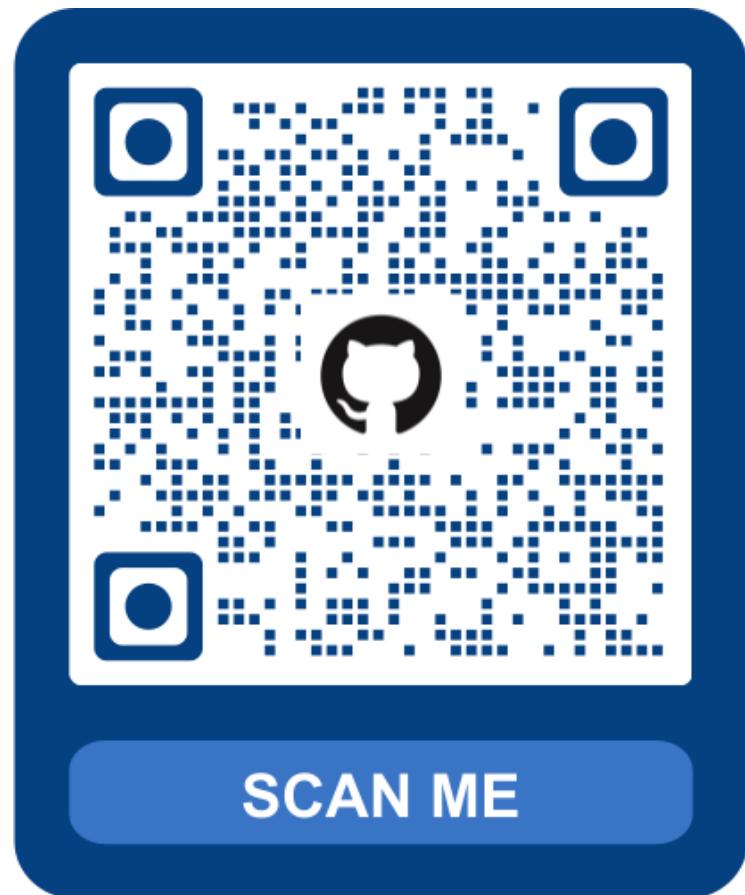




Material





Discovering reaction mechanisms with automated computational methods

EMILIO MARTÍNEZ-NÚÑEZ

