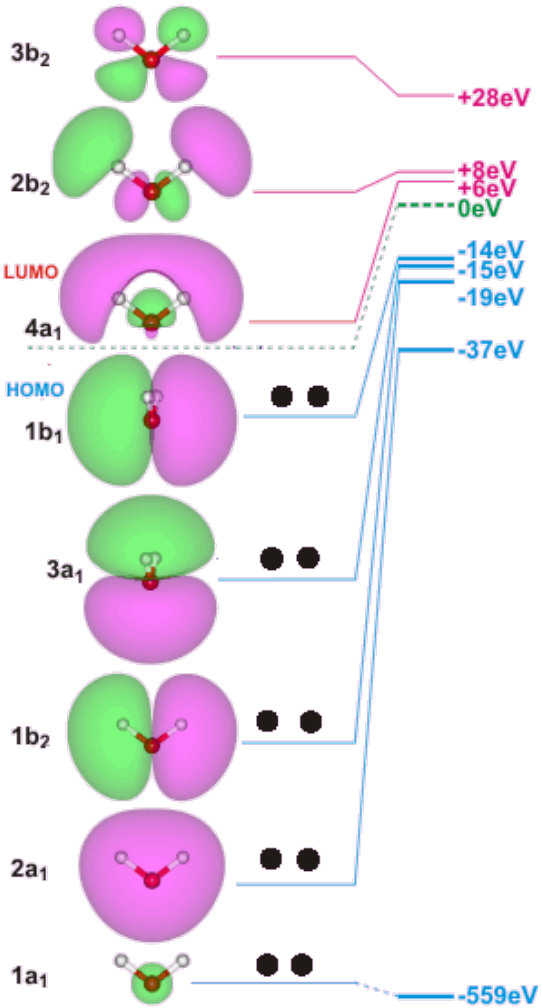


Fragmentation cross sections.

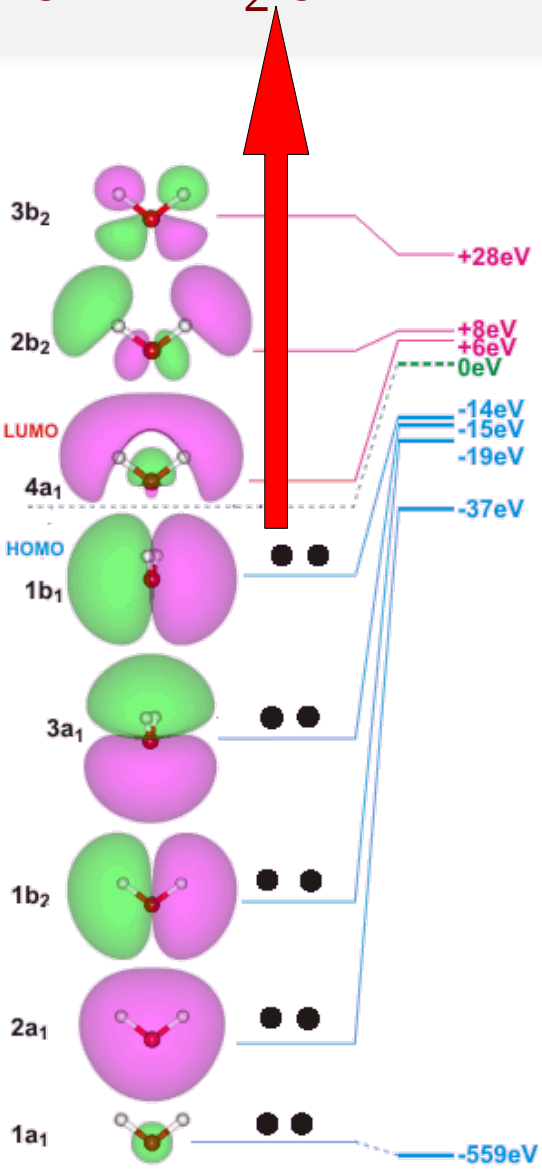


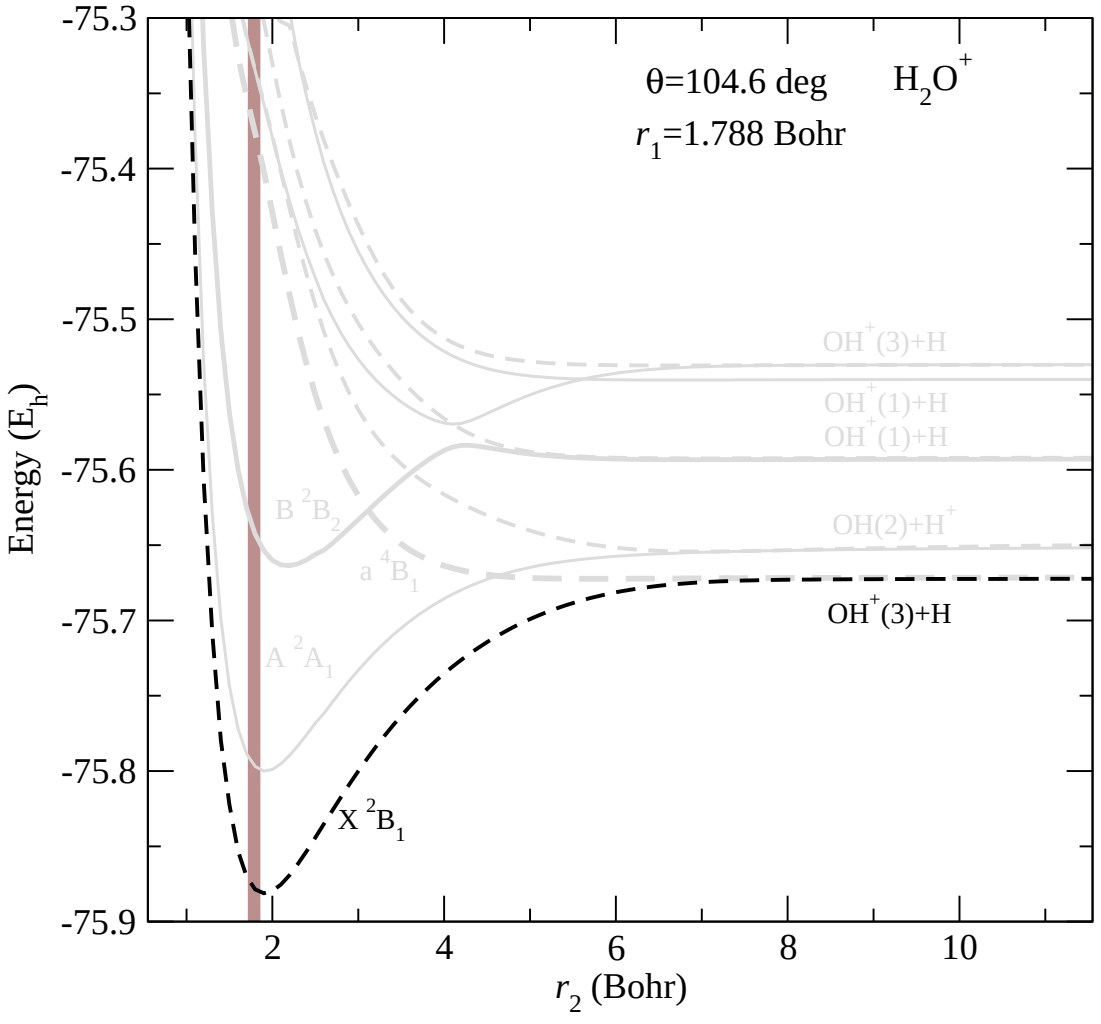
- The dissociation of H_2O^+ is a postcollisional process.
- There is not an *ab initio* study of the H_2O^+ breakdown reaction.

MO of H_2O and H_2O^+ PEC

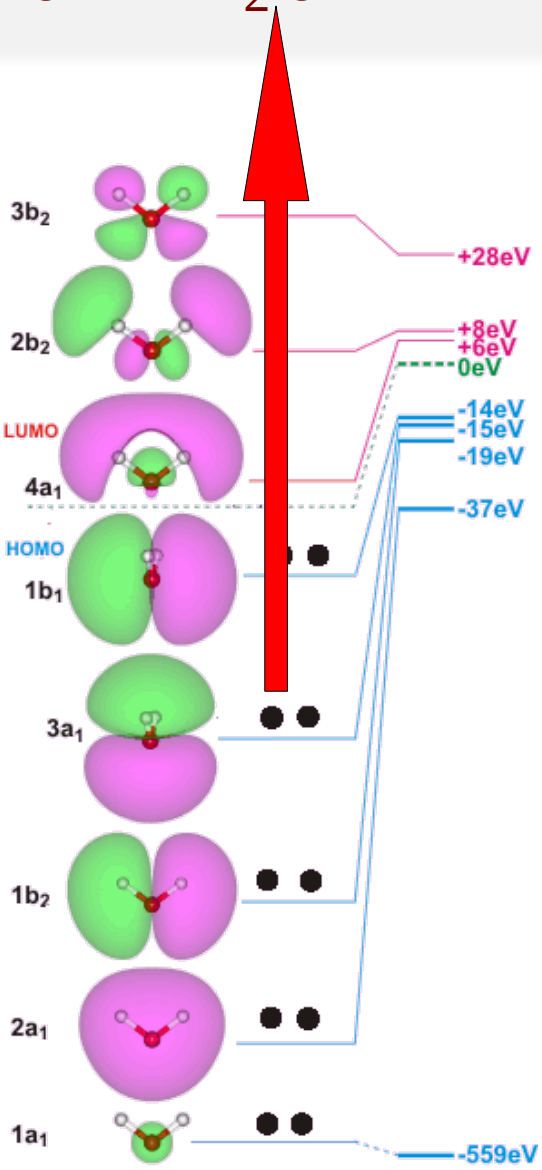


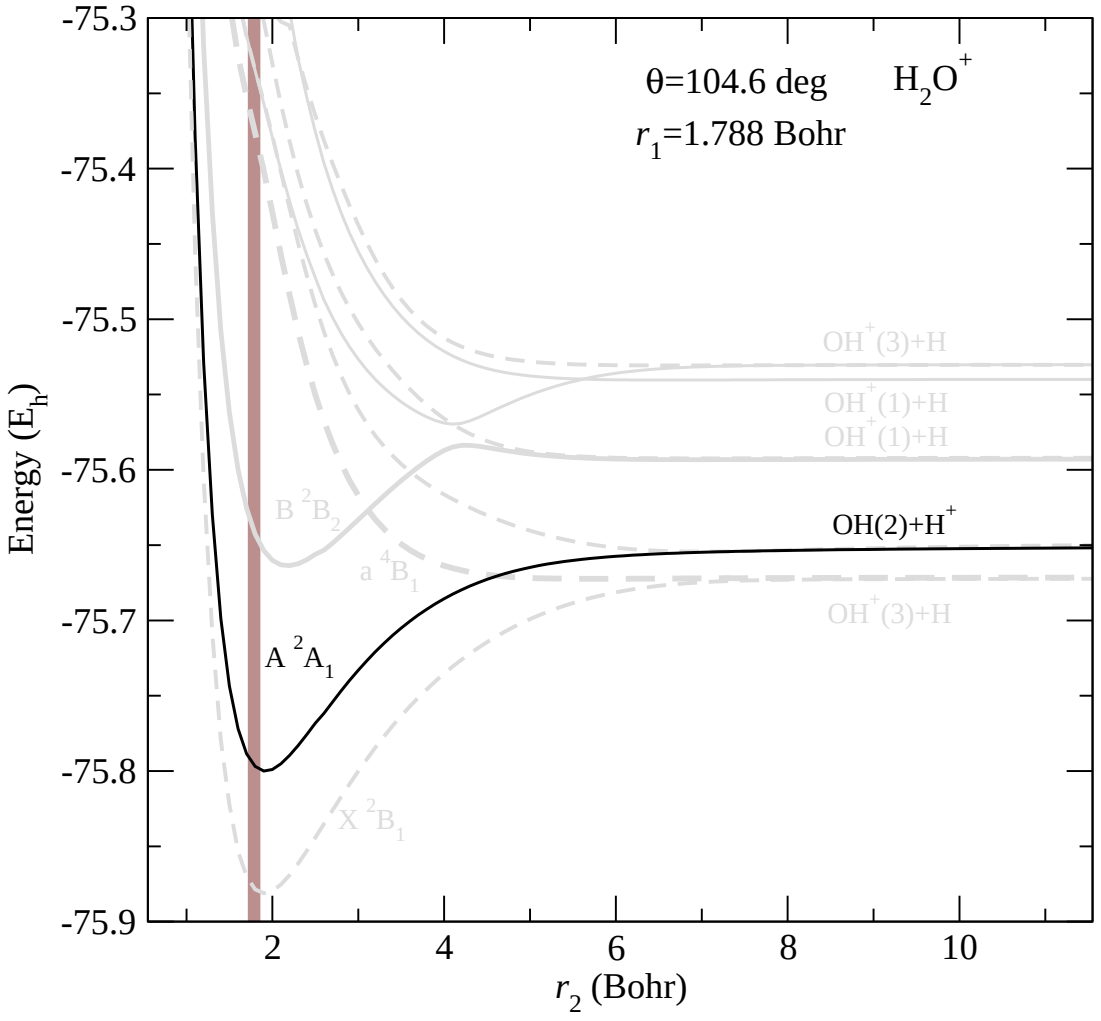
MO of H_2O and H_2O^+ PEC



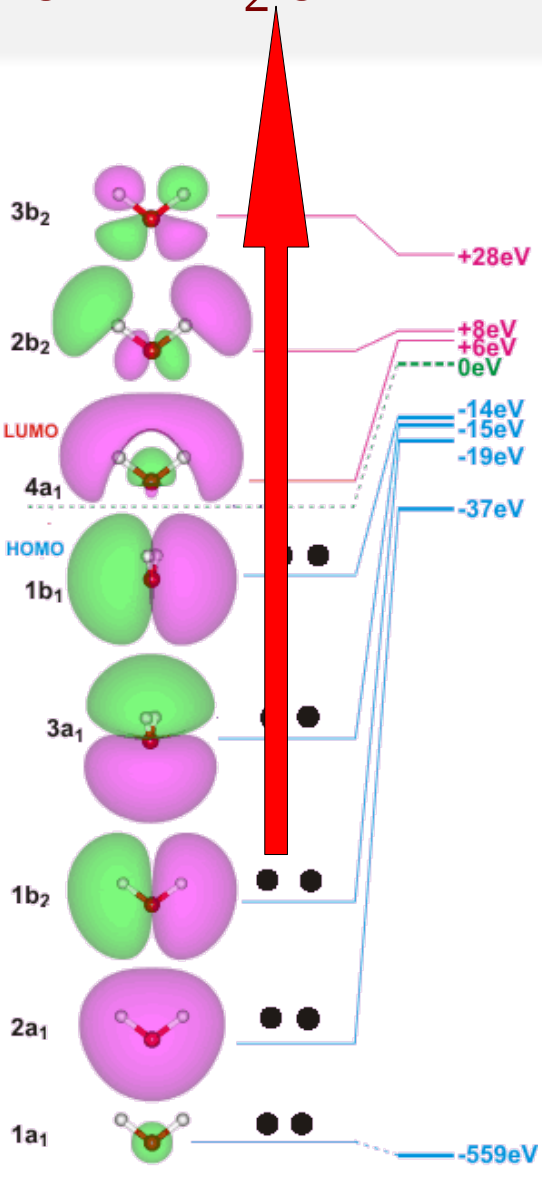


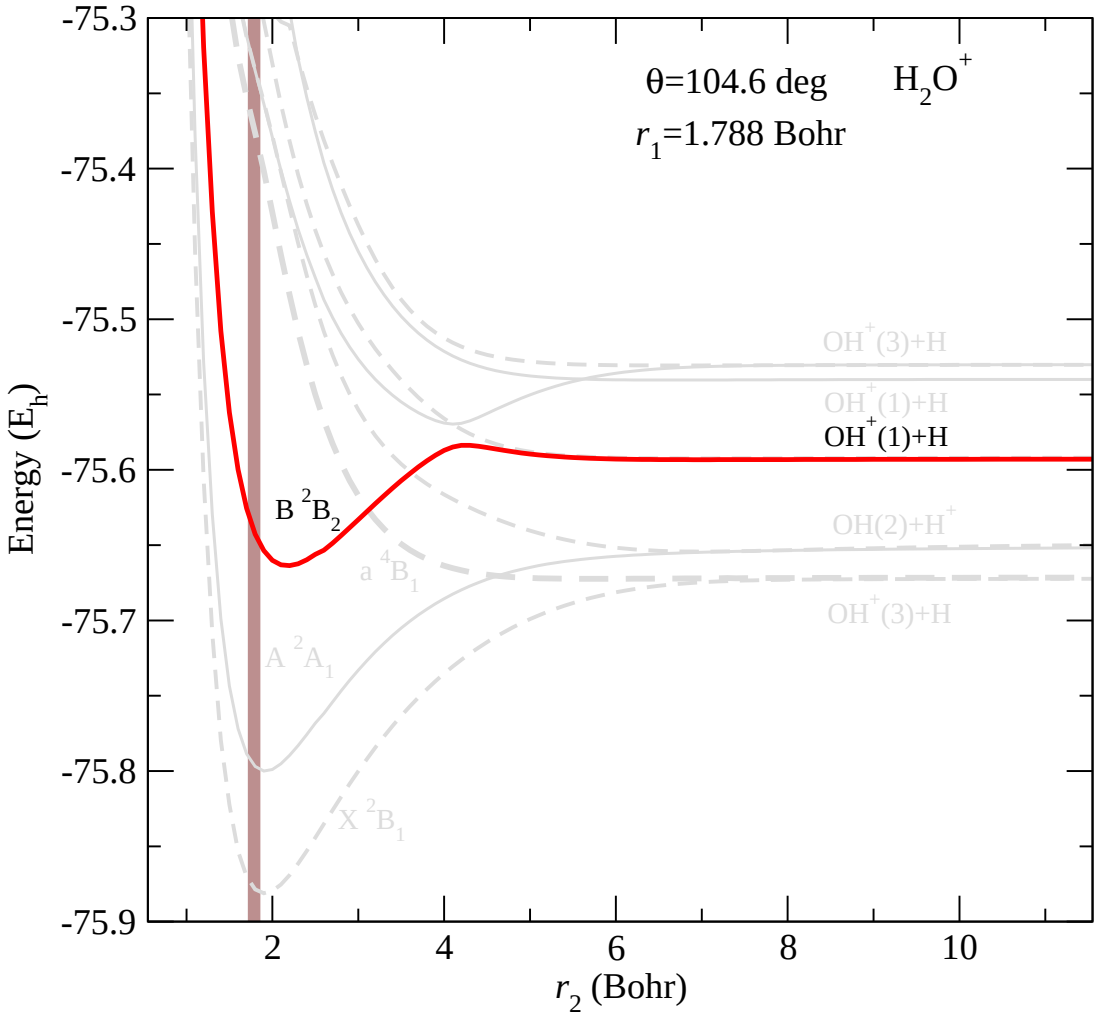
MO of H_2O and H_2O^+ PEC



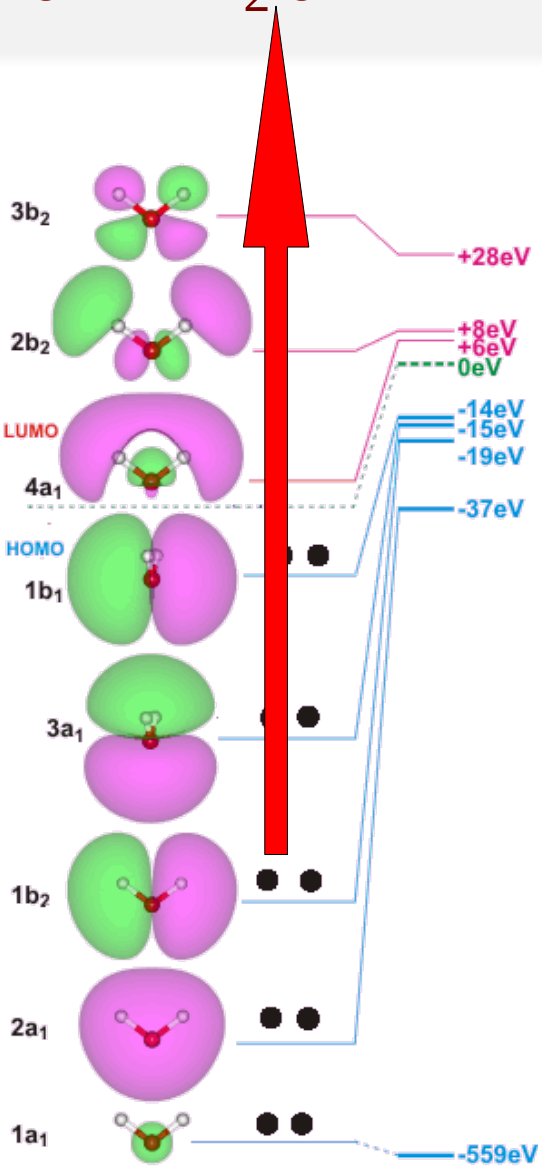


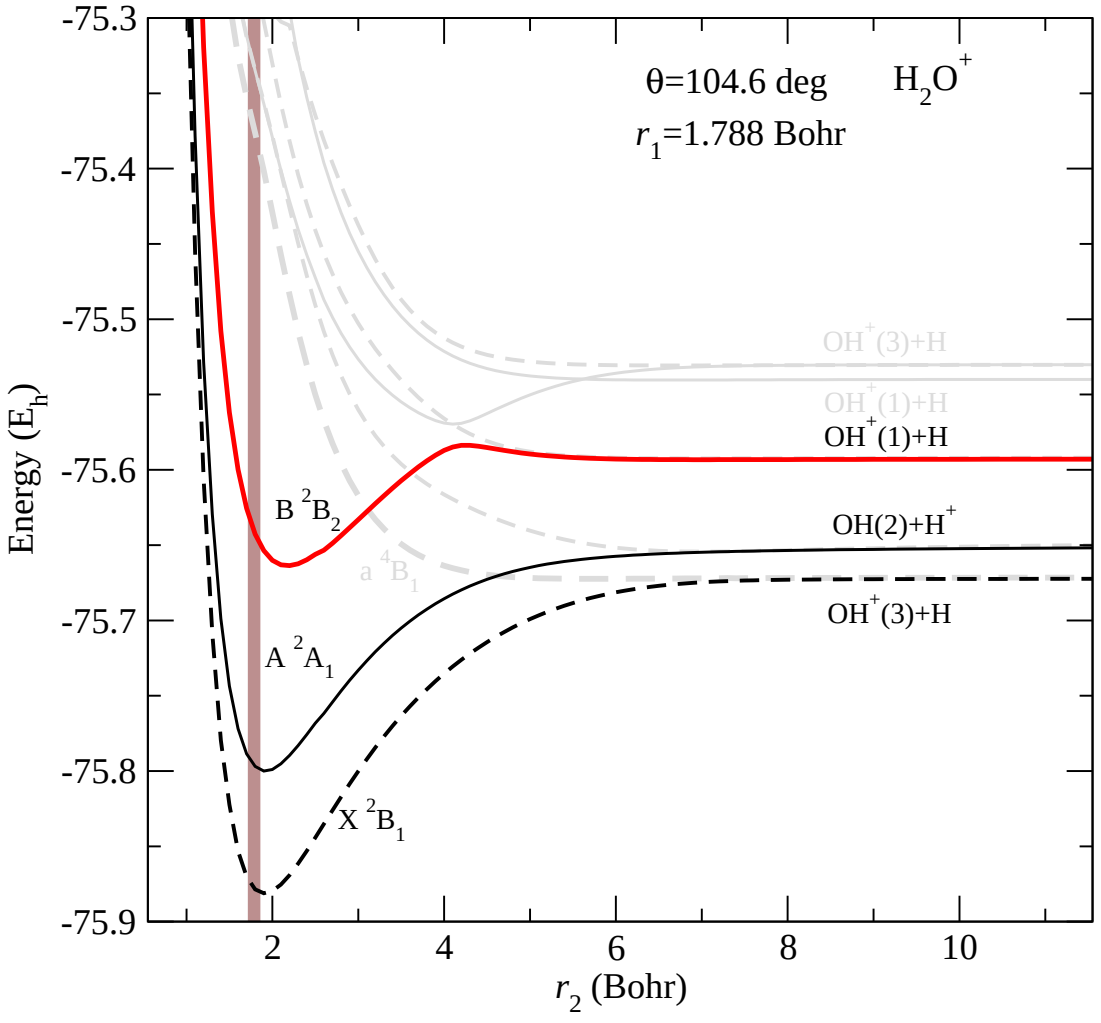
MO of H_2O and H_2O^+ PEC



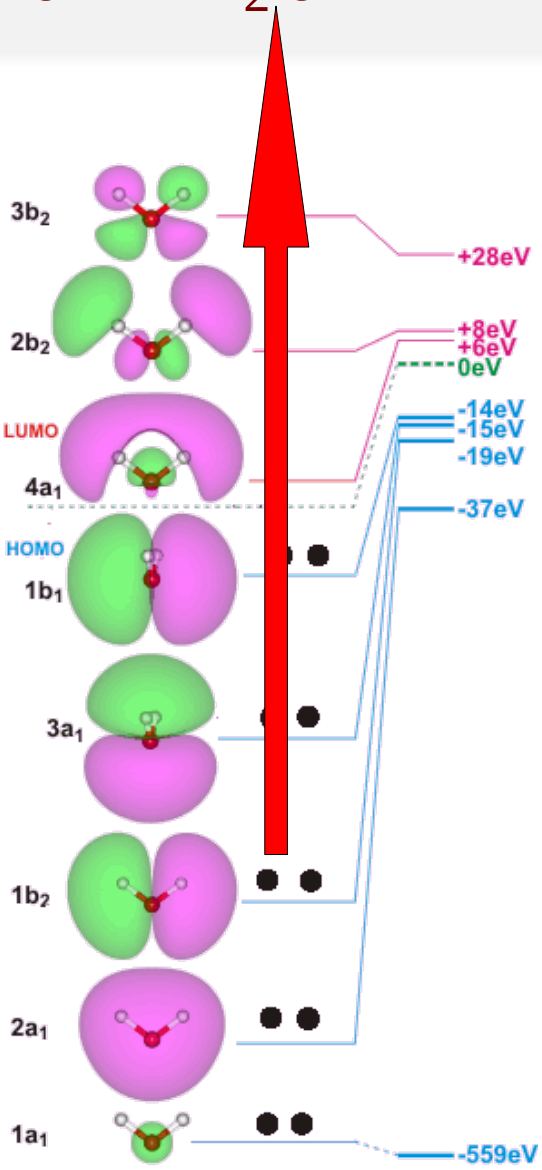


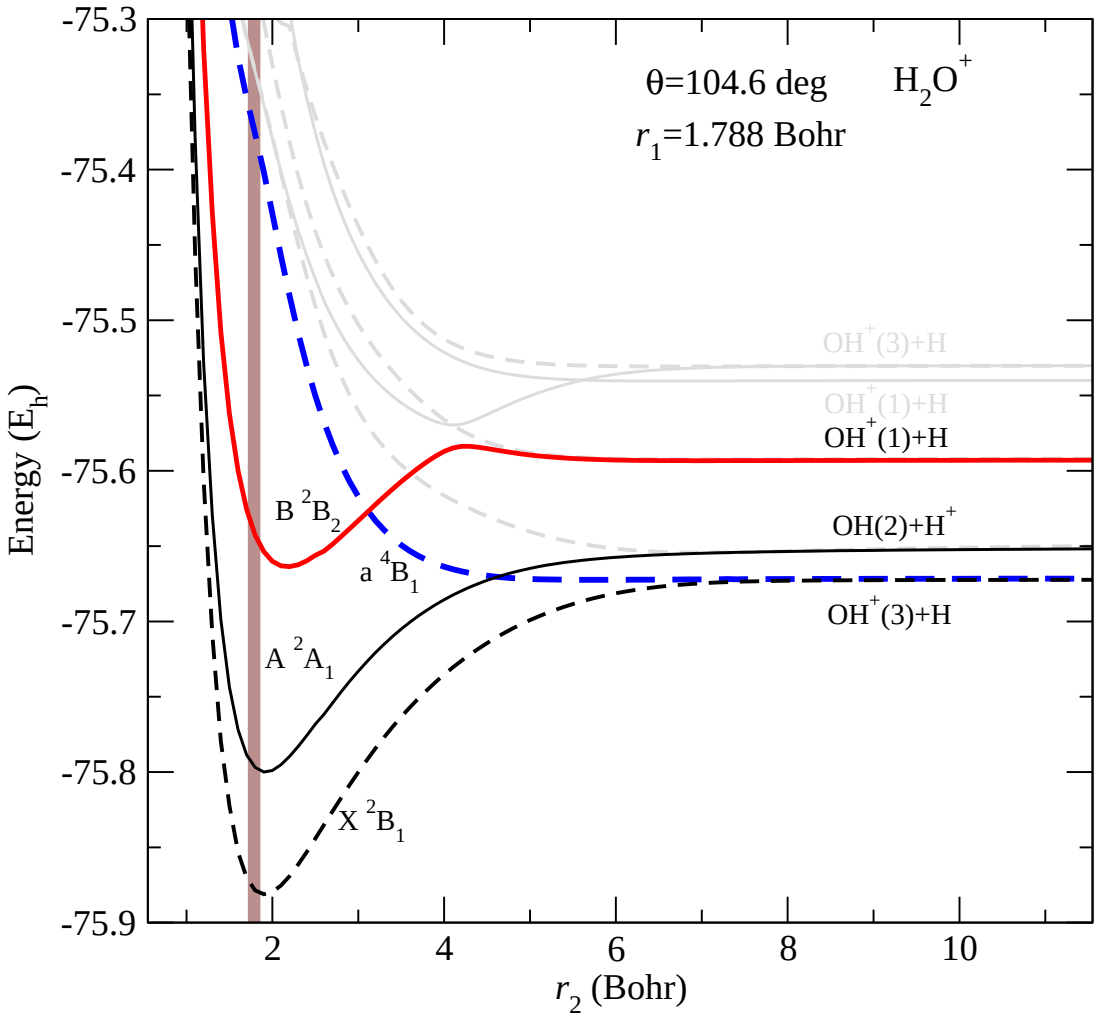
MO of H_2O and H_2O^+ PEC



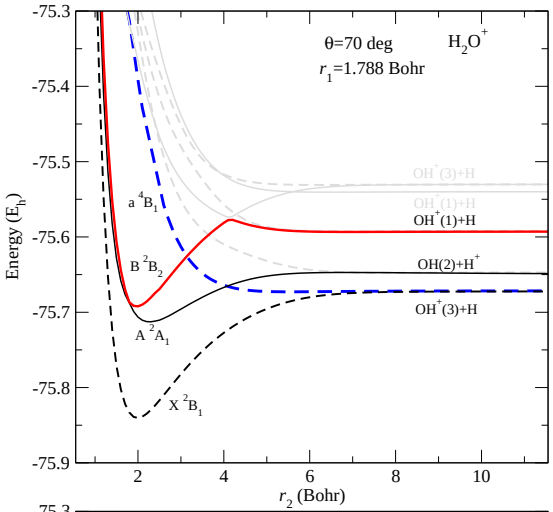


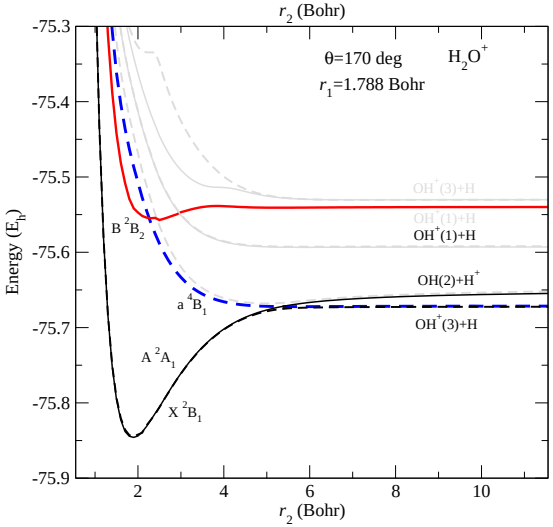
MO of H_2O and H_2O^+ PEC

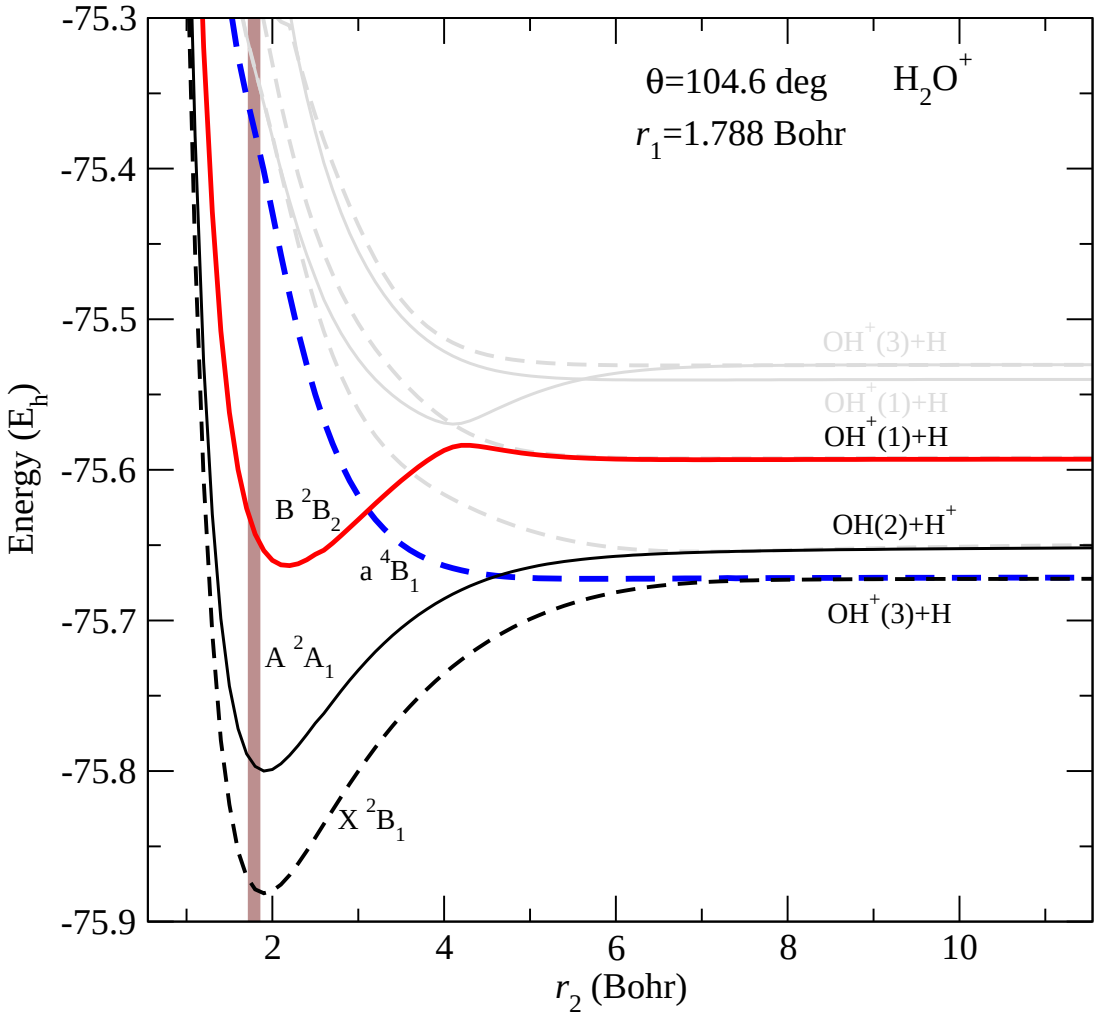




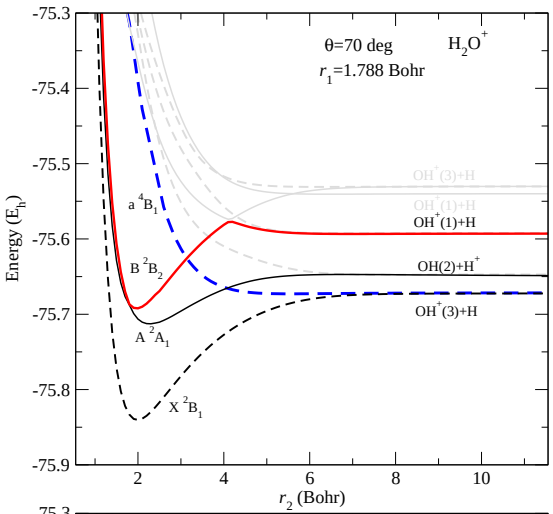
MO of H_2O and H_2O^+ PEC

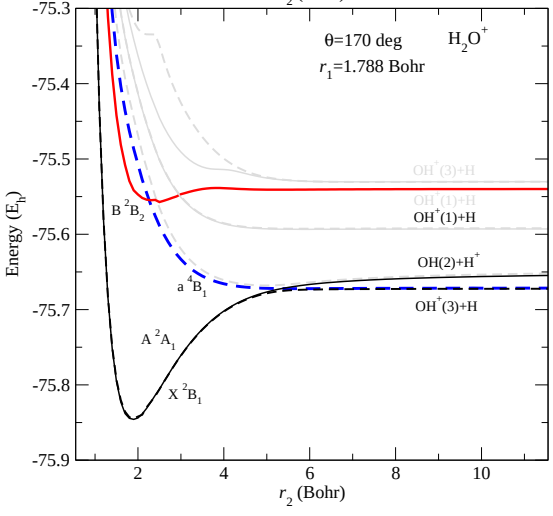


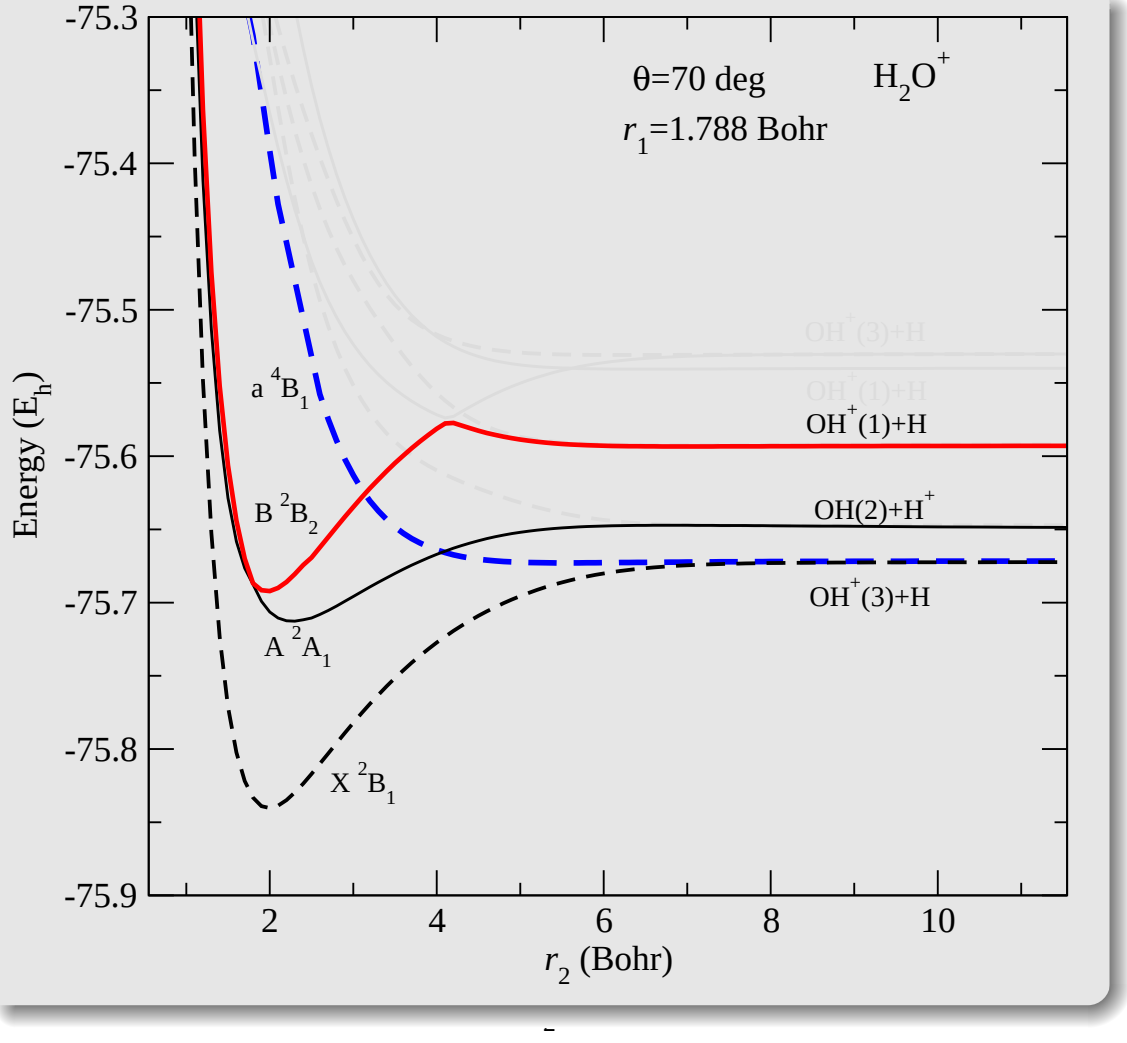




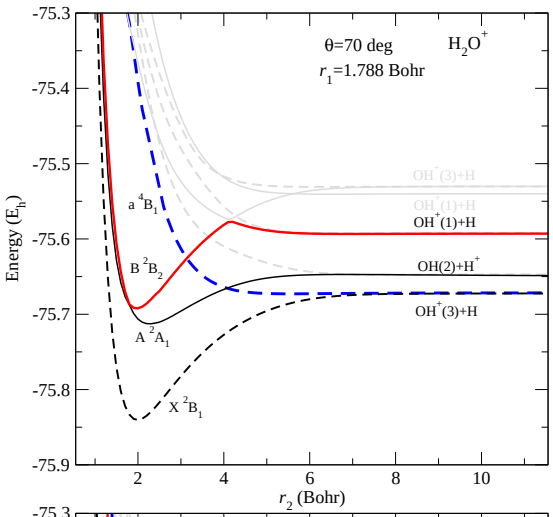
MO of H_2O and H_2O^+ PEC

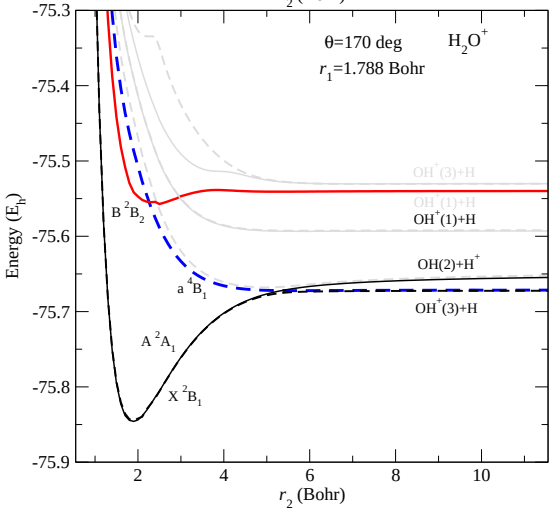


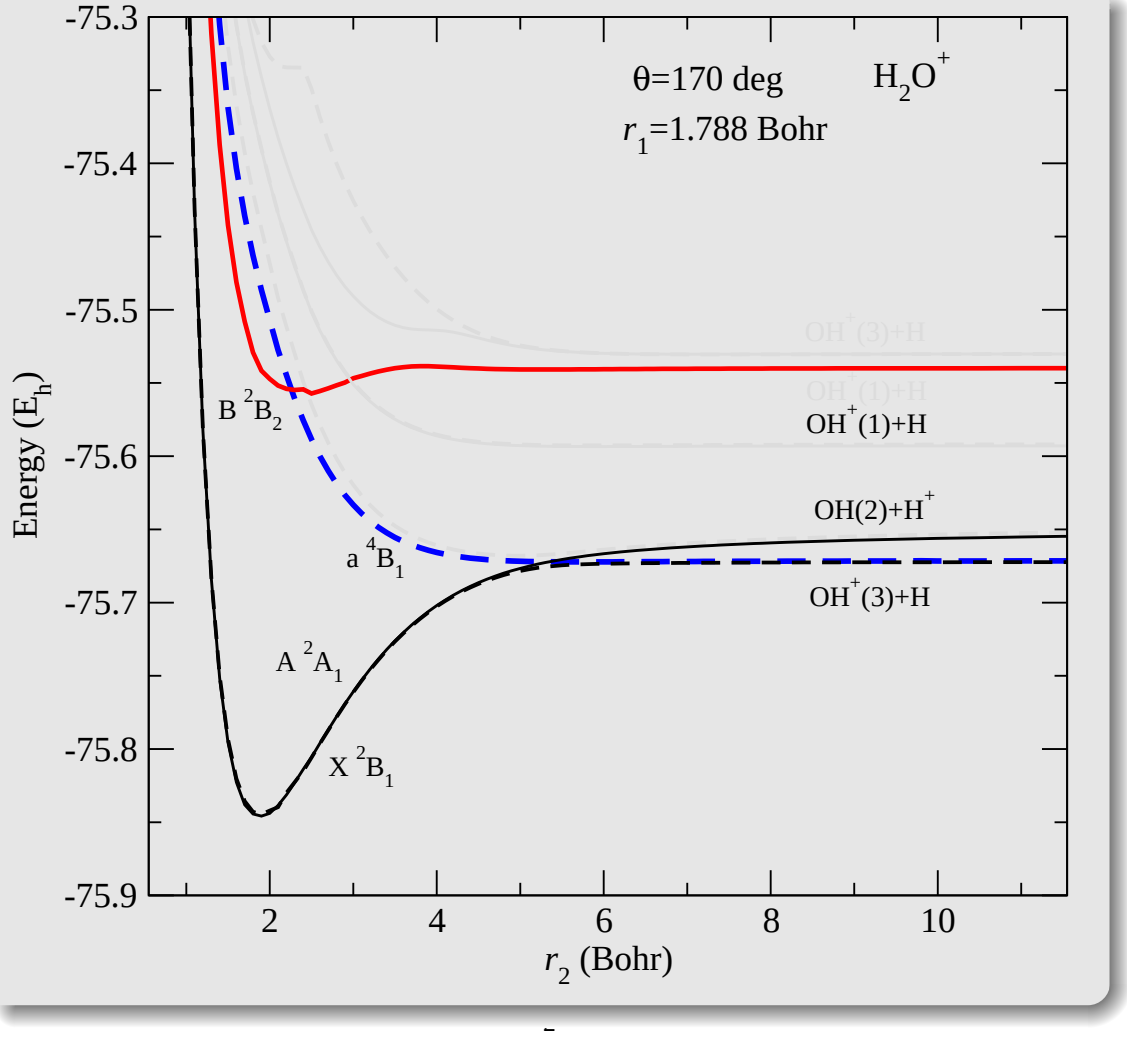




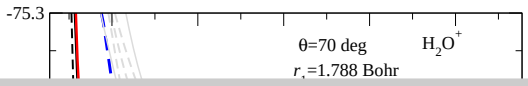
MO of H_2O and H_2O^+ PEC







MO of H_2O and H_2O^+ PEC

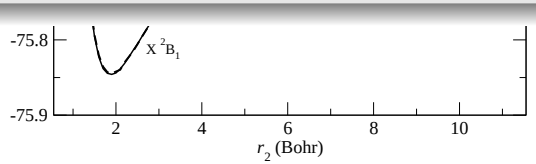


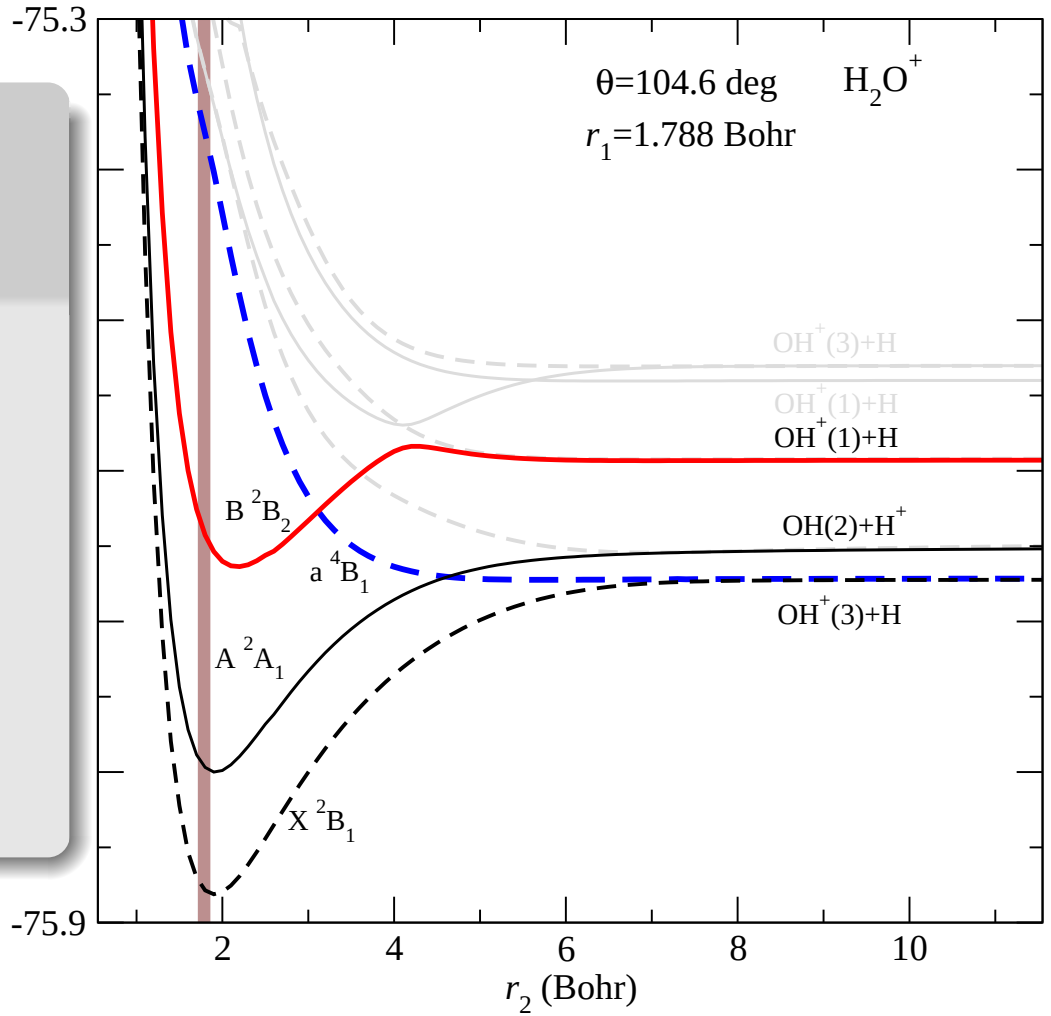
$1b_2$: Tan *et al* CP 29 299 (1978)

$$\sigma^{H_2O^+} = 0.08\ \sigma(1b_2)$$

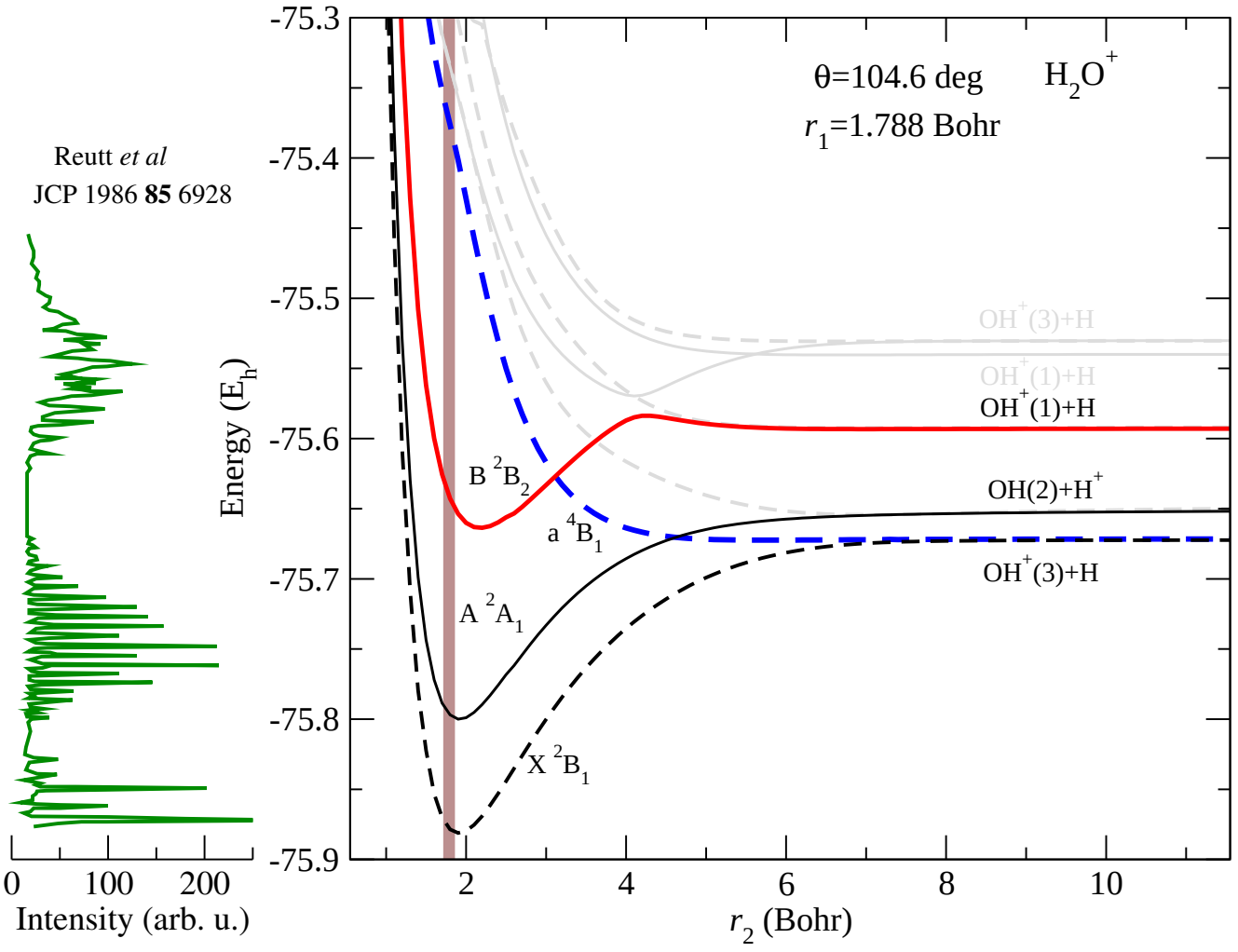
$$\sigma^{H^+} = 0.22\ \sigma(1b_2)$$

$$\sigma^{OH^+} = 0.70\ \sigma(1b_2)$$

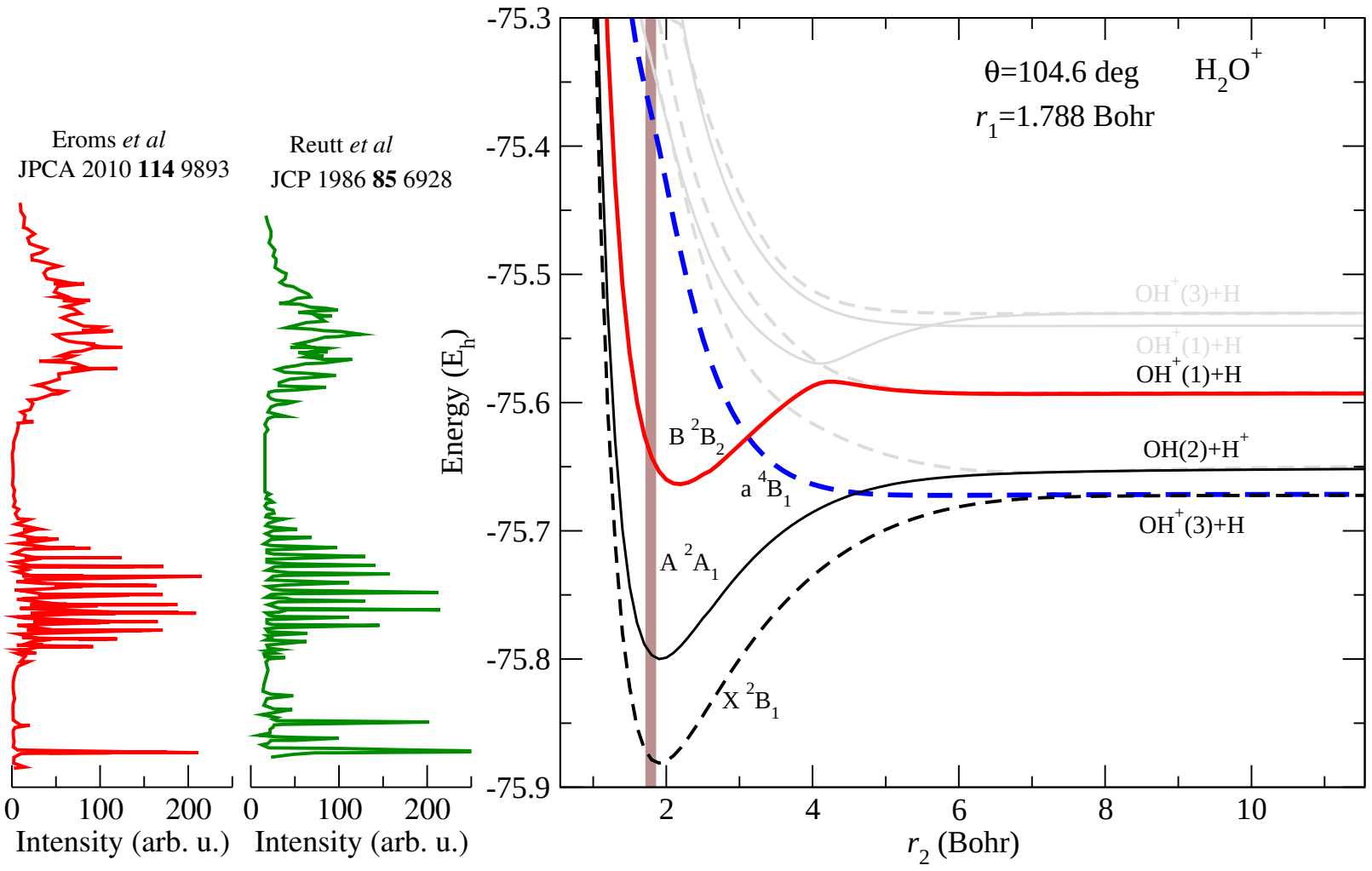




MO of H_2O and H_2O^+ PEC



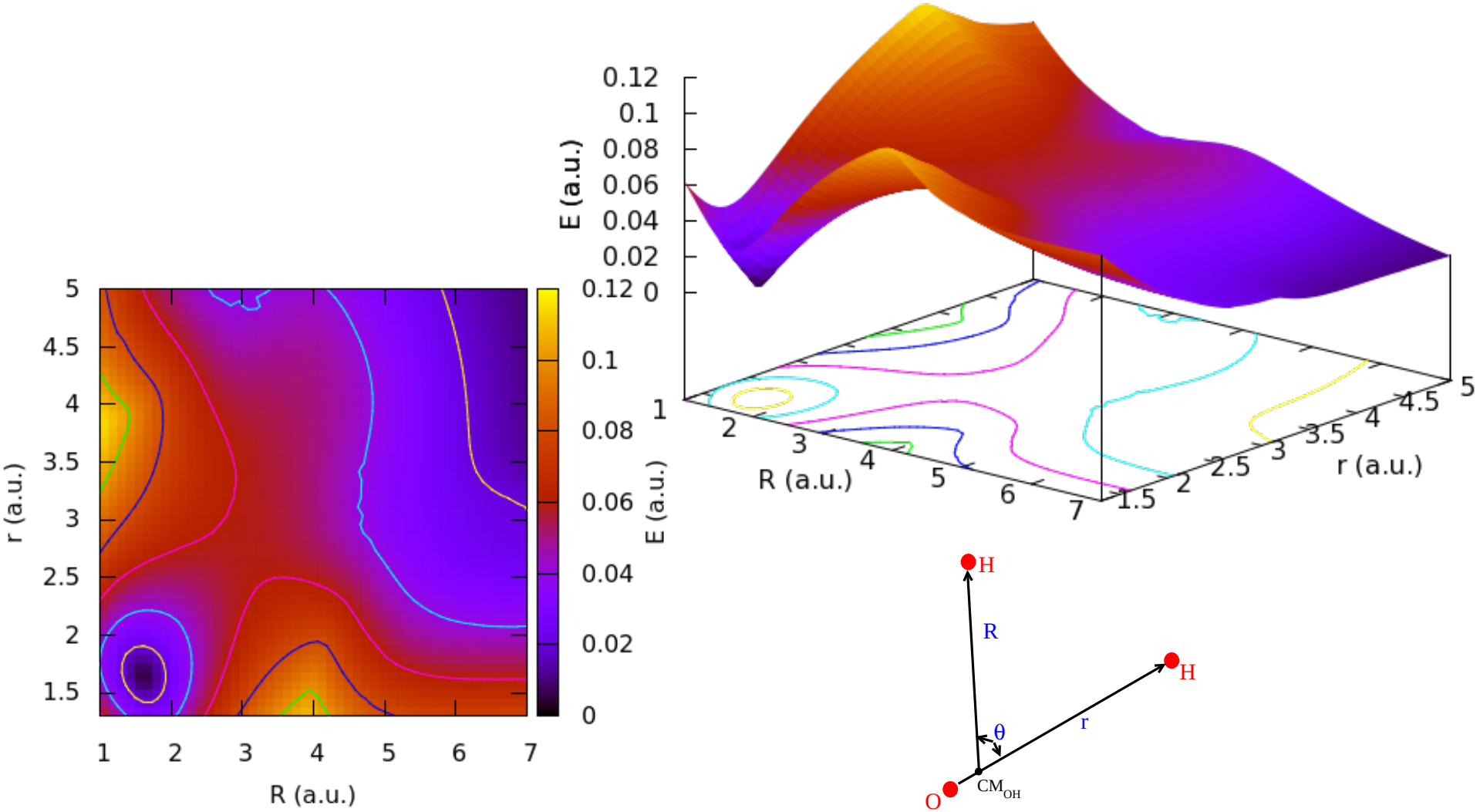
MO of H_2O and H_2O^+ PEC



PES details

- MOLPRO: MRCI wave functions.
- Basis: (O, aug-cc-pvqz; H, aug-cc-pvtz).
- 1.8 million uncontracted configurations (^{2}A' symmetry).
- $50 \times 50 \times 31 = 77500$ points in (r, R, θ) Jacobi coordenates.
- Slightly smaller calculations for symmetries ^{2}A" and ^{4}A" PES.
- Calculation of non-adiabatic couplings near the CI.

$\tilde{A}\ ^2A_1 - \tilde{B}\ ^2B_2$ CI ($\theta = 70^\circ$)

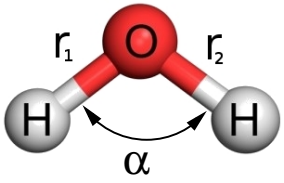


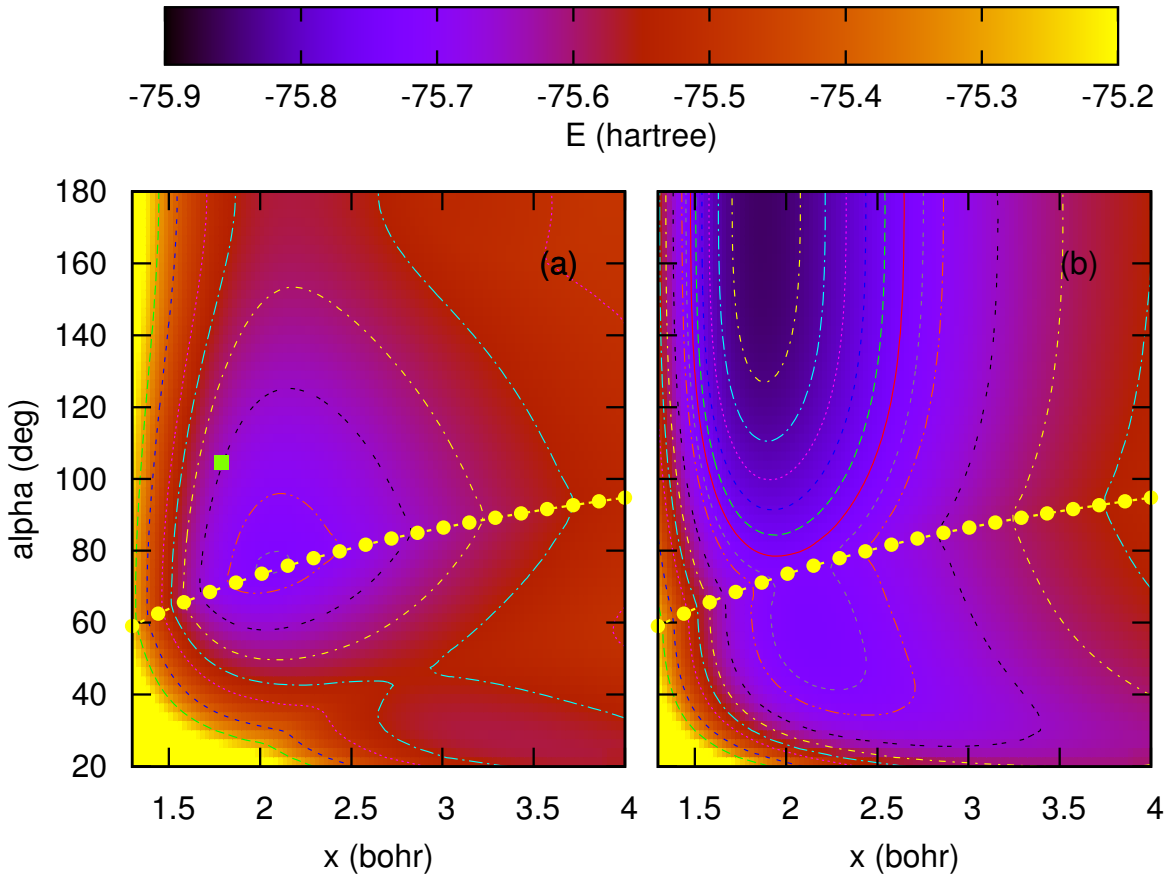
$\tilde{A}\ ^2A_1 - \tilde{B}\ ^2B_2$ CI

Symmetry coordinates

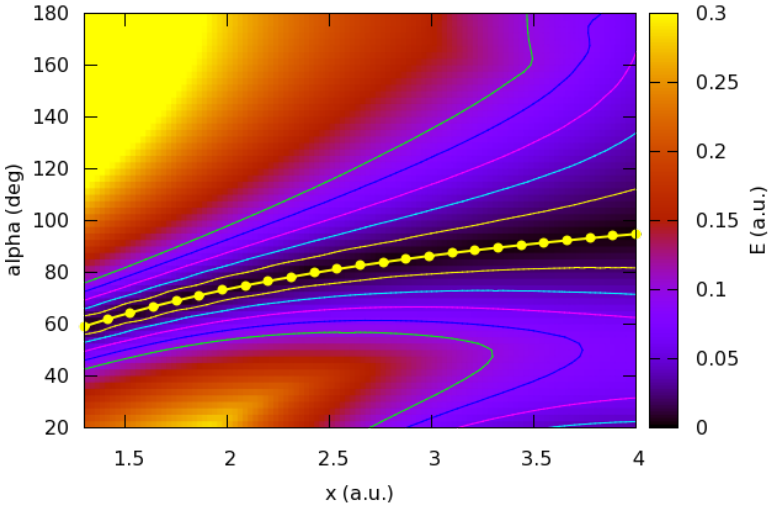
$x = \frac{r_1 + r_2}{2}$;

$y = \frac{r_1 - r_2}{2}$



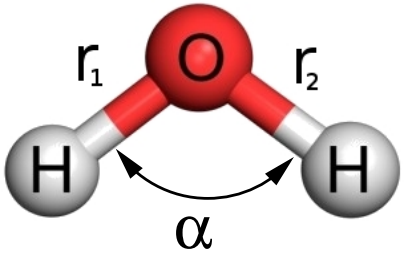


Regularization of $\tilde{B}\ ^2B_2$– $\tilde{A}\ ^2A_1$CI

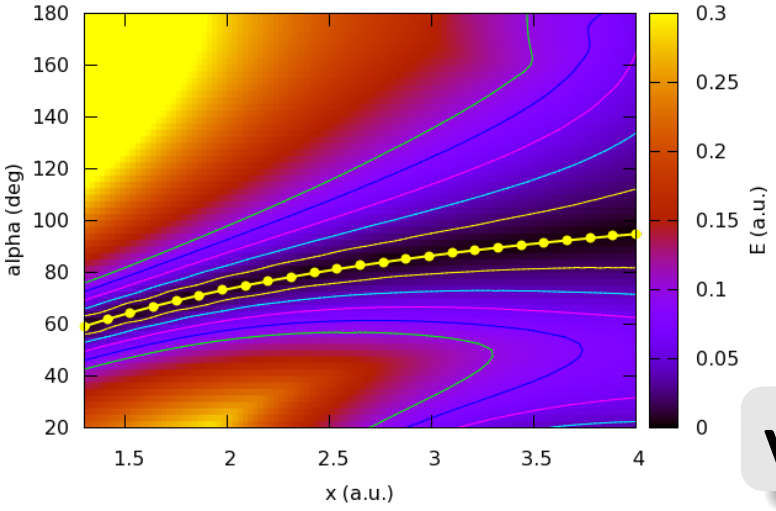


$$x = \frac{r_1+r_2}{2}\ ;\ y = \frac{r_1-r_2}{2}$$

$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$



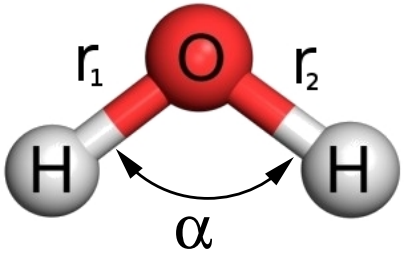
Regularization of $\tilde{B}\ ^2B_2$– $\tilde{A}\ ^2A_1$CI



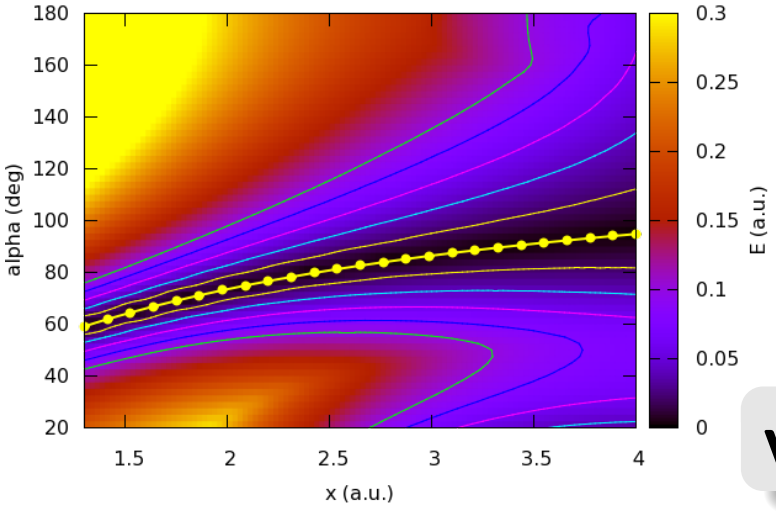
$$x = \frac{r_1+r_2}{2}\ ;\ y = \frac{r_1-r_2}{2}$$

$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

$$\mathbf{V}^d = \mathbf{S}^\dagger \mathbf{V} \mathbf{S}$$



Regularization of $\tilde{B}\ ^2B_2$– $\tilde{A}\ ^2A_1$CI

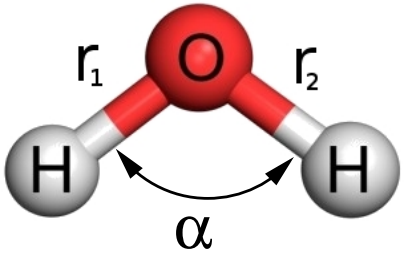


$$x = \frac{r_1+r_2}{2}\ ;\ y = \frac{r_1-r_2}{2}$$

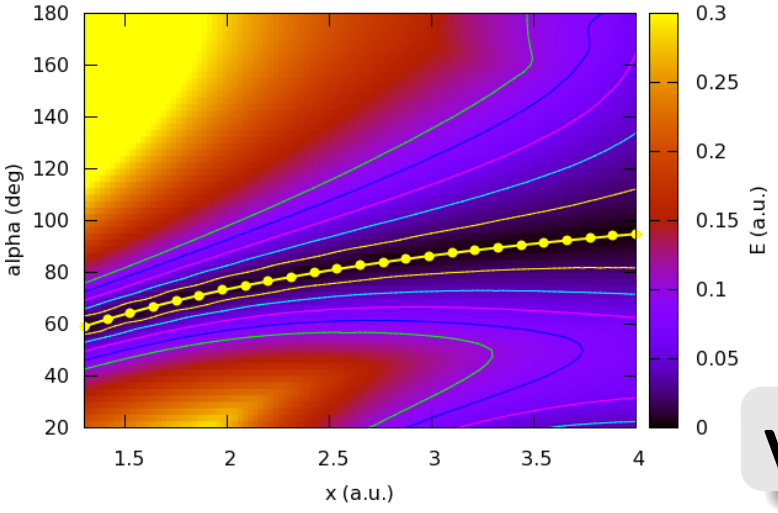
$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

$$\mathbf{V}^d = \mathbf{S}^\dagger \mathbf{V} \mathbf{S}$$

$$\mathbf{S} = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix}$$



Regularization of $\tilde{B}\ ^2B_2$– $\tilde{A}\ ^2A_1$CI



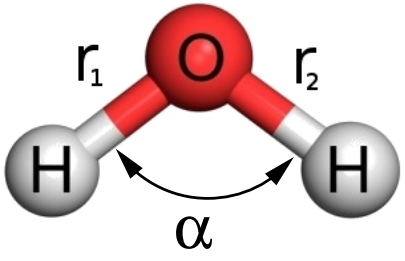
$$x = \frac{r_1+r_2}{2}\ ;\ y = \frac{r_1-r_2}{2}$$

$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

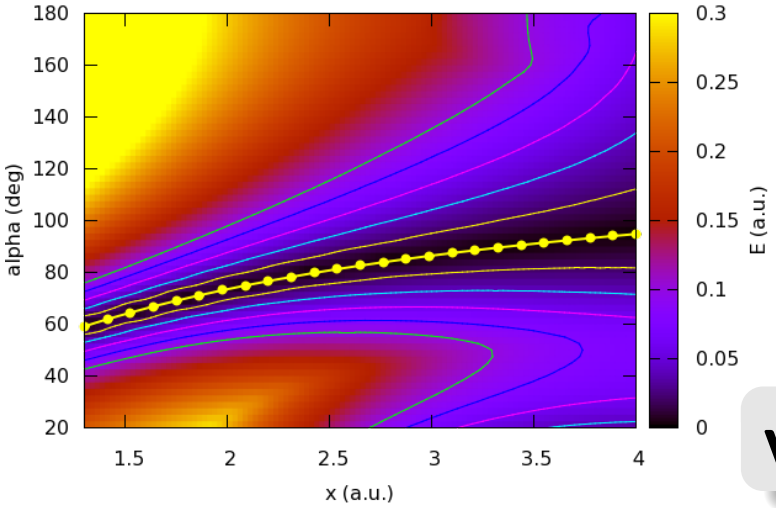
$$\mathbf{V}^d = \mathbf{S}^\dagger \mathbf{V} \mathbf{S}$$

$$\mathbf{S} = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix}$$

$$\Theta = \frac{1}{2}\arctan\left(\frac{2V_{12}^d}{\Delta V^d}\right)$$



Regularization of $\tilde{B}\ ^2B_2$– $\tilde{A}\ ^2A_1$CI



$$x = \frac{r_1+r_2}{2}\ ;\ y = \frac{r_1-r_2}{2}$$

$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

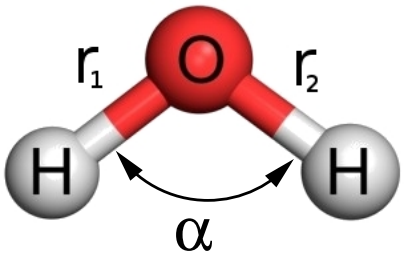
$$\mathbf{V}^d = \mathbf{S}^\dagger \mathbf{V} \mathbf{S}$$

$$\mathbf{S} = \begin{pmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{pmatrix}$$

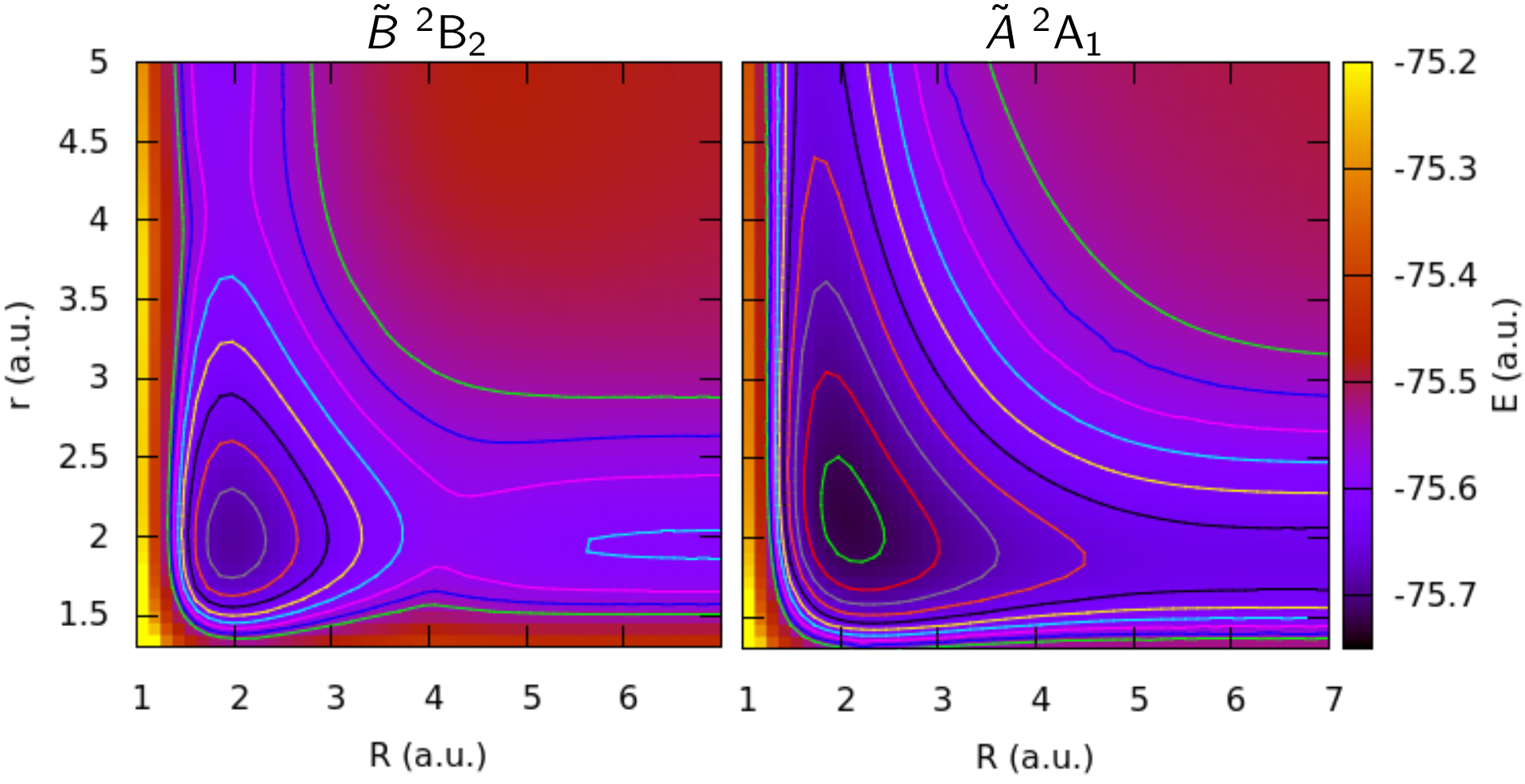
$$\Theta = \frac{1}{2}\arctan\left(\frac{2V_{12}^d}{\Delta V^d}\right)$$

$$\Delta V^d(\alpha, x) = (\alpha - \alpha_{CI})\sin(\pi/2 - \alpha'_{CI}) \approx d(p, CI)$$

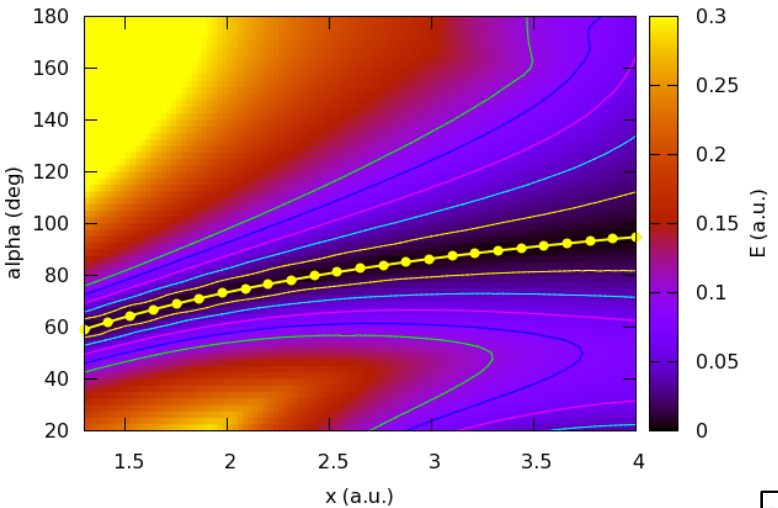
$$V_{12}^d(\alpha, y) = 0.18y + 0.77 - 0.050\alpha + 6.75\times10^{-4}\alpha^2$$



H_2O^+ Diabatic PES: $\theta = 70^\circ$



H_2O^+ PES: C_{2v} symmetry

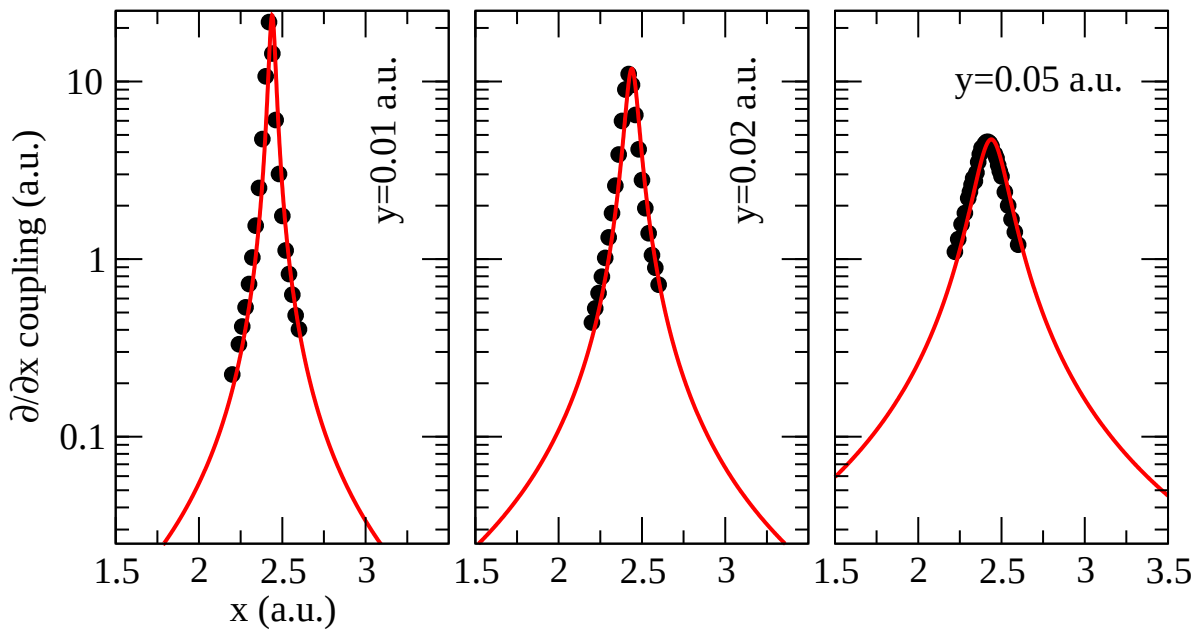


$$x = \frac{r_1+r_2}{2} \; ; \; y = \frac{r_1-r_2}{2}$$

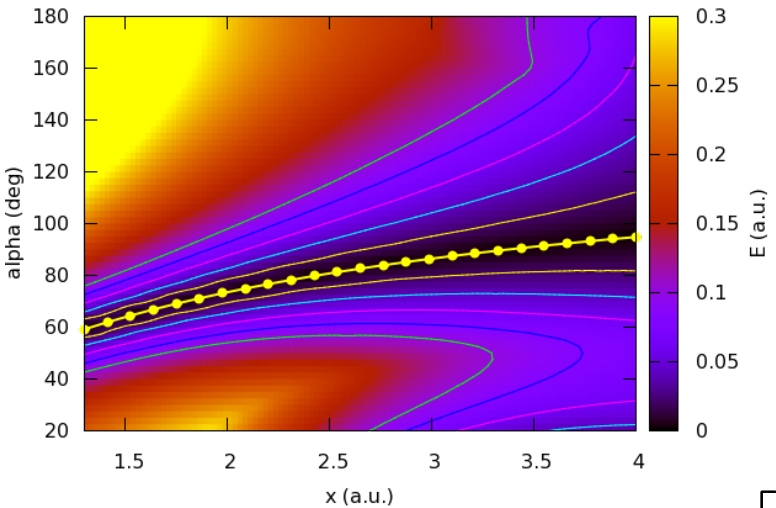
$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

$$A_x = \left\langle \Psi_1 \left| \frac{\partial \Psi_2}{\partial x} \right. \right\rangle$$

$$A_x = \frac{\partial \Theta}{\partial x}$$



H_2O^+ PES: C_{2v} symmetry

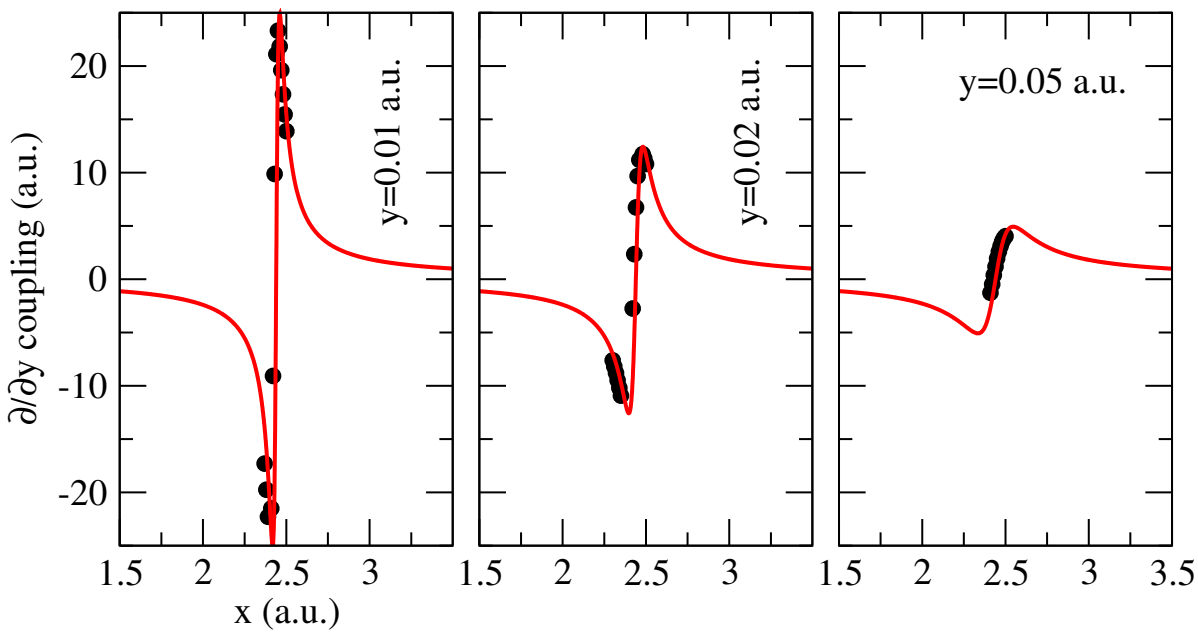


$$x = \frac{r_1+r_2}{2} \; ; \; y = \frac{r_1-r_2}{2}$$

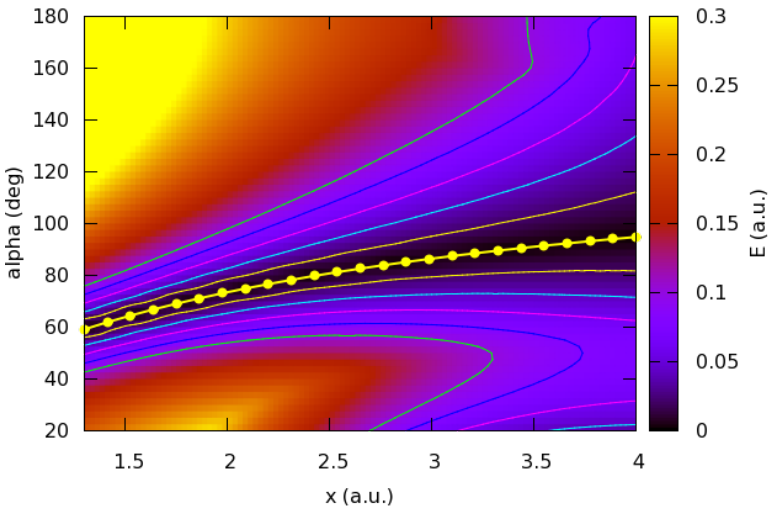
$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

$$A_y = \left\langle \Psi_1 \left| \frac{\partial \Psi_2}{\partial y} \right. \right\rangle$$

$$A_y = \frac{\partial \Theta}{\partial y}$$



H_2O^+ PES: C_{2v} symmetry

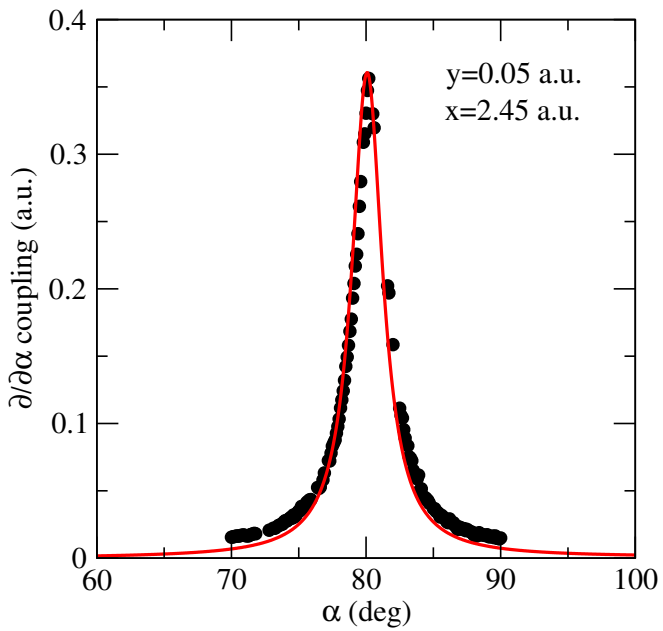


$$x = \frac{r_1+r_2}{2} \; ; \; y = \frac{r_1-r_2}{2}$$

$$\alpha_{CI}(x) = \frac{81.75x}{1+0.61x}$$

$$A_\alpha = \left\langle \Psi_1 \left| \frac{\partial \Psi_2}{\partial \alpha} \right. \right\rangle$$

$$A_\alpha = \frac{\partial \Theta}{\partial \alpha}$$



Renner-Teller coupling ($\tilde{X}\ ^2B_1$ – $\tilde{A}\ ^2A_1$)

In the $C_{\infty v}$ limit, the angular momentum operators:

total: $\hat{J}_z \longrightarrow K$

elect: $\hat{l}_z \longrightarrow \Lambda$

nuclear: $\hat{j}_z \longrightarrow k$

$$\boxed{k = K - \Lambda}$$

In the limit $\theta \rightarrow 180^\circ$ $\tilde{\mathbf{A}}^2\mathbf{A}_1$ and $\tilde{\mathbf{X}}^2\mathbf{B}_1$ correlate with the two components of $^2\mathbf{\Pi}_\mathbf{u}$ ($|\Lambda| = \pm 1$).

$$\begin{pmatrix} \Psi_+ \\ \Psi_- \end{pmatrix} = \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix} \begin{pmatrix} \Psi_A \\ \Psi_X \end{pmatrix} \qquad \begin{matrix} (k = K - 1) \\ (k = K + 1) \end{matrix}$$

Renner-Teller coupling ($\tilde{X}\ ^2B_1$ – $\tilde{A}\ ^2A_1$)

In the $C_{\infty v}$ limit, the angular momentum operators:

$$\left.\begin{array}{lll} \text{total:} & \hat{J}_z & \longrightarrow \quad K \\ \text{elect:} & \hat{l}_z & \longrightarrow \quad \Lambda \\ \text{nuclear:} & \hat{j}_z & \longrightarrow \quad k \end{array}\right\} \quad \boxed{k = K - \Lambda}$$

In the limit $\theta \rightarrow 180^\circ$ $\mathbf{\tilde{A}^2A_1}$ and $\mathbf{\tilde{X}^2B_1}$ correlate with the two components of $^2\mathbf{\Pi_u}$ ($|\Lambda| = \pm 1$).

$$\begin{pmatrix} \Psi_+ \\ \Psi_- \end{pmatrix} = \begin{pmatrix} 1 & i \\ 1 & -i \end{pmatrix} \begin{pmatrix} \Psi_A \\ \Psi_X \end{pmatrix} \qquad \begin{array}{l} \mathbf{(k = K - 1)} \\ \mathbf{(k = K + 1)} \end{array}$$

Renner-Teller coupling ($\tilde{X}\ ^2B_1$ – $\tilde{A}\ ^2A_1$)

Introducing the **rotation out-of-plane** term:

$$\begin{aligned}\mathbf{H}_J = & -\frac{\hbar^2}{2\mu_R}\frac{\partial^2}{\partial R^2} - \frac{\hbar^2}{2\mu_r}\frac{\partial^2}{\partial r^2} \\ & -\frac{1}{2}\left(\frac{1}{\mu_R R^2} + \frac{1}{\mu_r r^2}\right)\left(\frac{\hbar^2}{\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial}{\partial\theta} - \frac{\hat{\mathbf{j}}_z^2}{\sin^2\theta}\right) \\ & +V(R,r,\theta)\end{aligned}$$

In the low $\mathbf{J}^2$ limit, we can neglect the Coriolis coupling.

Renner-Teller coupling ($\tilde{X}\ ^2B_1$ – $\tilde{A}\ ^2A_1$)

Introducing the **rotation out-of-plane** term:

$$\mathbf{H}_J \approx -\frac{\hbar^2}{2\mu_R}\frac{\partial^2}{\partial R^2} - \frac{\hbar^2}{2\mu_r}\frac{\partial^2}{\partial r^2} - \frac{\hbar^2}{2}\left(\frac{1}{\mu_R R^2} + \frac{1}{\mu_r r^2}\right)\left(\frac{\partial^2}{\partial\theta^2} + \cot\theta\frac{\partial}{\partial\theta} - \frac{\mathbf{k^2}}{\sin^2\theta}\right) + V(R, r, \theta)$$

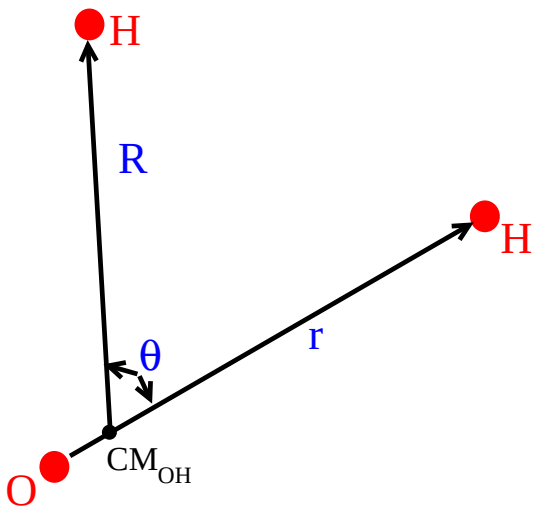
Since $\boxed{\mathbf{k = K \pm 1}}$ Including **Renner-Teller** transitions involves calculations with different values of K

(Haxton et al. PRA 75, 01271)

Kinetic energy operator

In Jacobi coordinates $(R,\, r,\, \theta)$ and $J = 0$:

$$\mathbf{T} = -\frac{\hbar^2}{2\mu_R}\frac{\partial^2}{\partial R^2} - \frac{\hbar^2}{2\mu_r}\frac{\partial^2}{\partial r^2} - \frac{\hbar^2}{2}\left(\frac{1}{\mu_R R^2} + \frac{1}{\mu_r r^2}\right)\left(\frac{\partial^2}{\partial \theta^2} + \cot\theta\frac{\partial}{\partial\theta}\right)$$



Evaluation of $\mathbf{H}\Psi$

$$\mathbf{H}\Psi = \mathbf{T}\Psi + \mathbf{V}\Psi$$

$V(x_1, \ldots, x_{N_d}) \quad \Longrightarrow$ Diagonal matrix elements

$T = \sum_i -\frac{\hbar^2}{2m_i}\partial_i^2 \quad \Longrightarrow$ Non-diagonal matrix elements

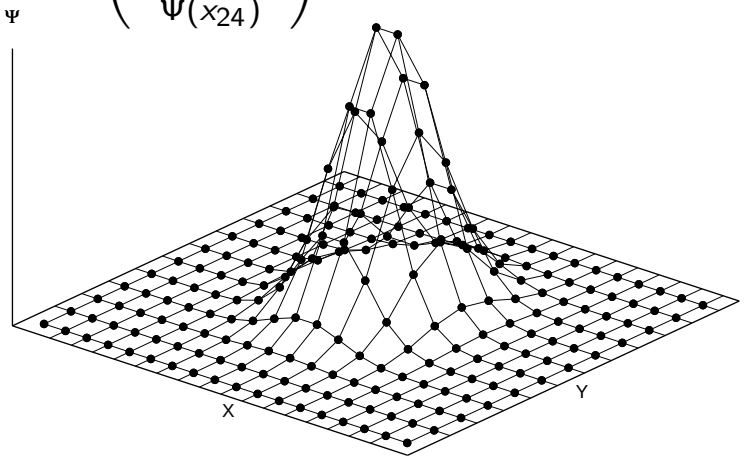
Finite differences method (Program Grid-TDSE, Suarez et al. CPC 180, 2025)

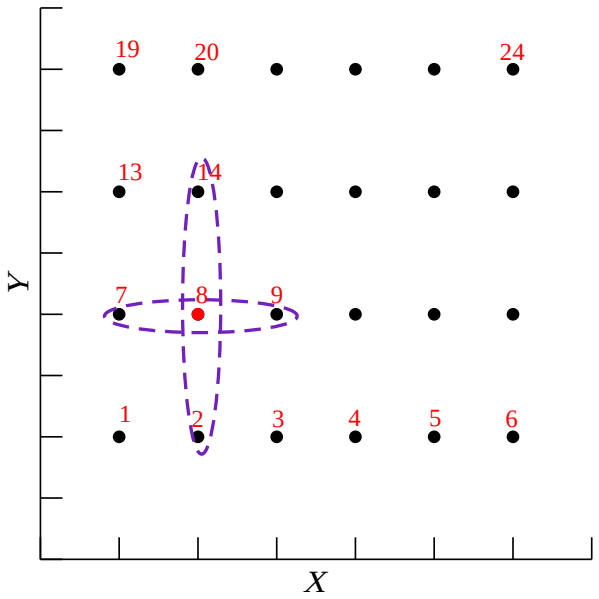
$\mathbf{T}$ is approximated considering only n_s neighboring grid points:

$$\Psi(x) \approx \Psi_N(x) = \sum_k \Psi(x_k) L_k(x) \Rightarrow (\nabla^2\Psi)_k \approx \sum_{j=1}^{n_s} b_{kj}^2 \Psi_N(x_j)$$

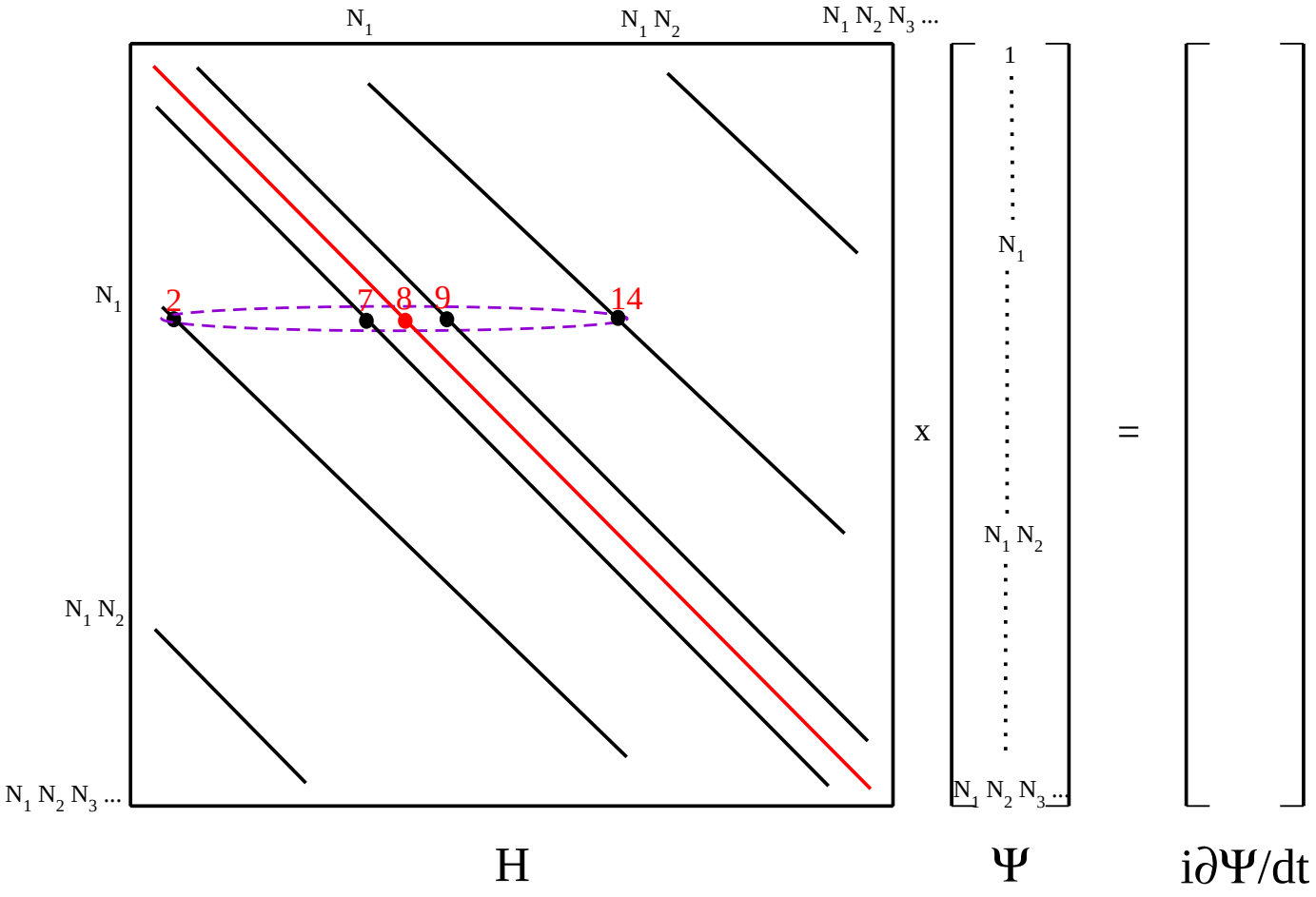
Discretization of Ψ

$$\Psi = \begin{pmatrix} \Psi(x_1) \\ \Psi(x_2) \\ \Psi(x_3) \\ \vdots \\ \Psi(x_7) \\ \Psi(x_8) \\ \vdots \\ \Psi(x_{24}) \end{pmatrix}$$





Evaluation of **HΨ**



Propagation in time of $\Psi(t)$

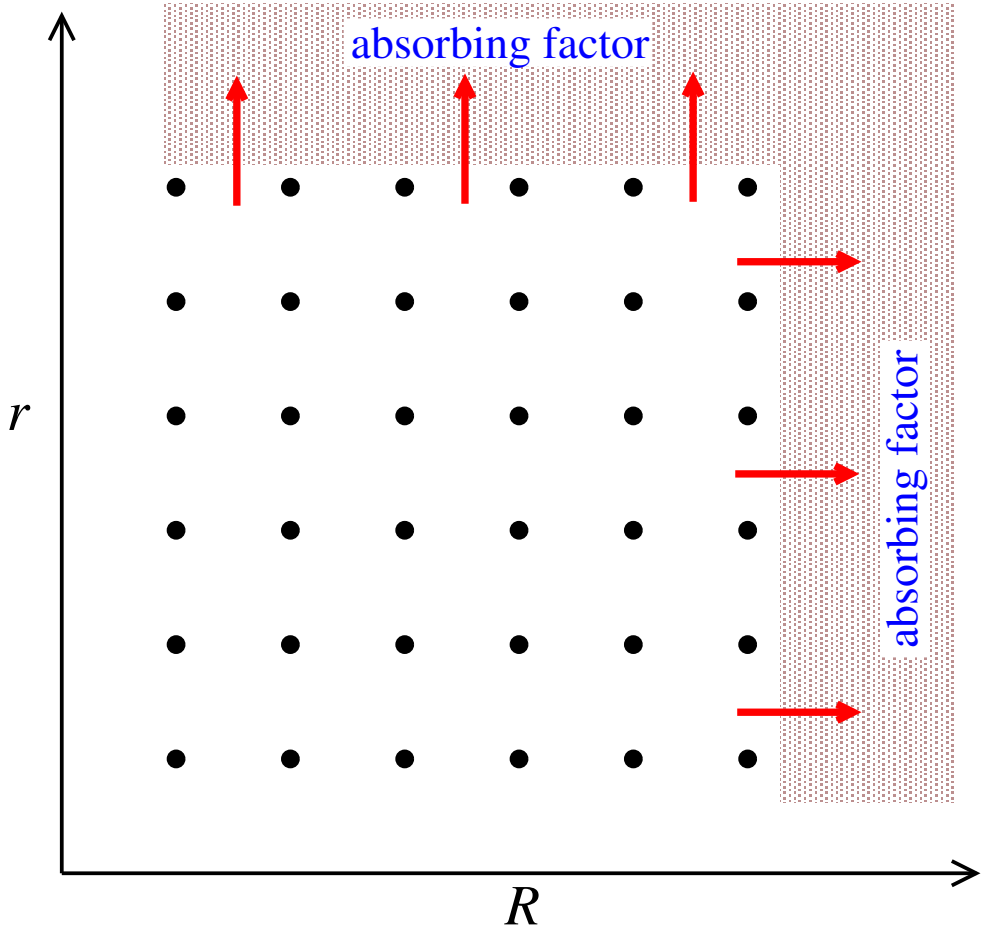
Second order difference method (SOD):

$$\Psi(t+\Delta) = e^{-i\mathbf{H}\Delta/\hbar}\Psi(t) \approx \Psi(t-\Delta) - 2i\Delta\mathbf{H}\Psi(t)$$

- Recursive method.
- Two previous points needed.
- Norm and energy conserved.
- Accuracy $O(\Delta)^2$.

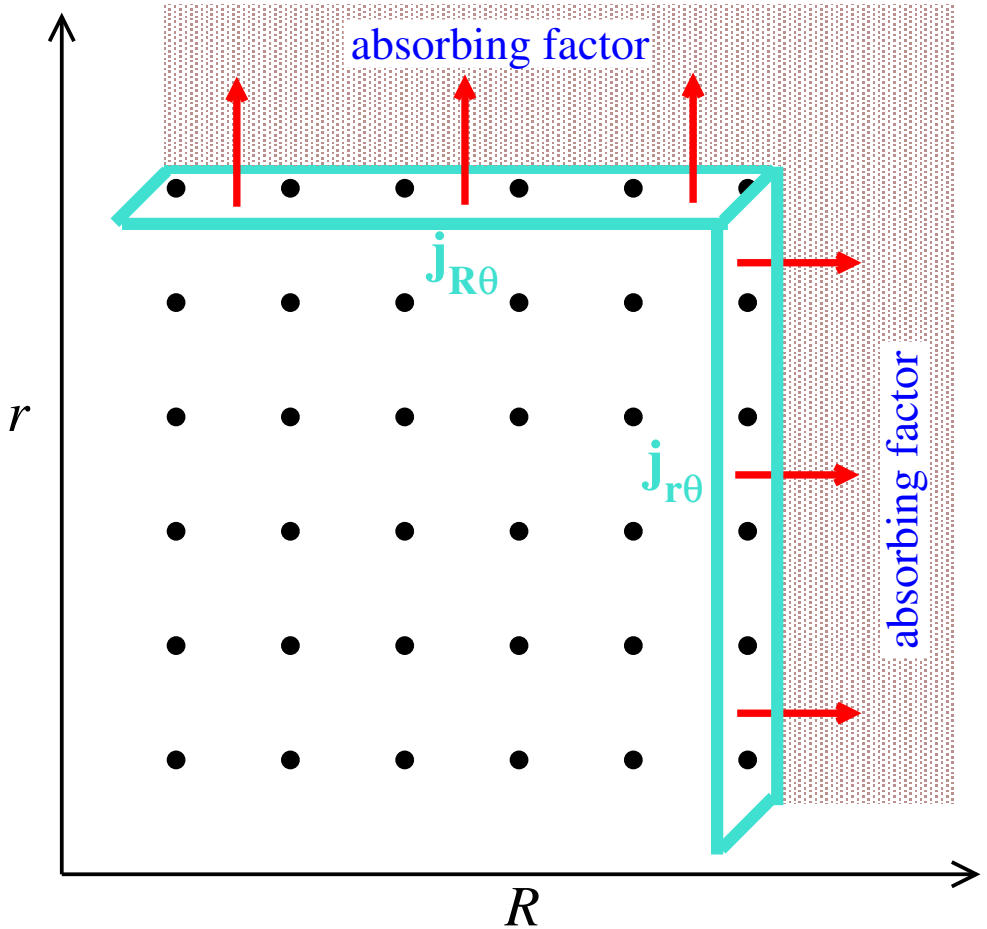
Absorbing boundary conditions

Dumping factor to avoid reflections at borders



Absorbing boundary conditions

Dumping factor to avoid reflections at borders



Flux:

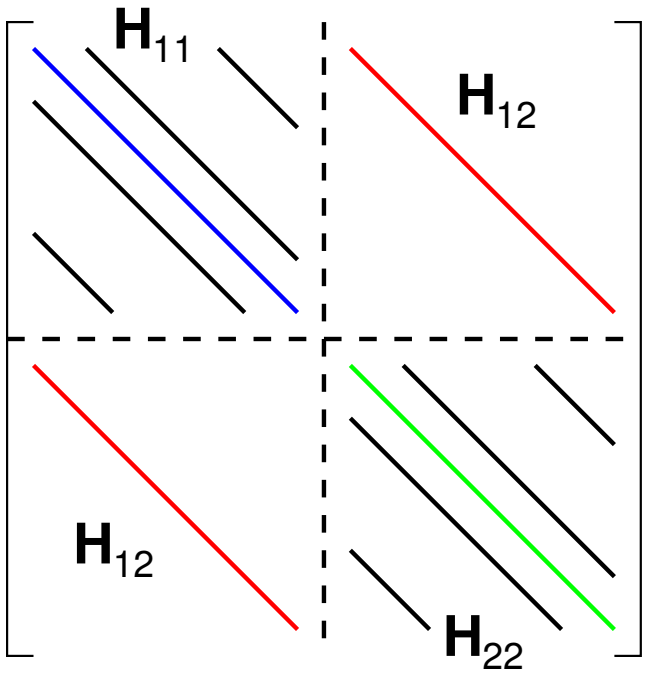
$$\vec{j}(\vec{r},t) = \frac{\hbar}{m}\mathrm{Im}\left\{\Psi^*(\nabla\Psi)\right\}$$

Continuity Equation:

$$\boxed{\frac{\partial\rho}{\partial t} + \nabla\vec{j} = 0}$$

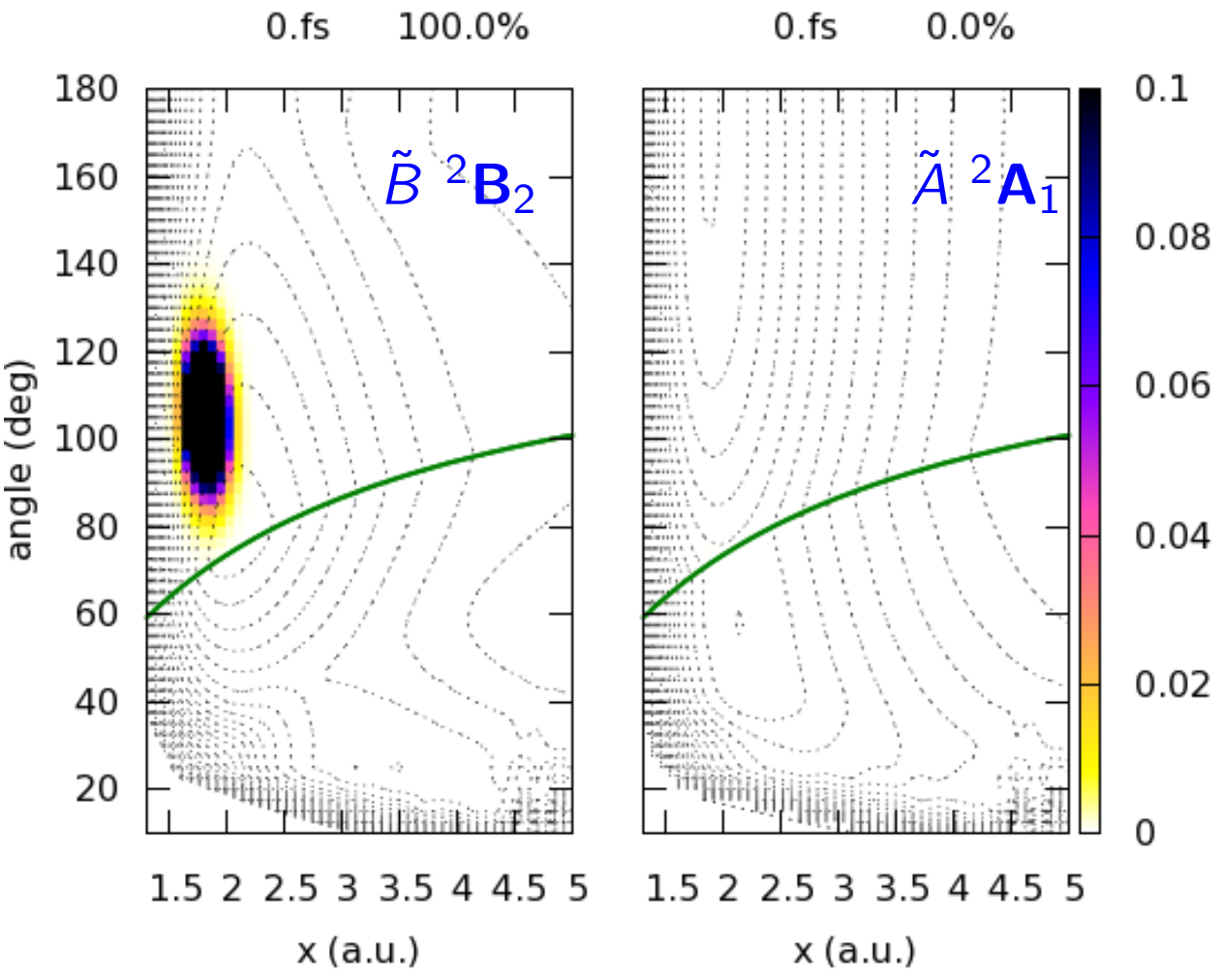
Two-state matrix hamiltonian

$$\begin{pmatrix} \mathbf{H}^{\mathrm{d}}_{11} & \mathbf{H}^{\mathrm{d}}_{12} \\ \mathbf{H}^{\mathrm{d}}_{12} & \mathbf{H}^{\mathrm{d}}_{22} \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = i\hbar \begin{pmatrix} \dot{\psi}_1 \\ \dot{\psi}_2 \end{pmatrix}$$

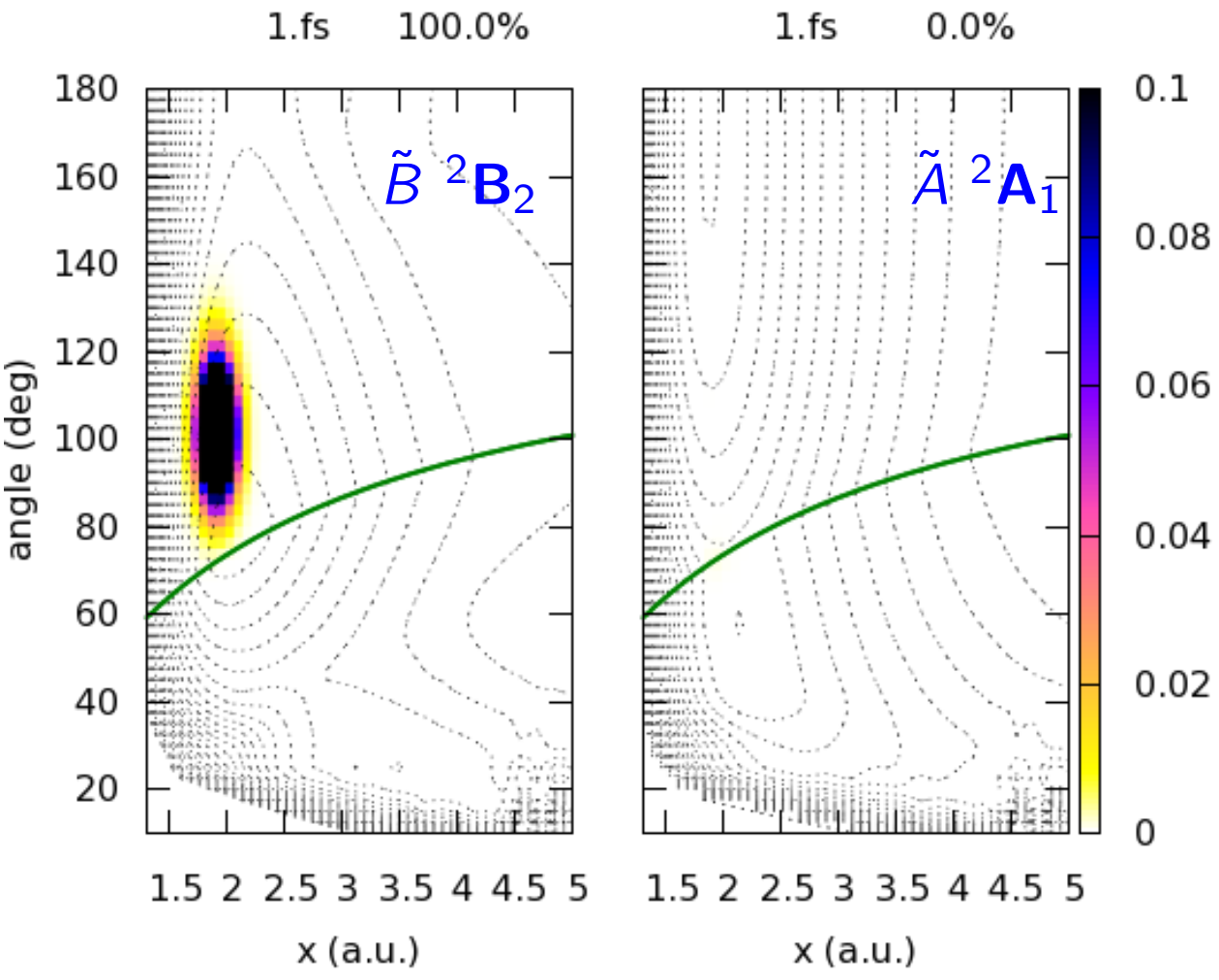


WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)

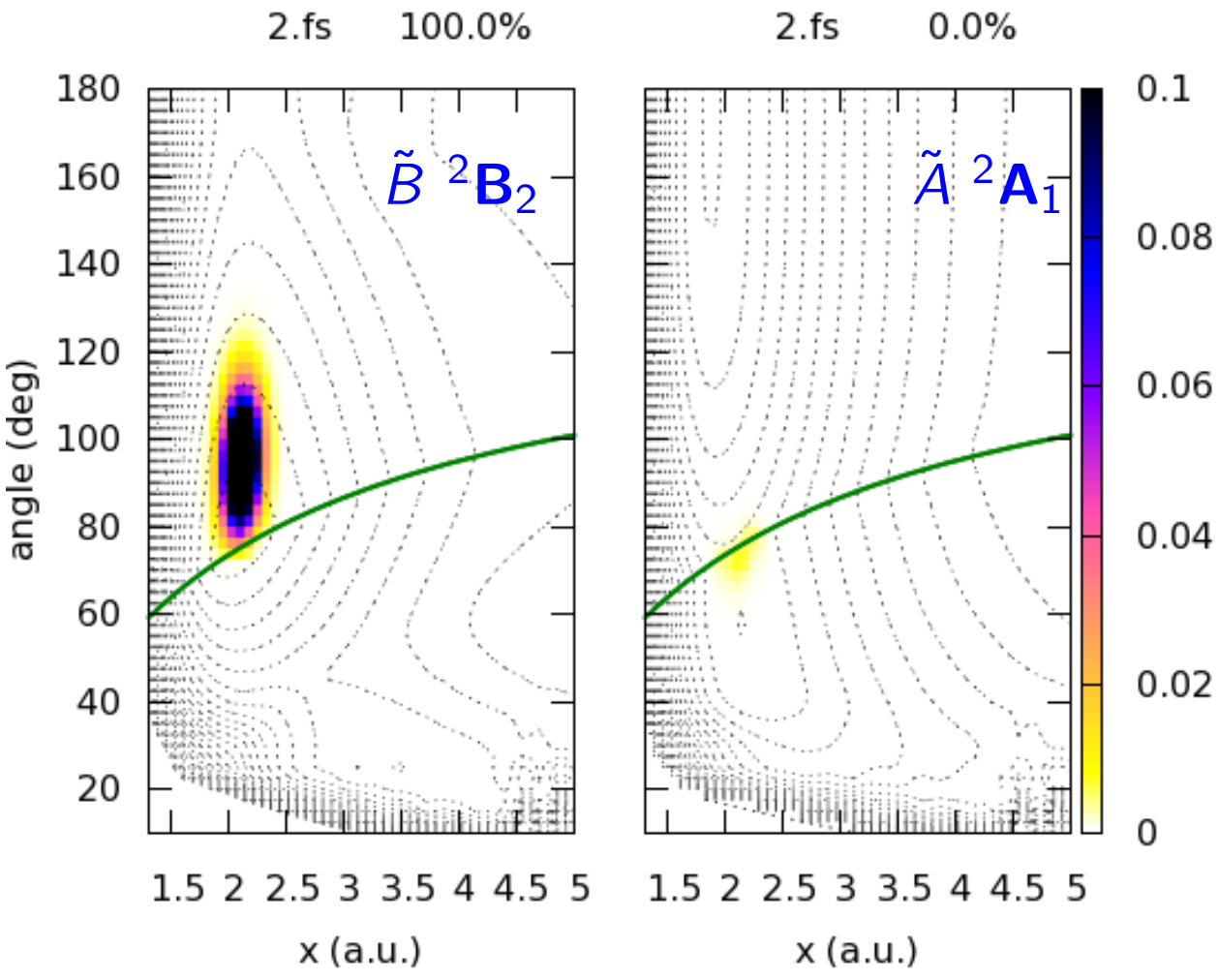
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



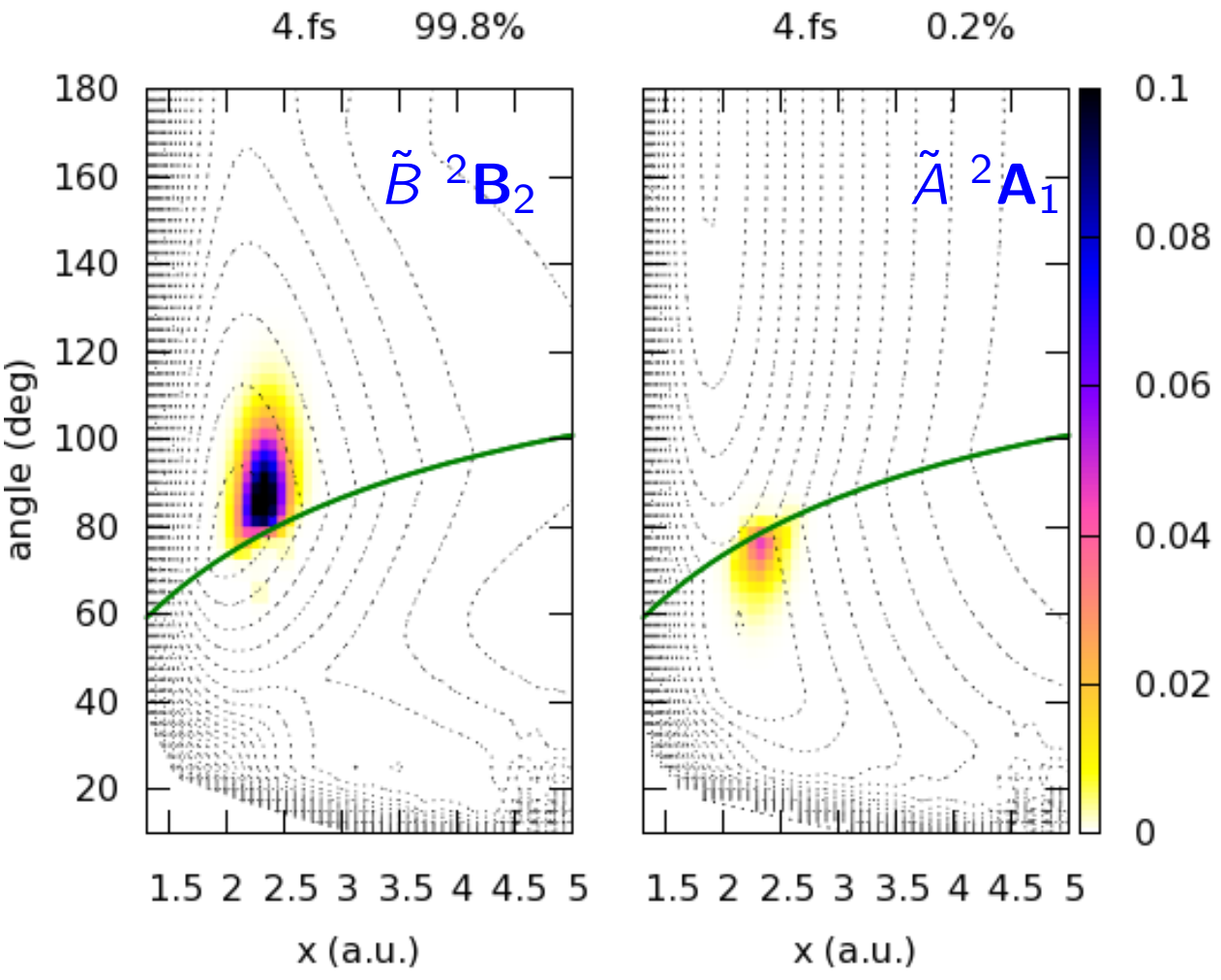
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



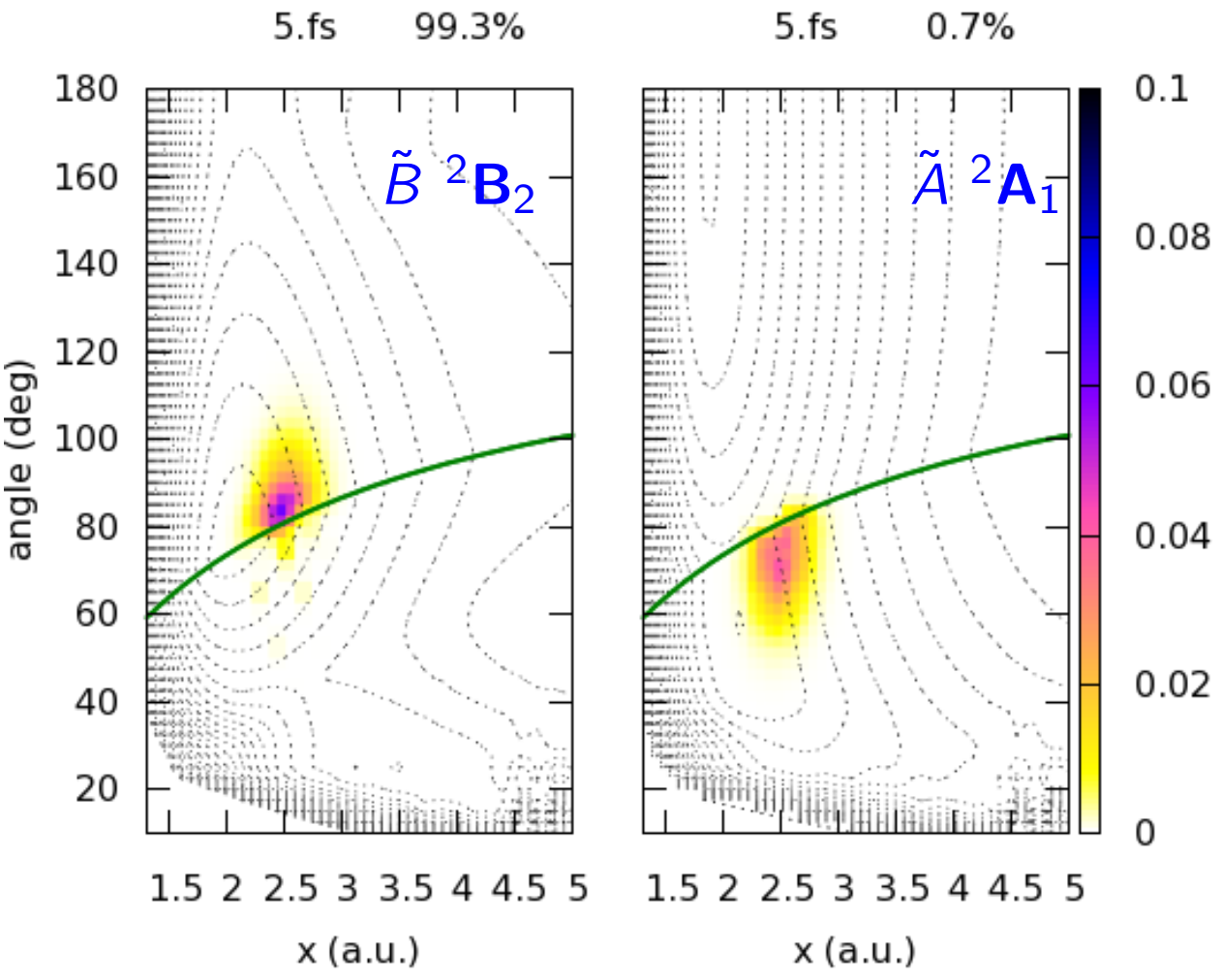
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



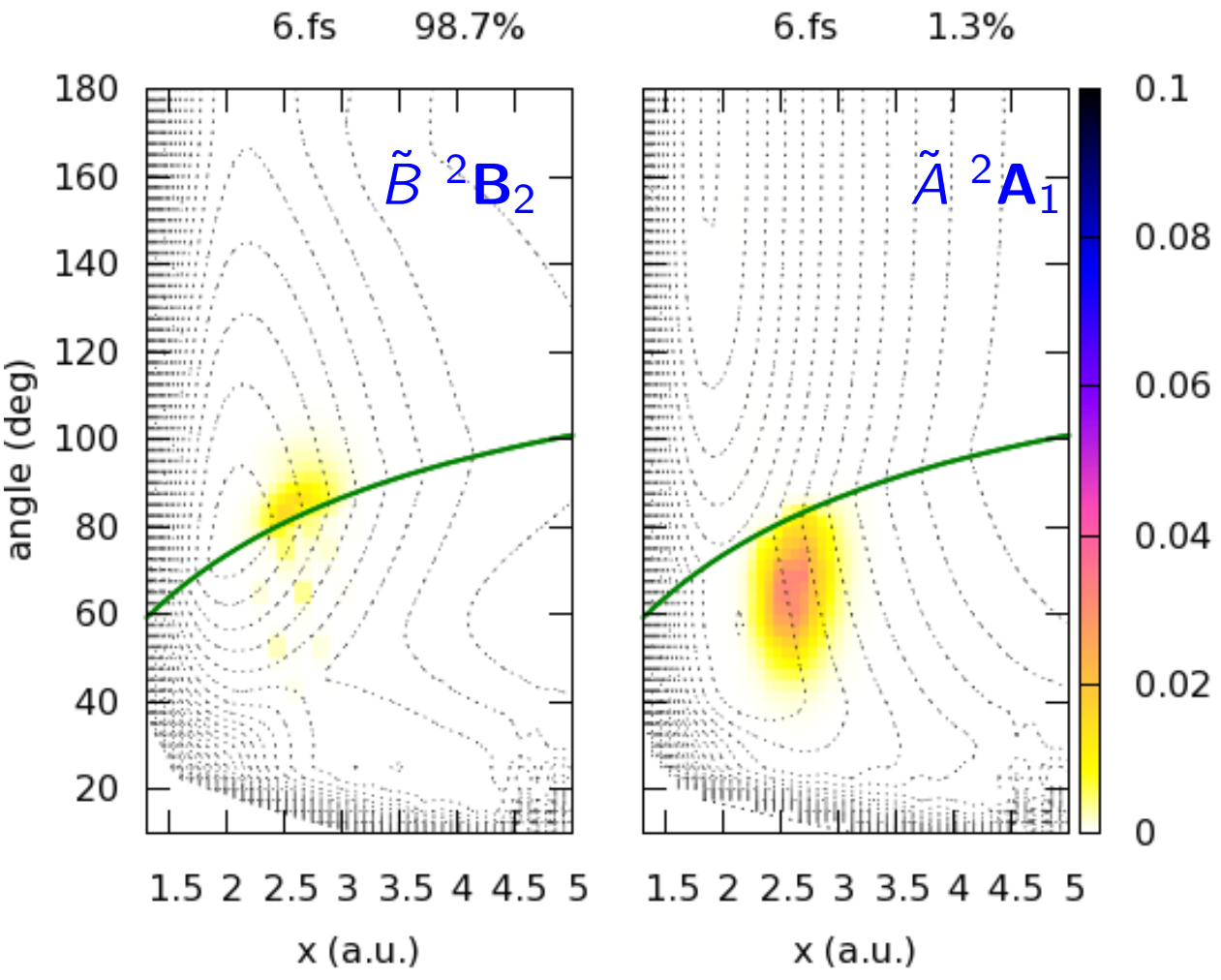
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



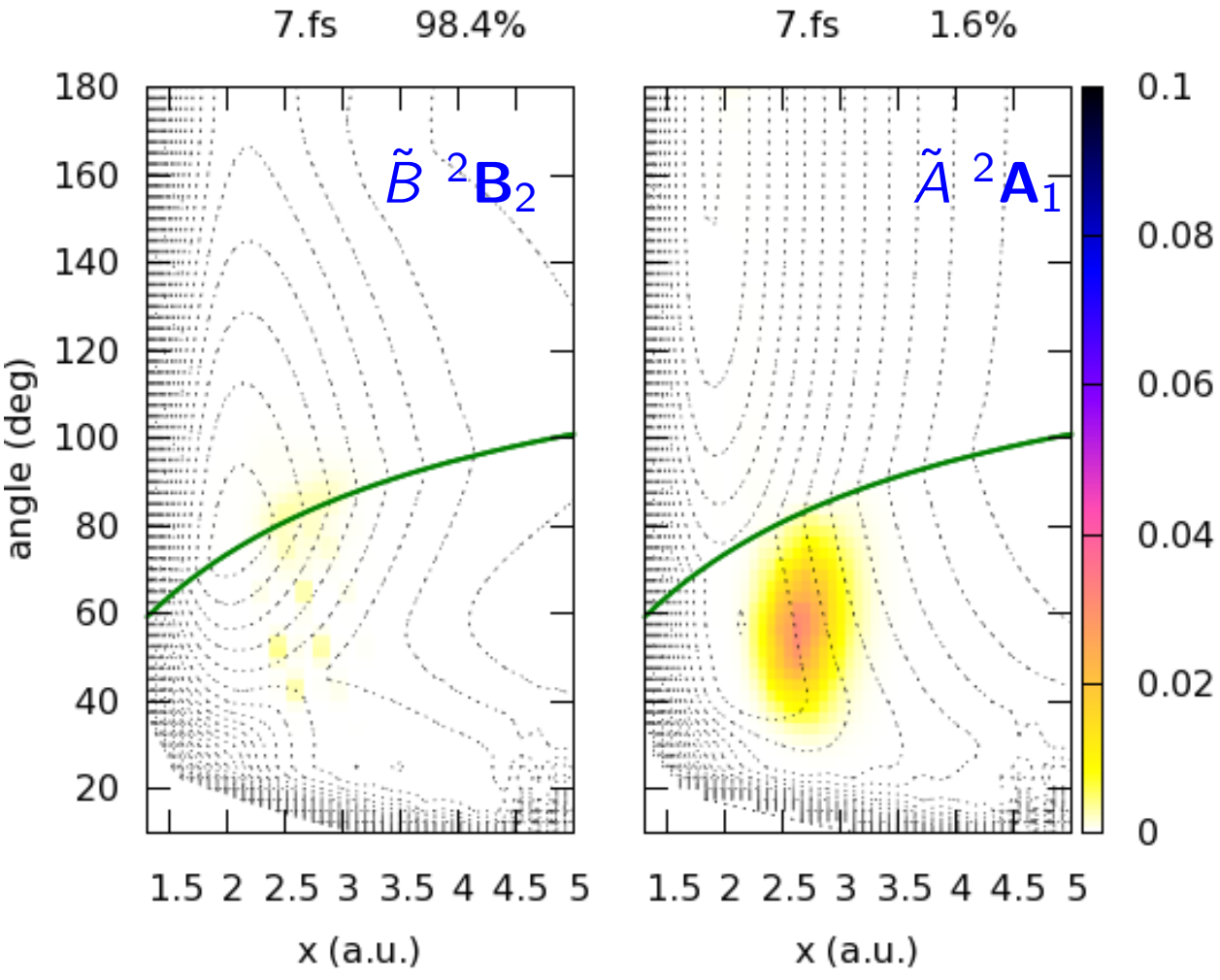
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



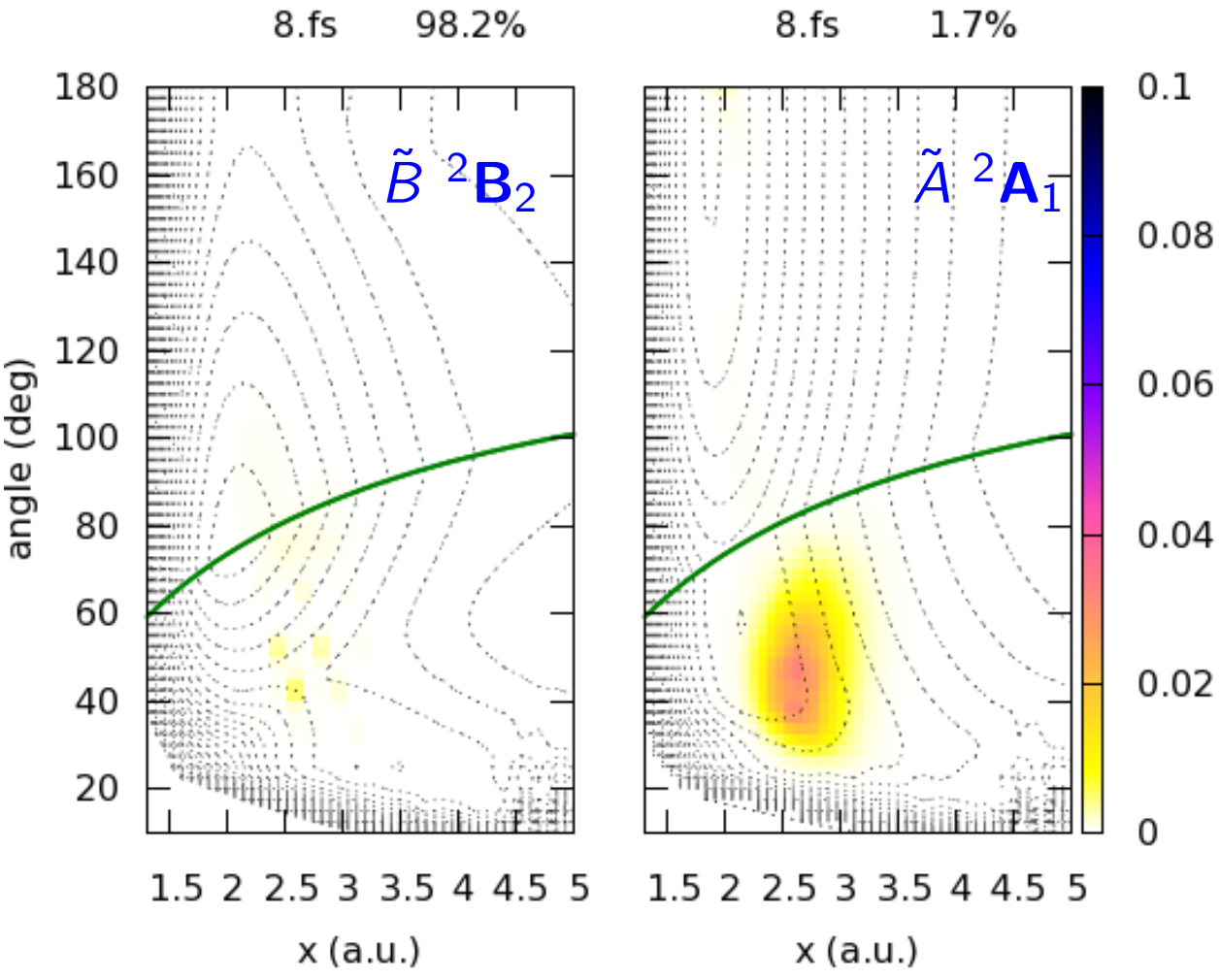
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



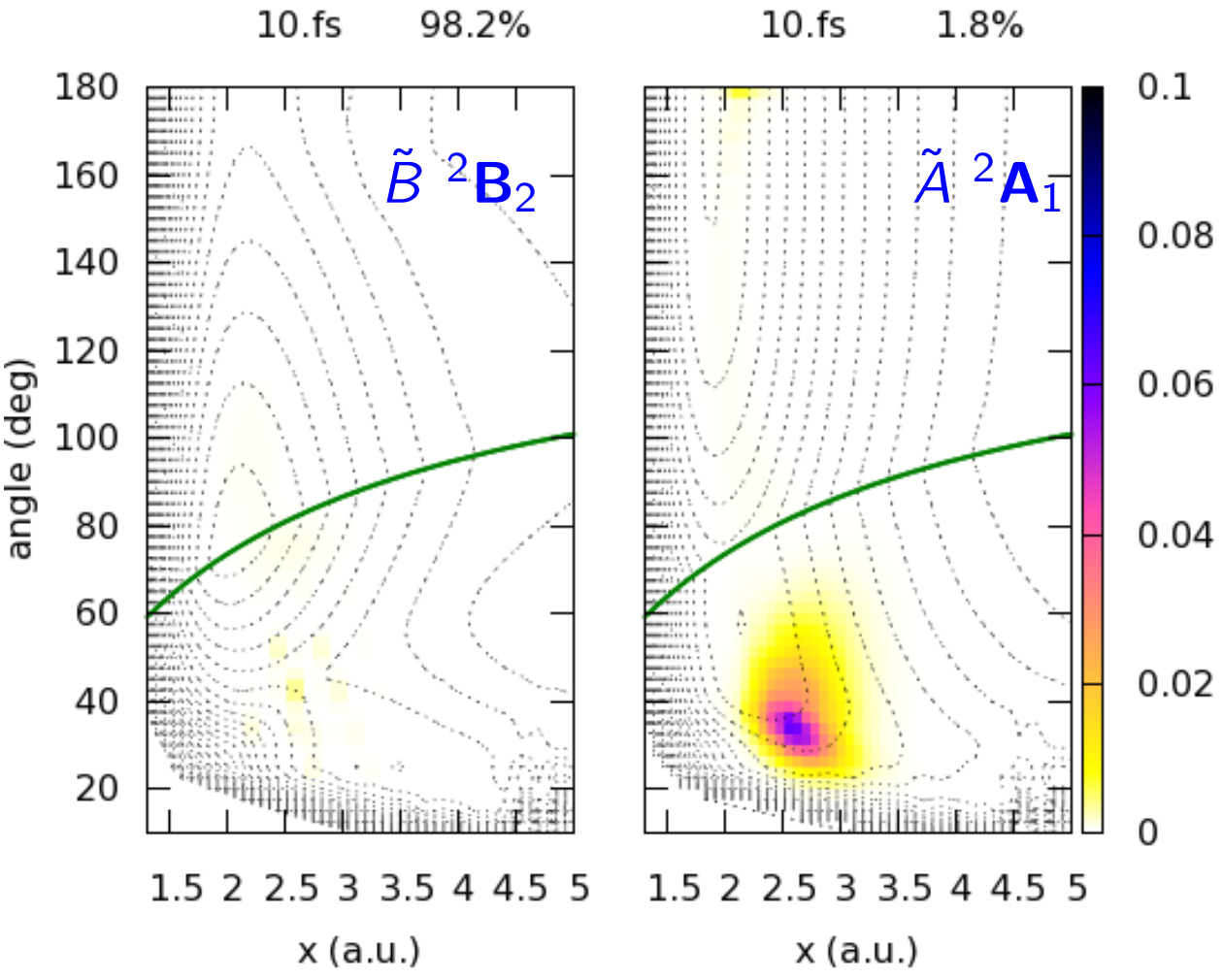
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



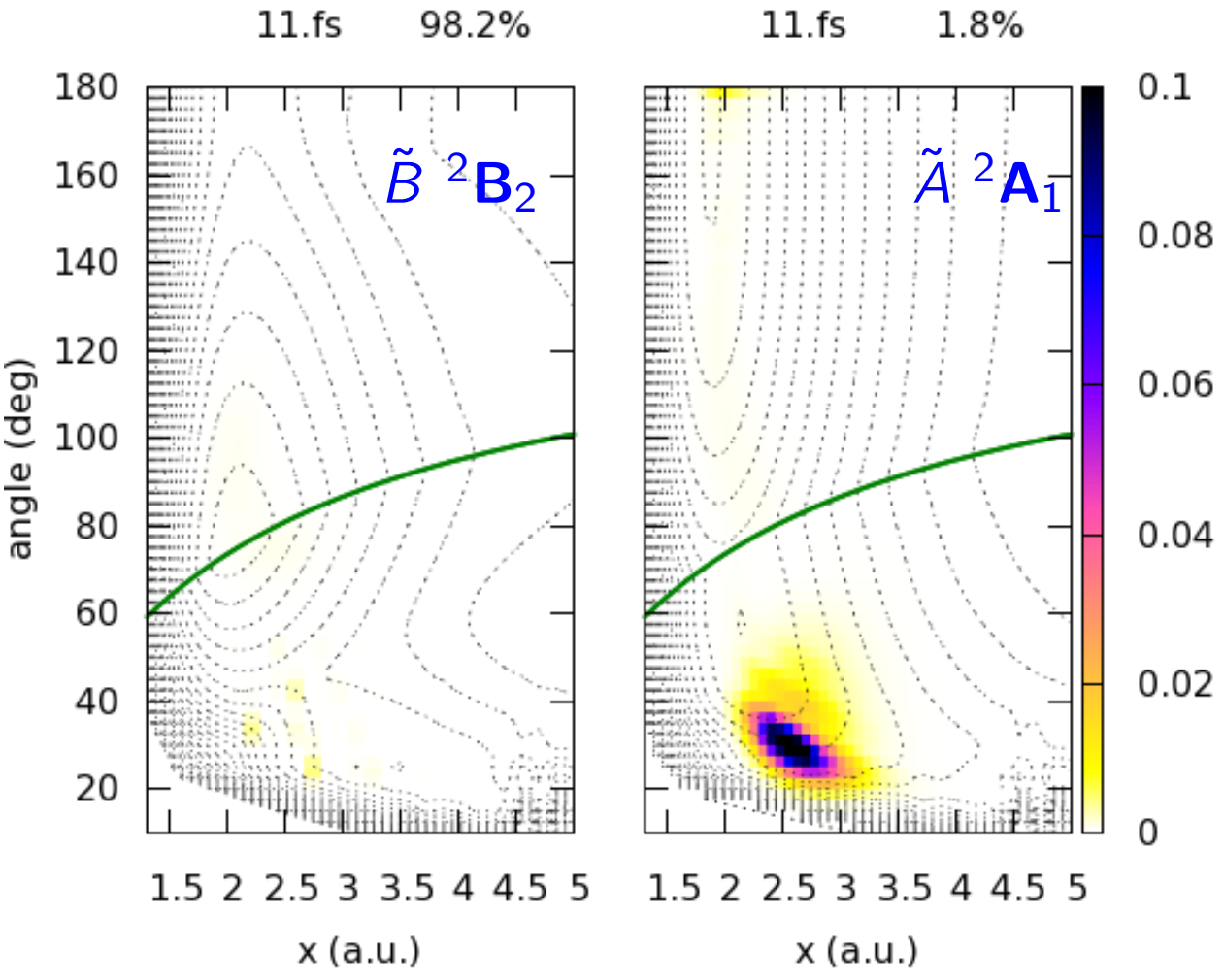
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



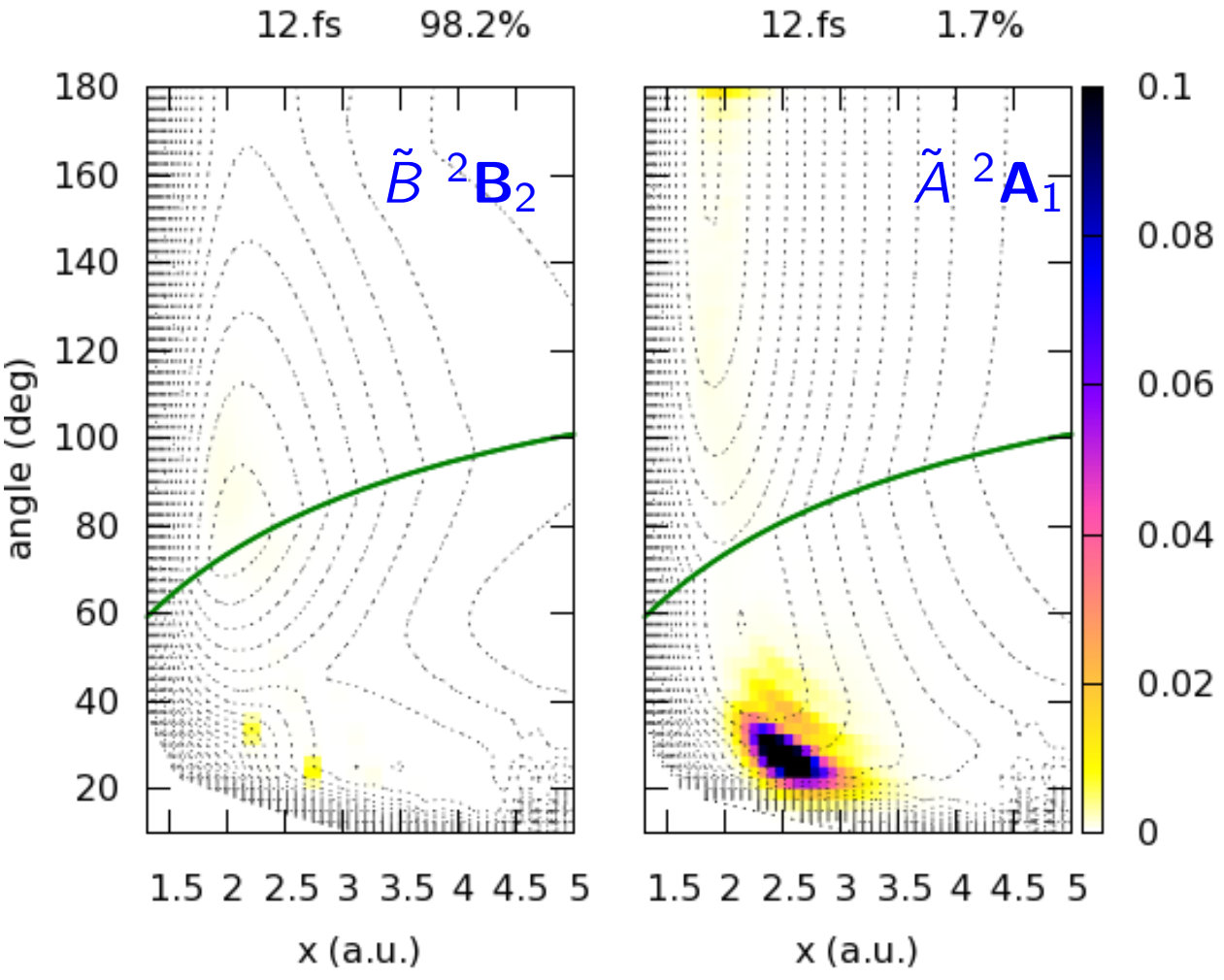
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



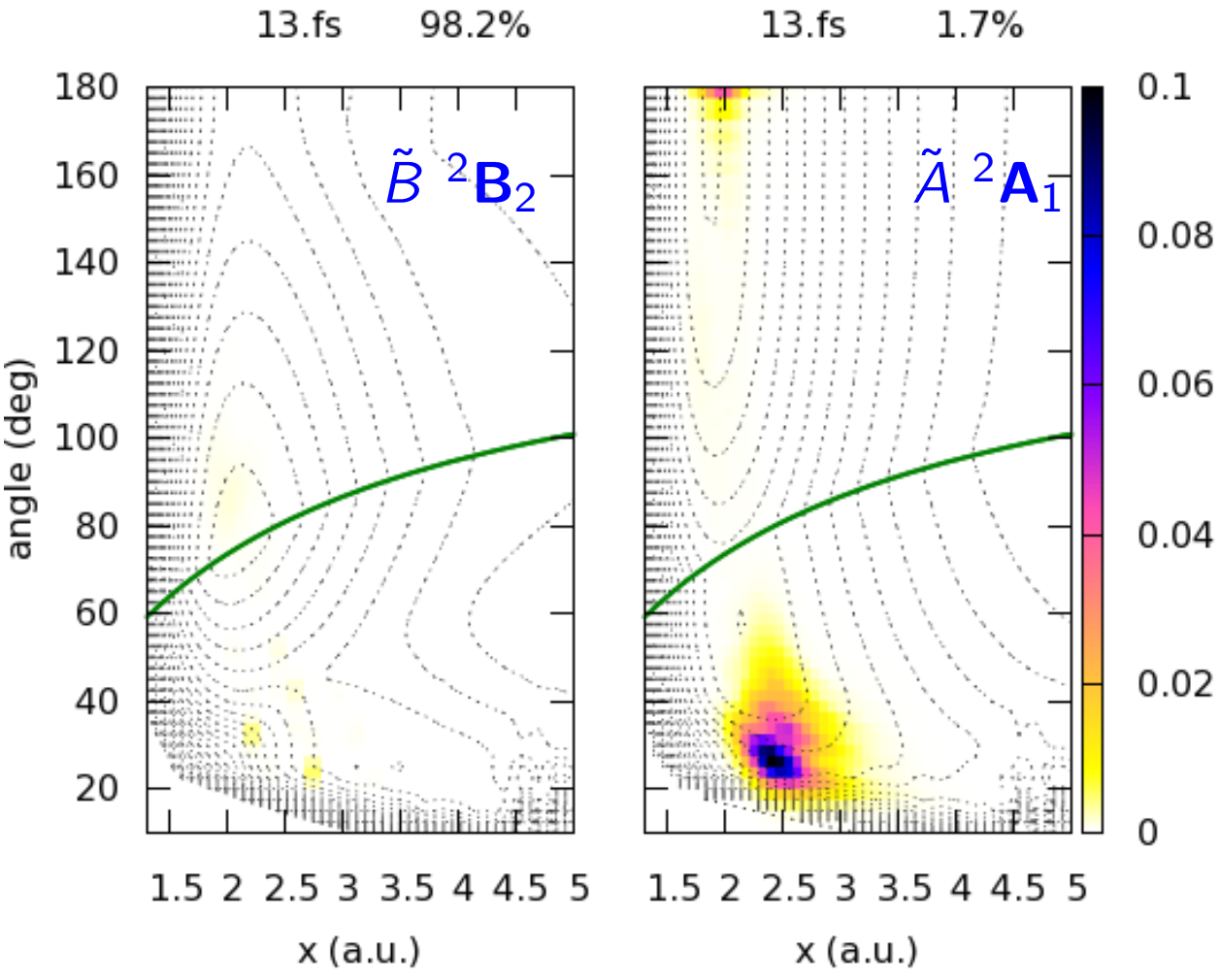
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



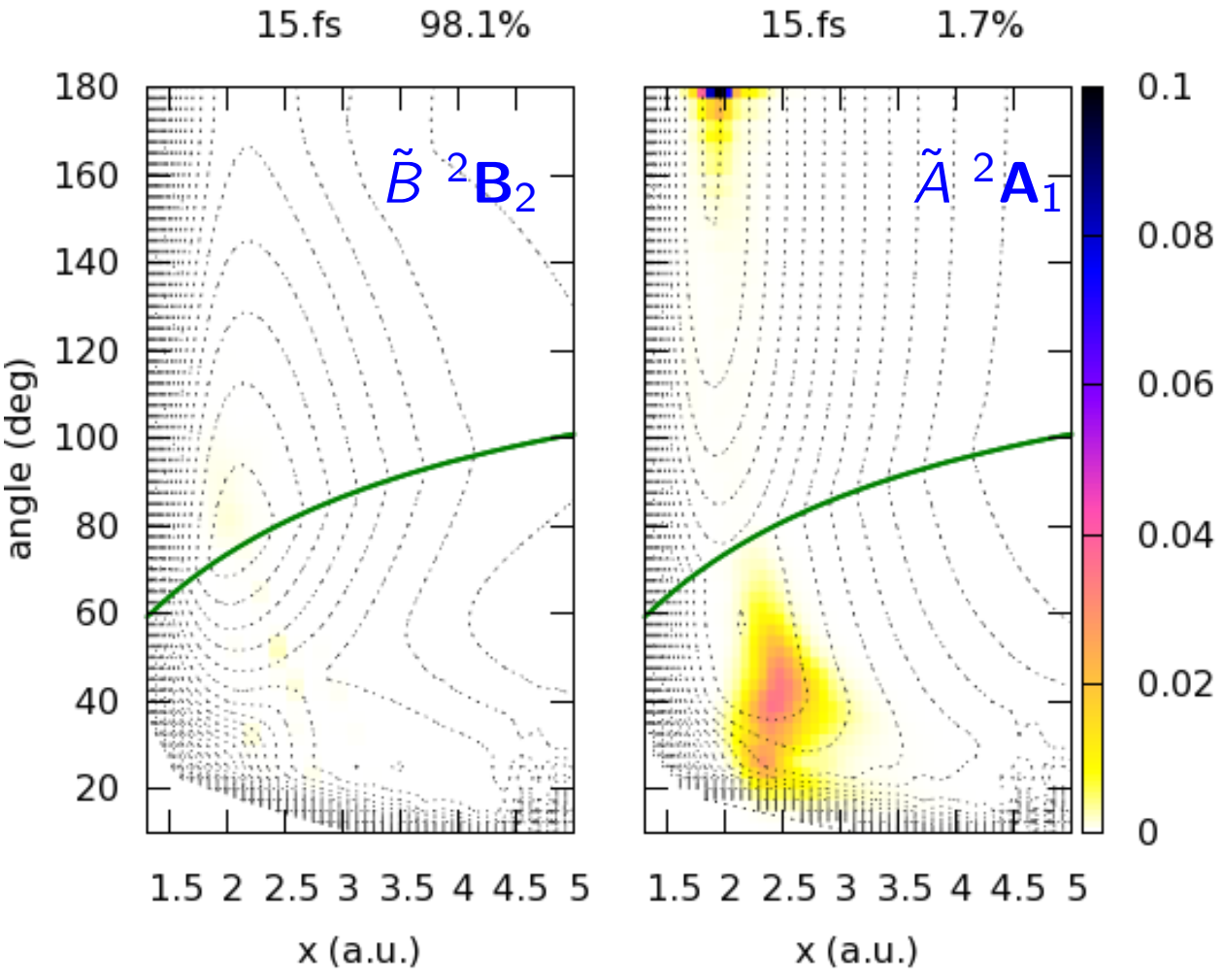
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



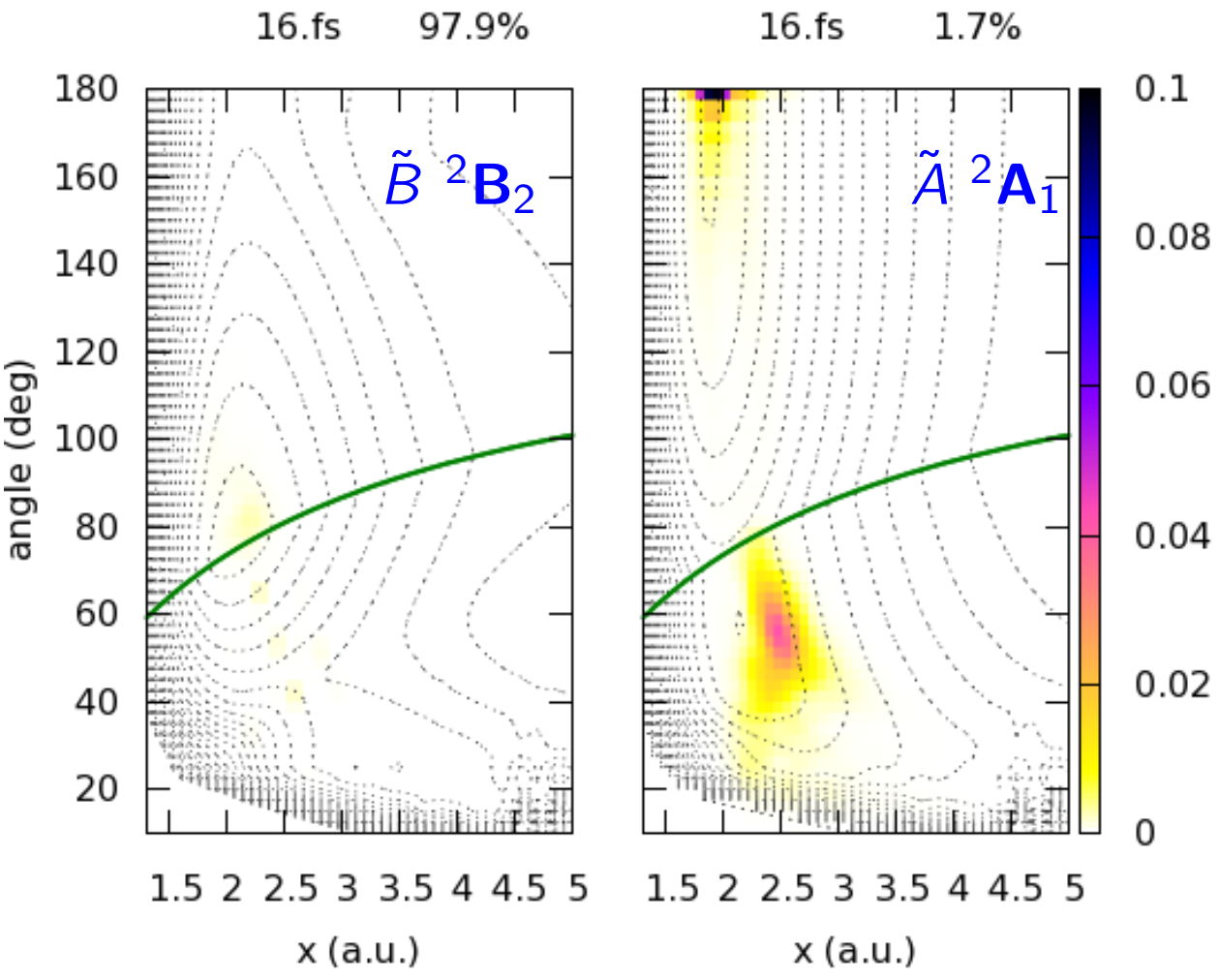
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



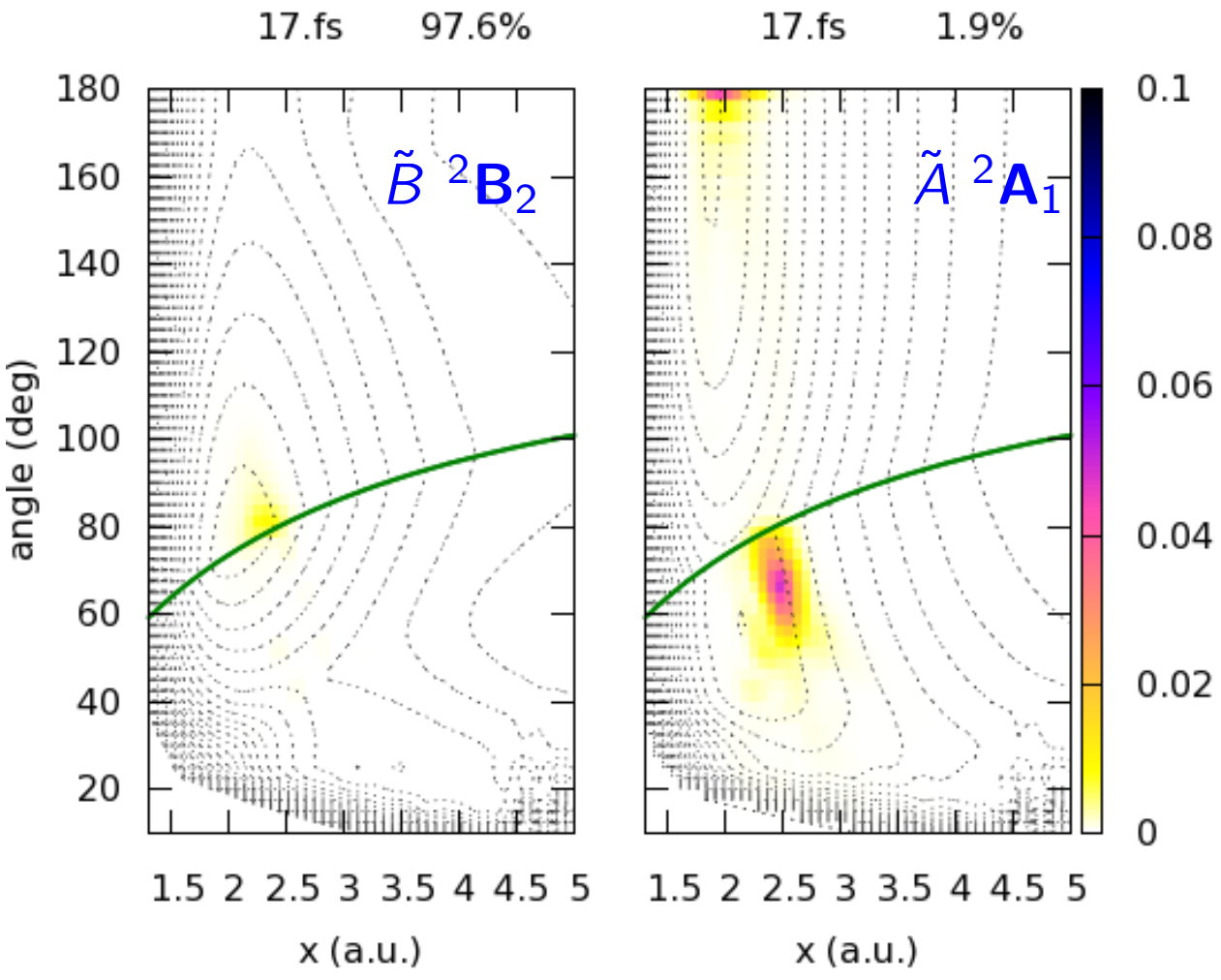
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



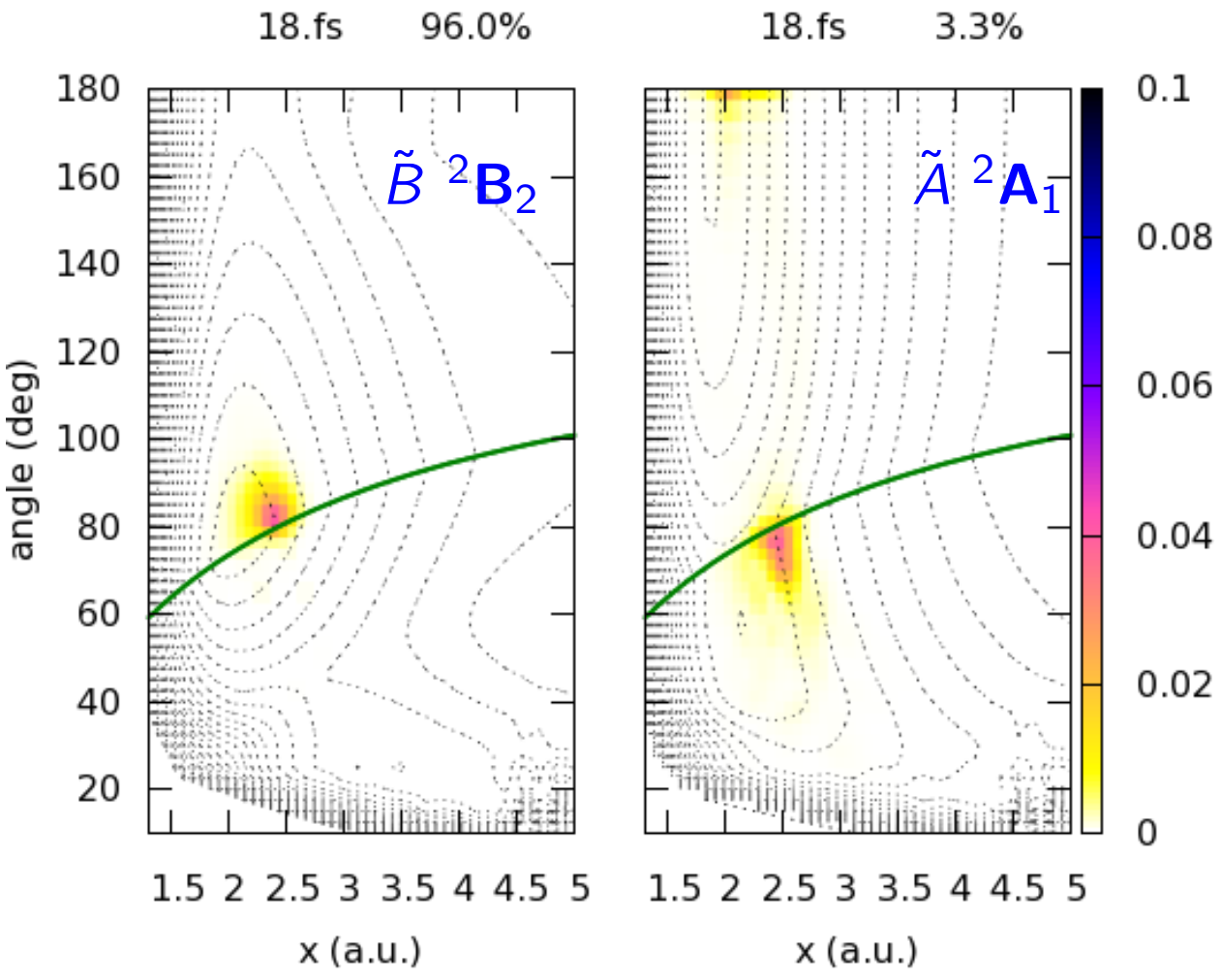
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



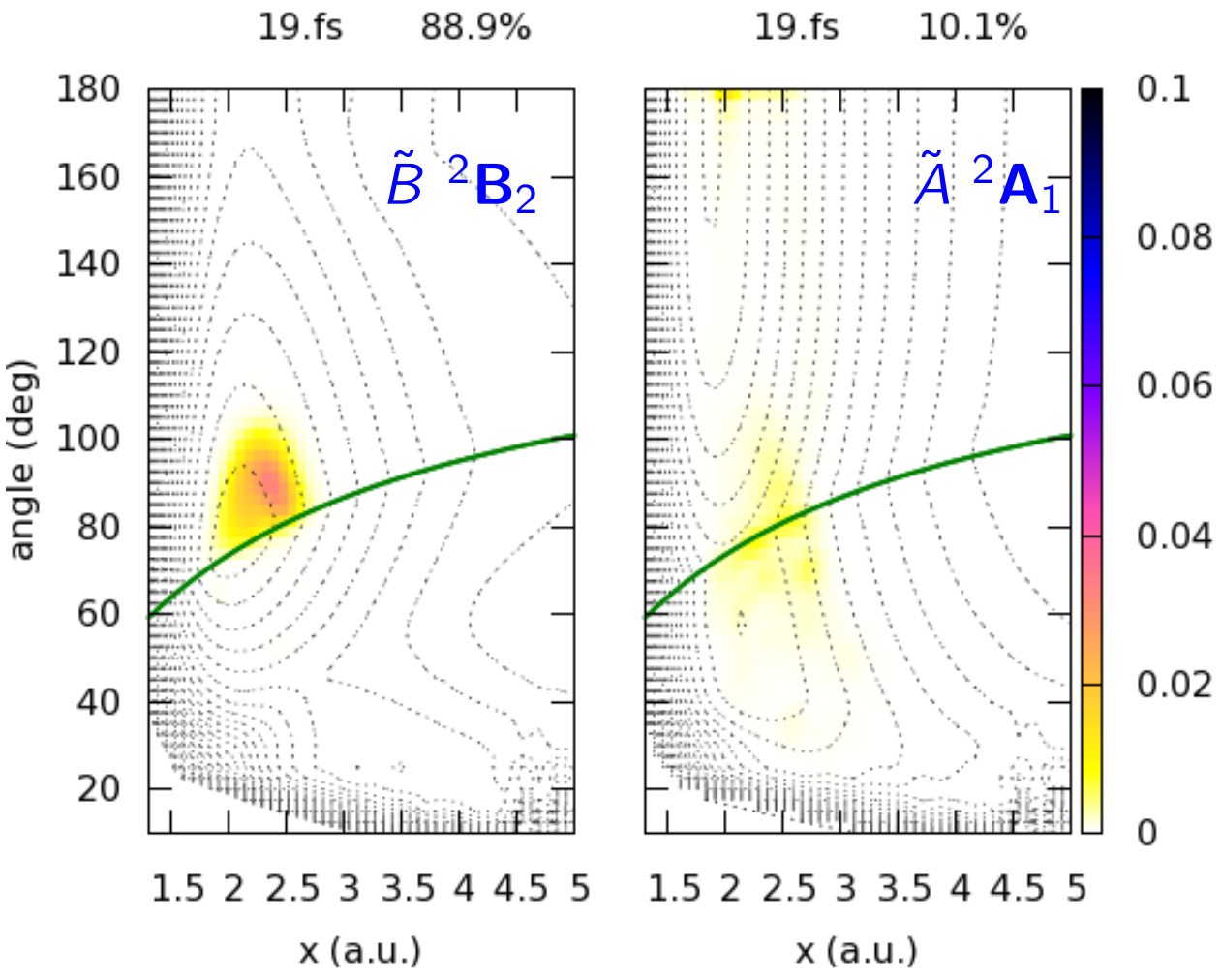
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



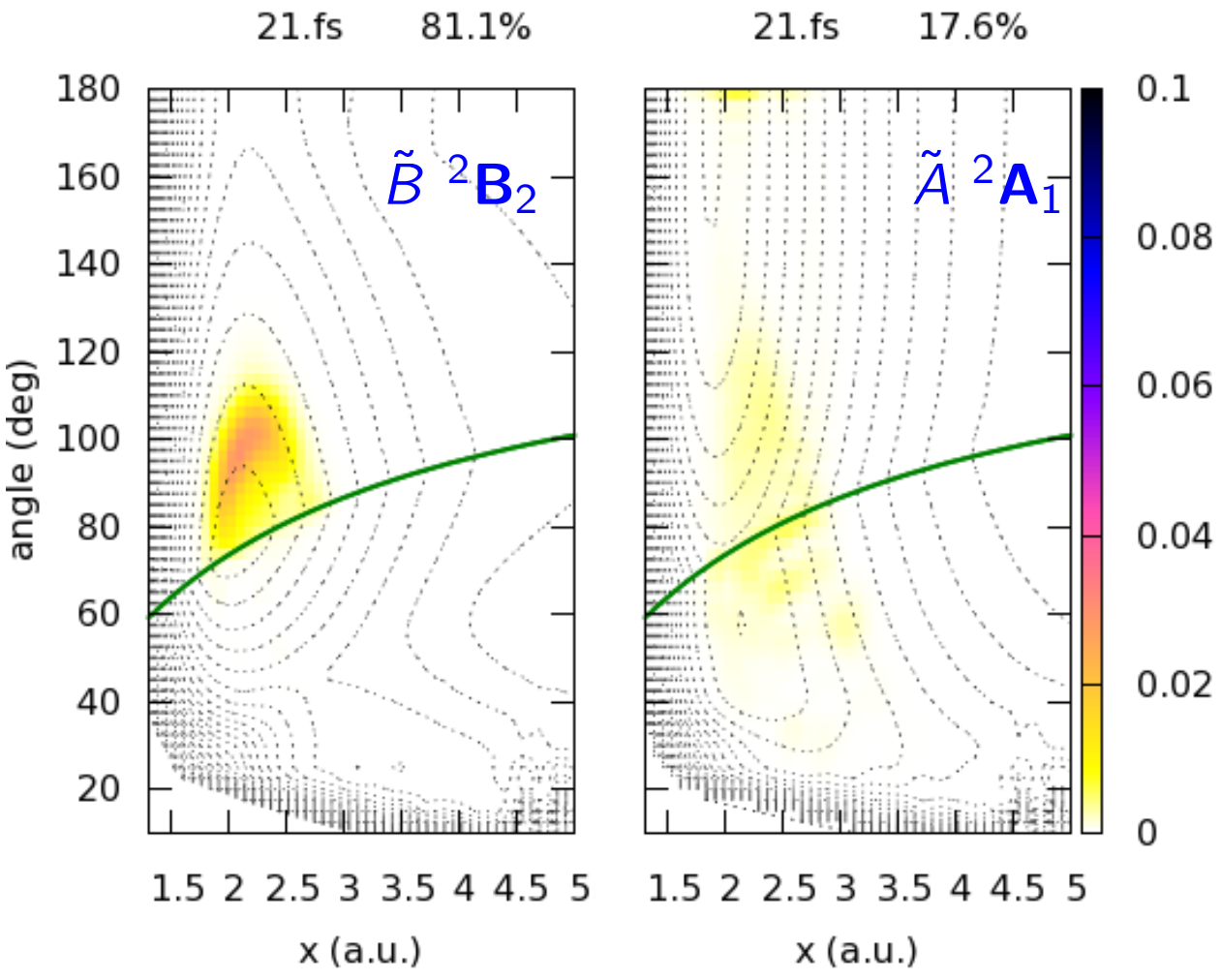
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



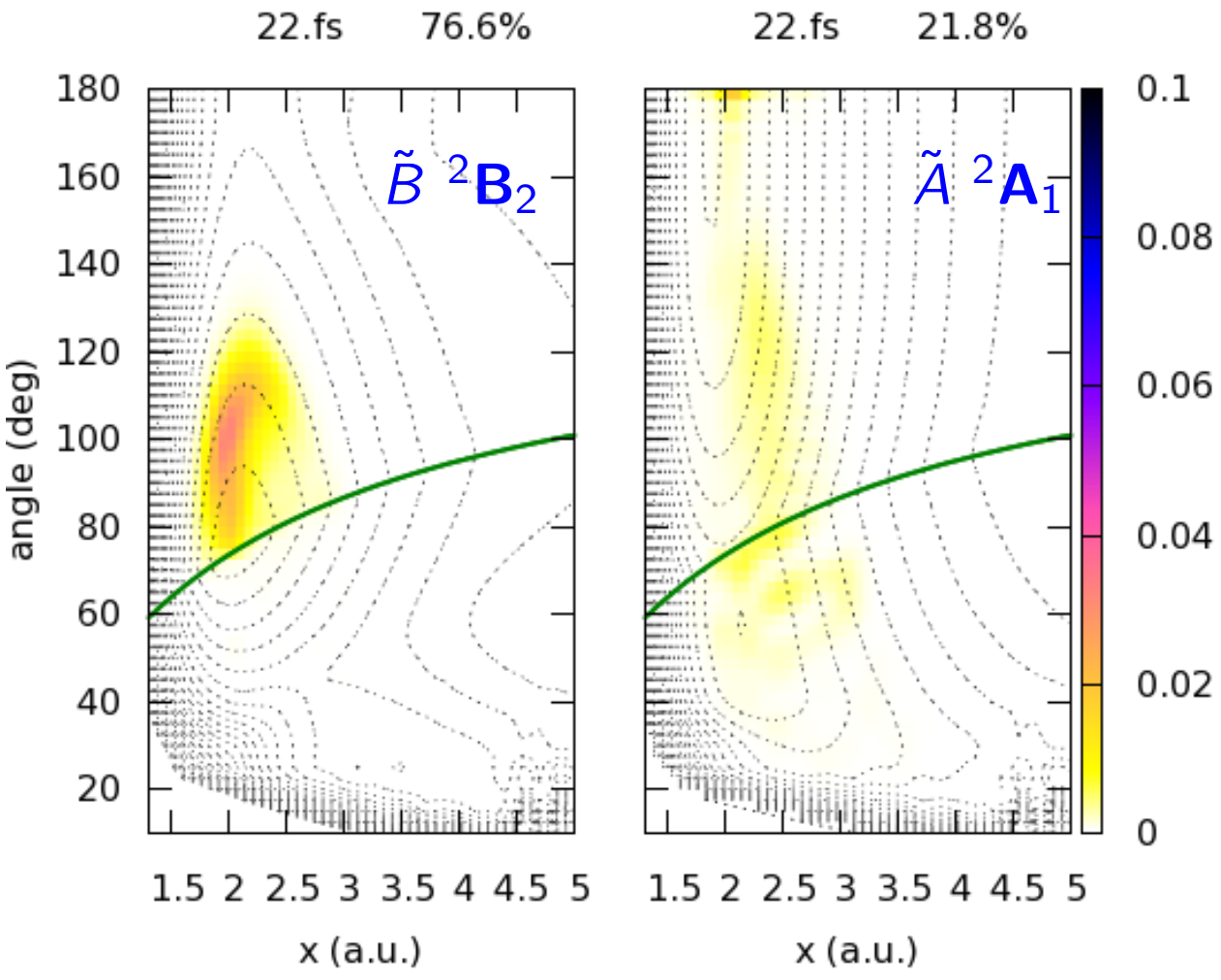
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



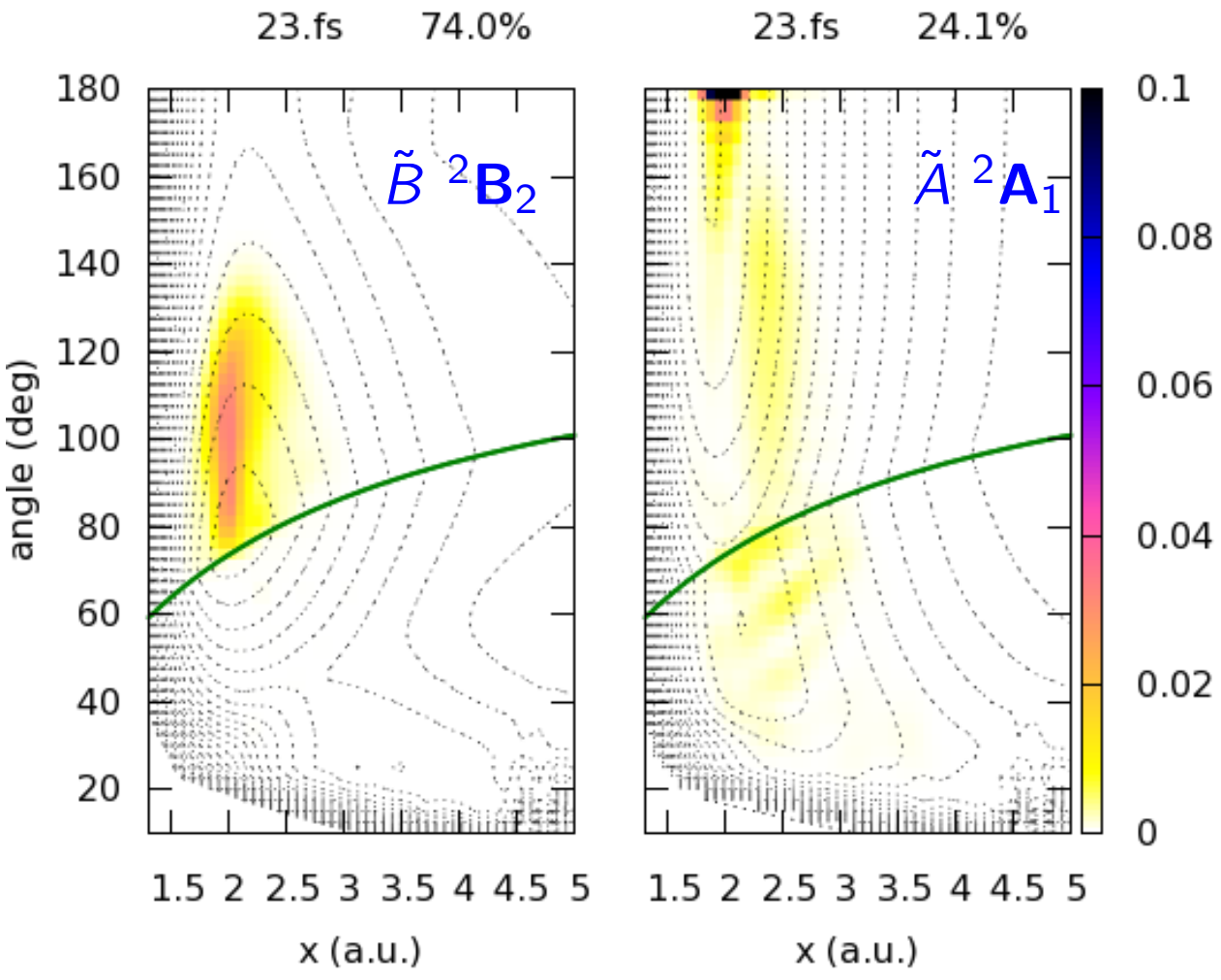
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



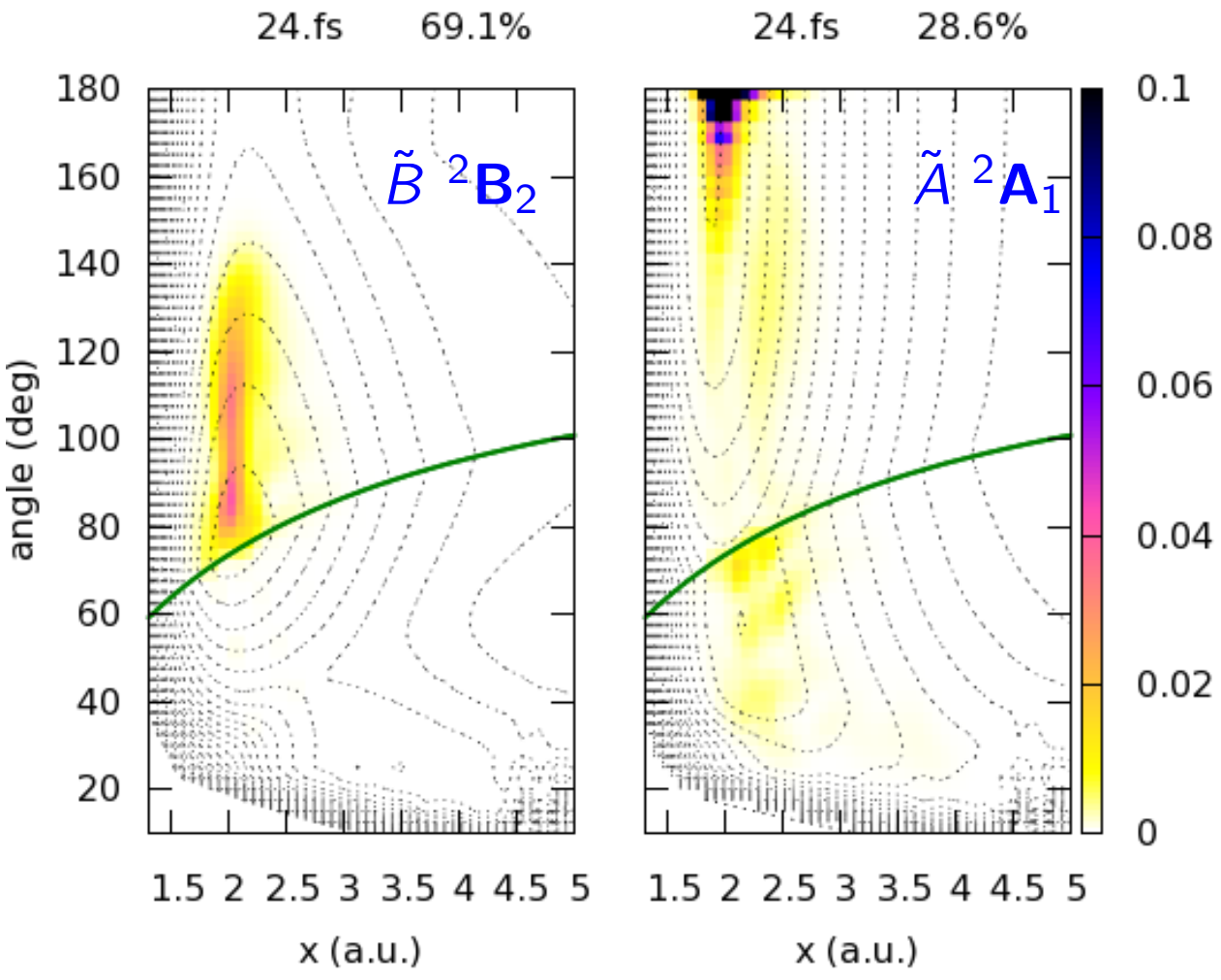
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



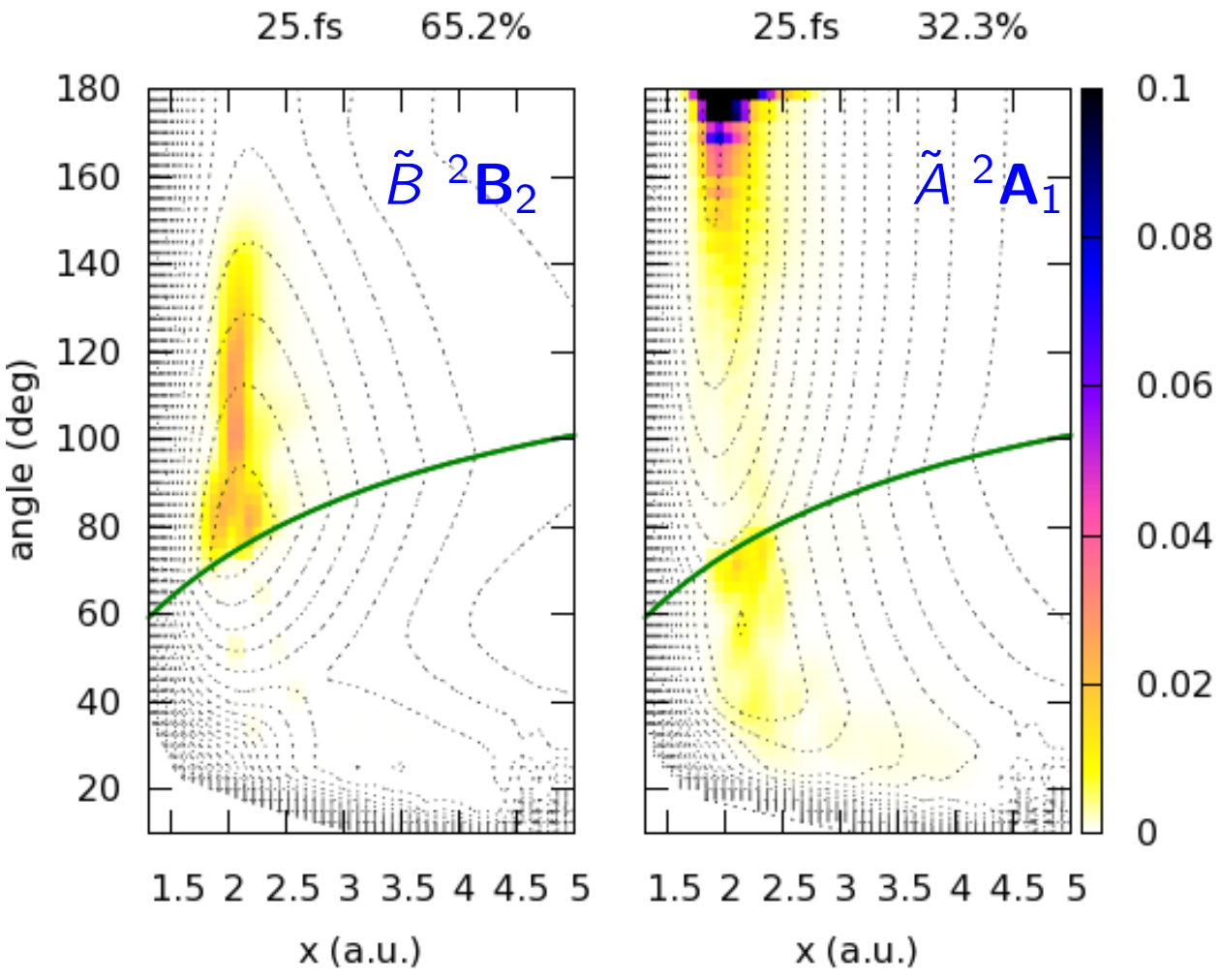
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



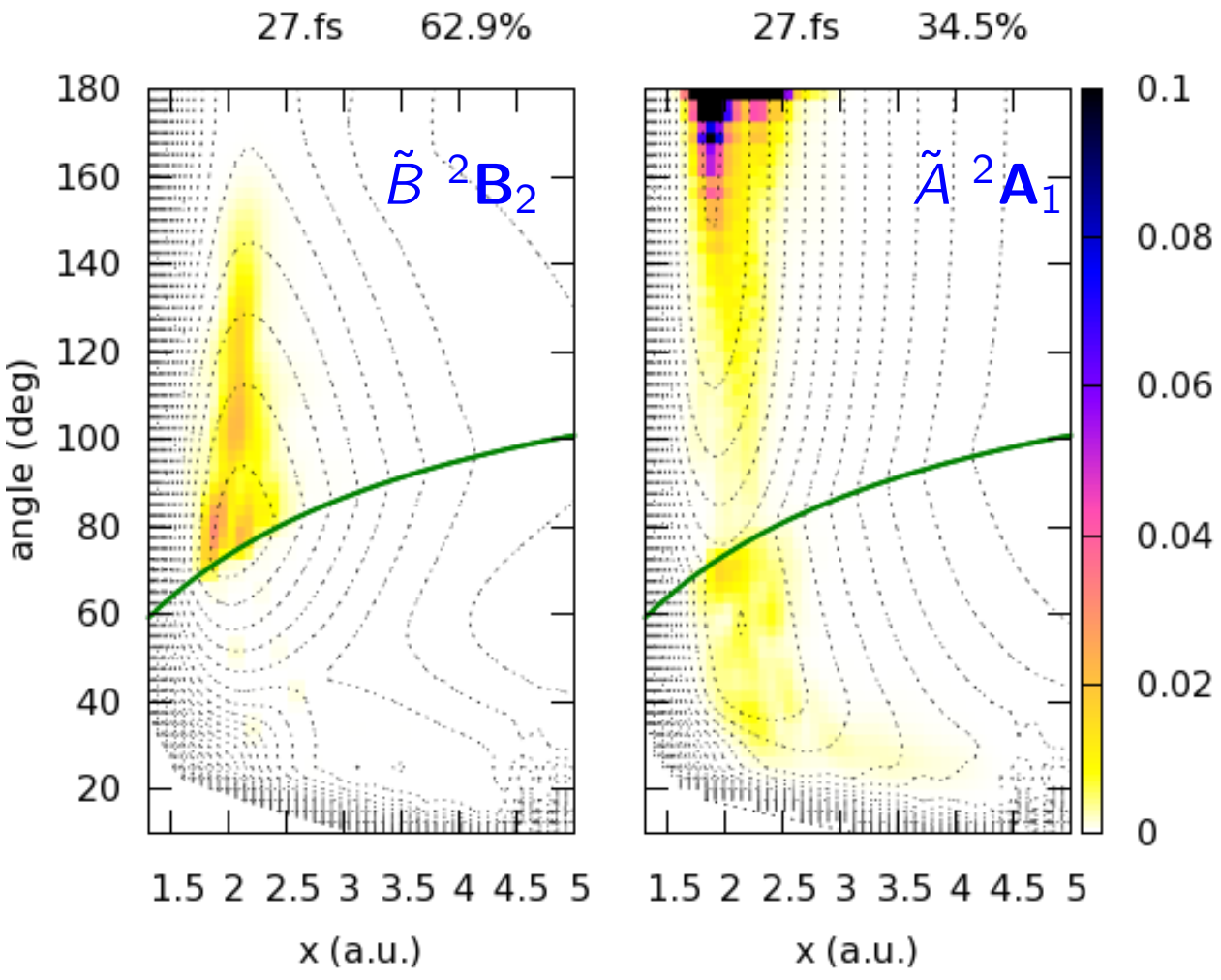
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



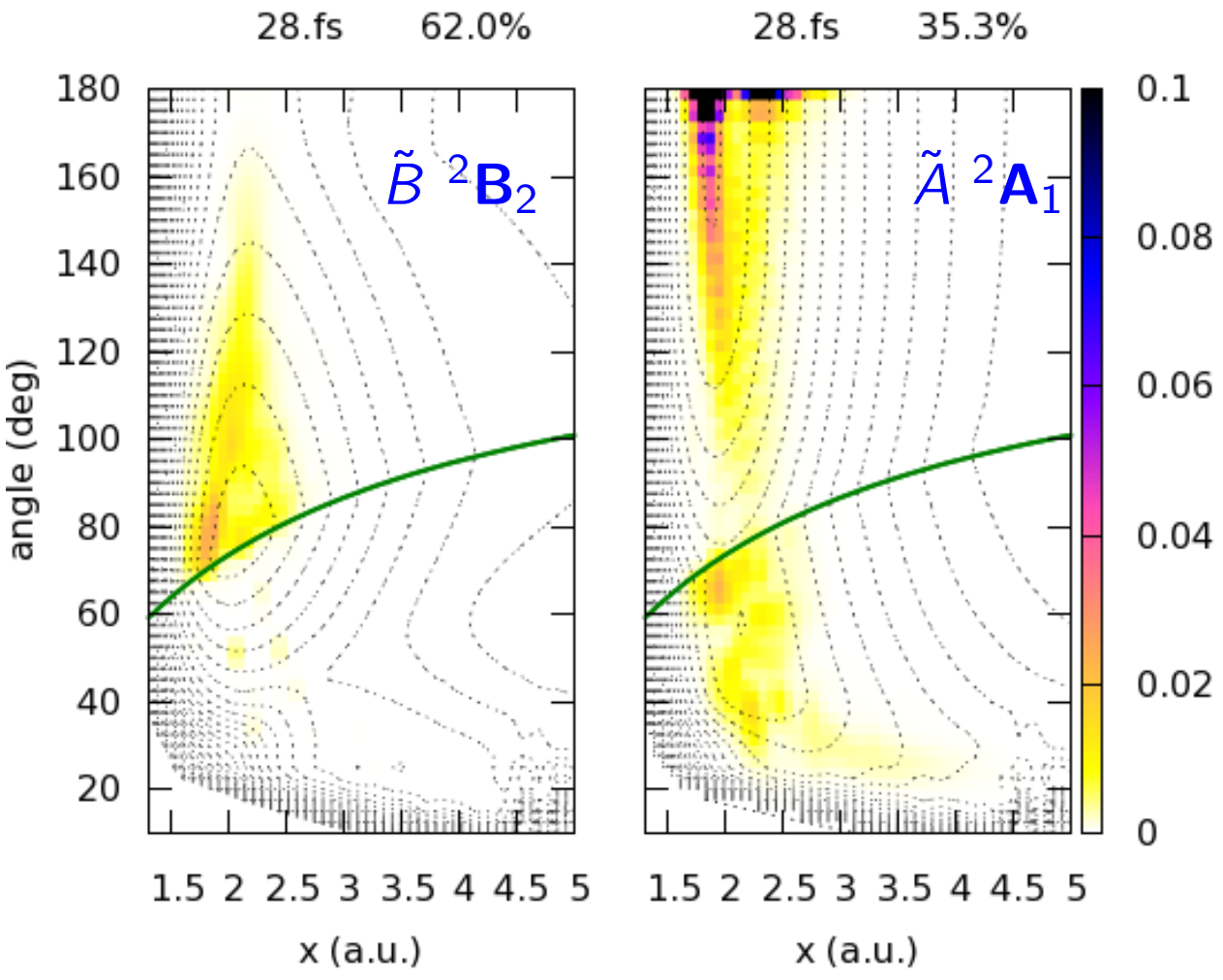
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



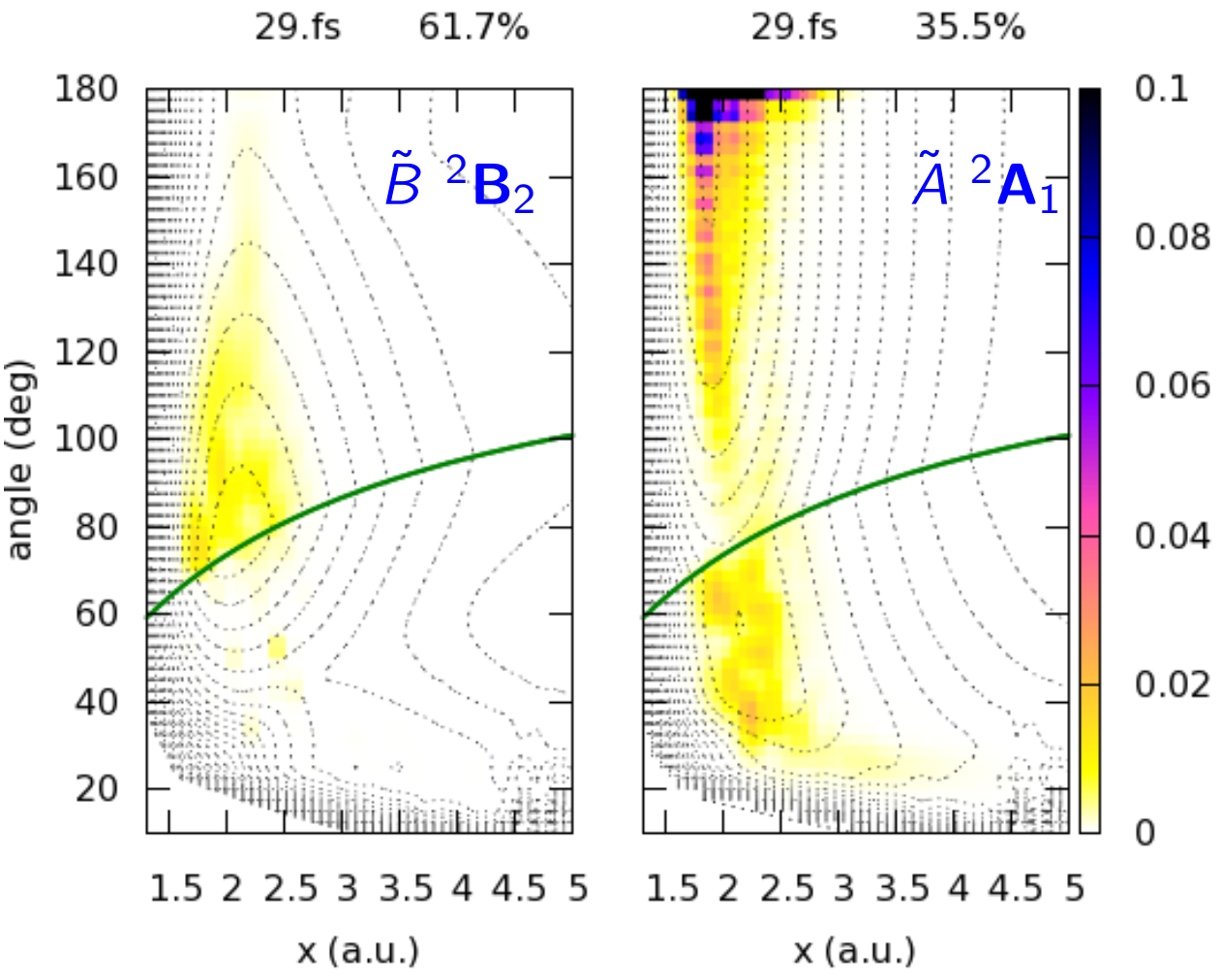
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



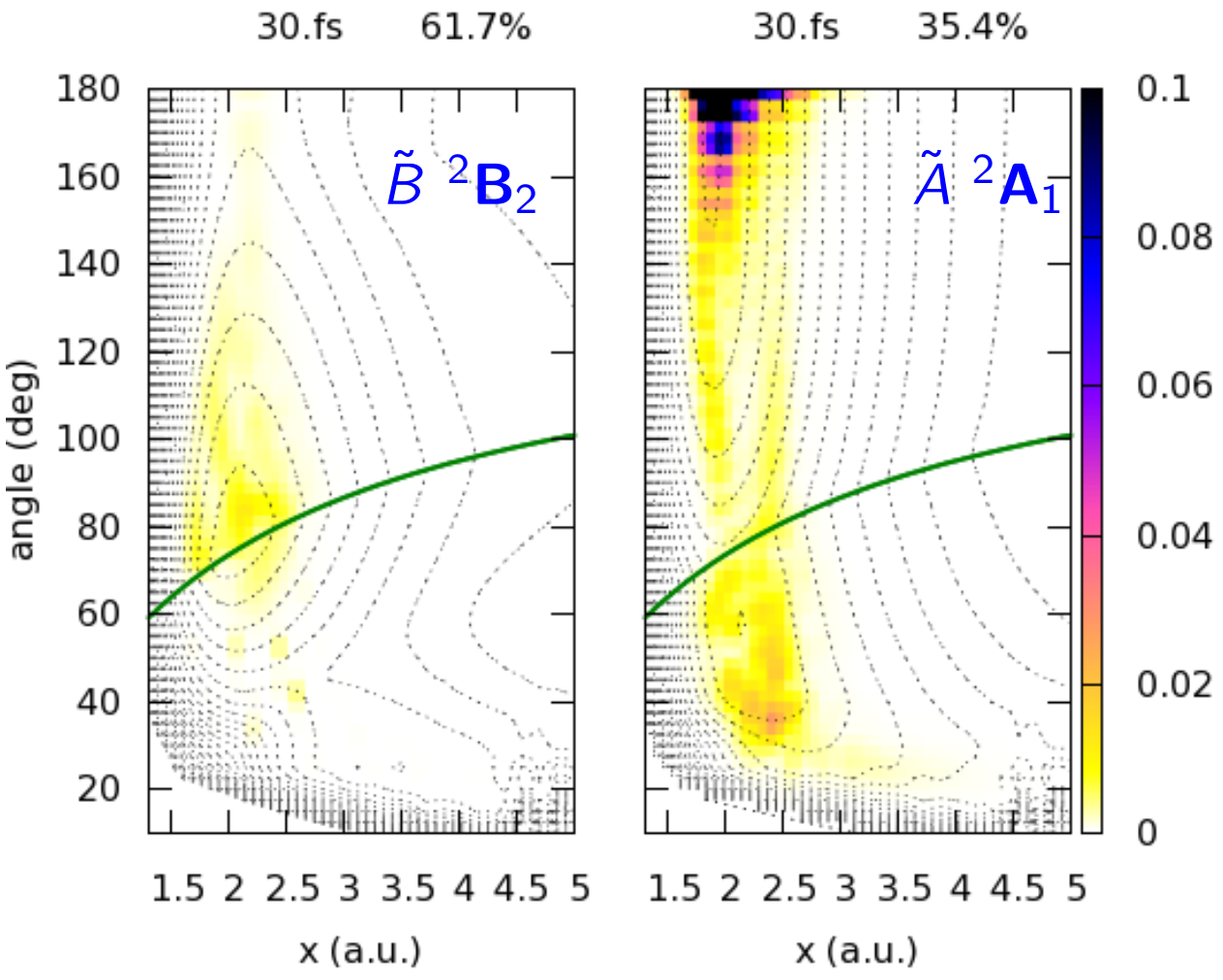
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



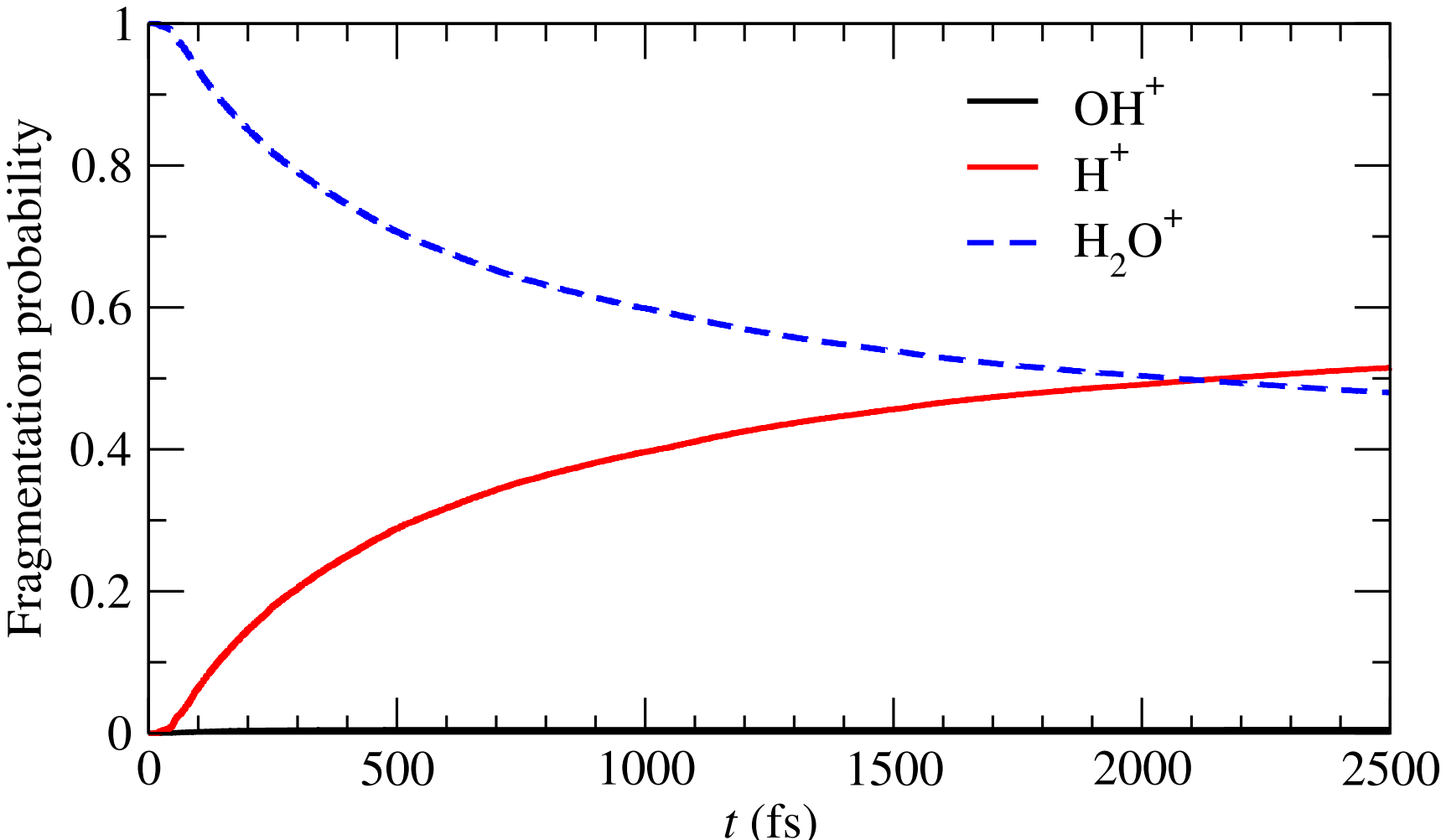
WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



WP in H_2O^+($\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$)



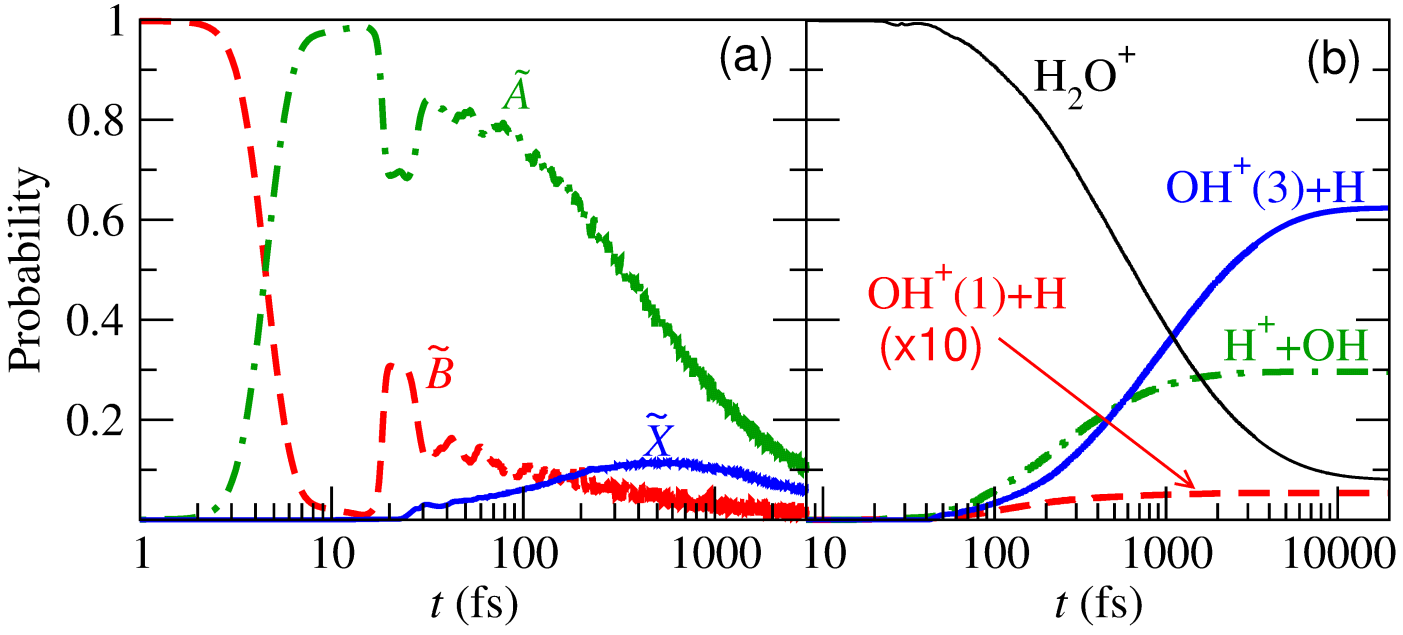
Fragmentation probability with only CI: $\tilde{B}\ ^2B_2$ and $\tilde{A}\ ^2A_1$



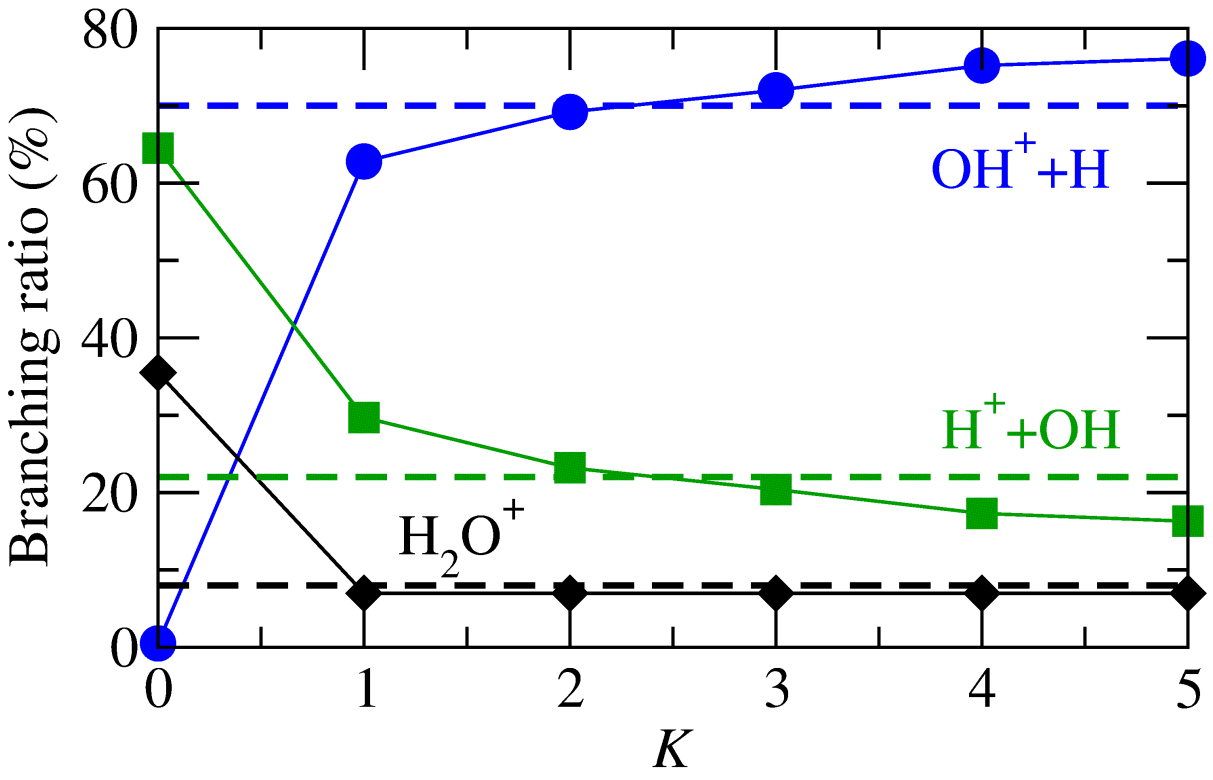
WP in H_2O^+ ($\tilde{B}\ ^2B_2$, $\tilde{A}\ ^2A_1$, $\tilde{X}\ ^2B_1$; $K = 1$)

(wavepacket-animation)

WP in H_2O^+ ($\tilde{B}\ ^2B_2$, $\tilde{A}\ ^2A_1$, $\tilde{X}\ ^2B_1$; $K = 1$)



Fragmentation probabilities ($\tilde{B}\ ^2B_2$, $\tilde{A}\ ^2A_1$, $\tilde{X}\ ^2B_1$)



The dashed lines are the experimental branching ratios of Tan et al.

Summary

- Calculation of four PESs of H_2O^+: $\tilde{B}\ ^2B_2$, $\tilde{A}\ ^2A_1$, $\tilde{a}\ ^4B_1$and $\tilde{X}\ ^2B_1$.
- Regularization of the CI between $\tilde{B}\ ^2B_2$, $\tilde{A}\ ^2A_1$PESs.
- Inclusion of the Renner-Teller coupling between $\tilde{X}\ ^2B_1$and $\tilde{A}\ ^2A_1$.
- Modification of the Grid-TDSE code to treat non-adiabatic transitions.
- Unimportant SO transitions $\tilde{B}\ ^2B_2 \rightarrow \tilde{a}\ ^4B_1$.
- The mechanism $\tilde{B}\ ^2B_2 \rightarrow \tilde{A}\ ^2A_1 \rightarrow \tilde{X}\ ^2B_1$ leads to a breakdown scheme that agrees with the experiments.

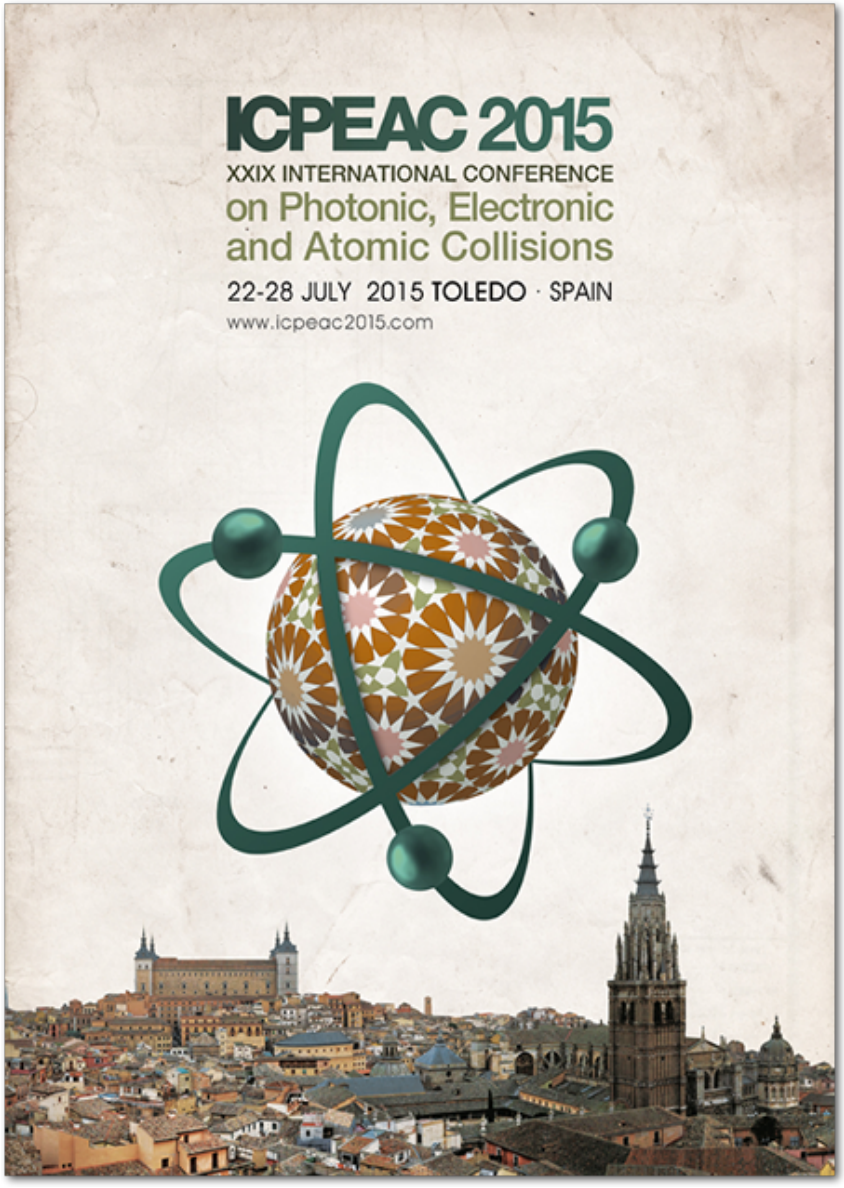
Coworkers

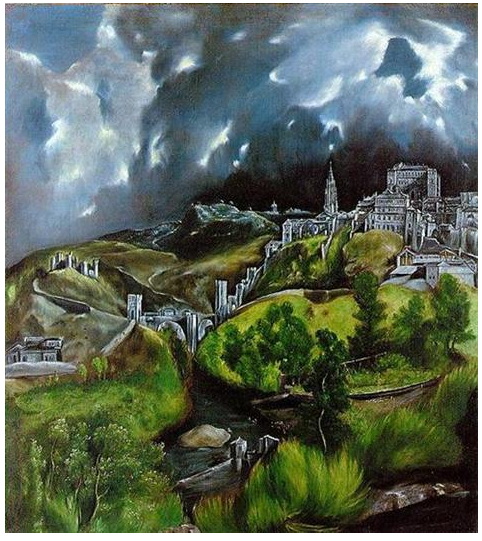
- TCAM group : Luis Errea, Clara Illescas, Alba Jorge, Ismanuel Rabadán, Jaime Suárez.

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

UAM UNIVERSIDAD AUTONOMA DE MADRID

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY


ICPEAC 2015
XXIX INTERNATIONAL CONFERENCE
on Photonic, Electronic
and Atomic Collisions
22-28 JULY 2015 TOLEDO · SPAIN
www.icpeac2015.com



Thank you for your attention!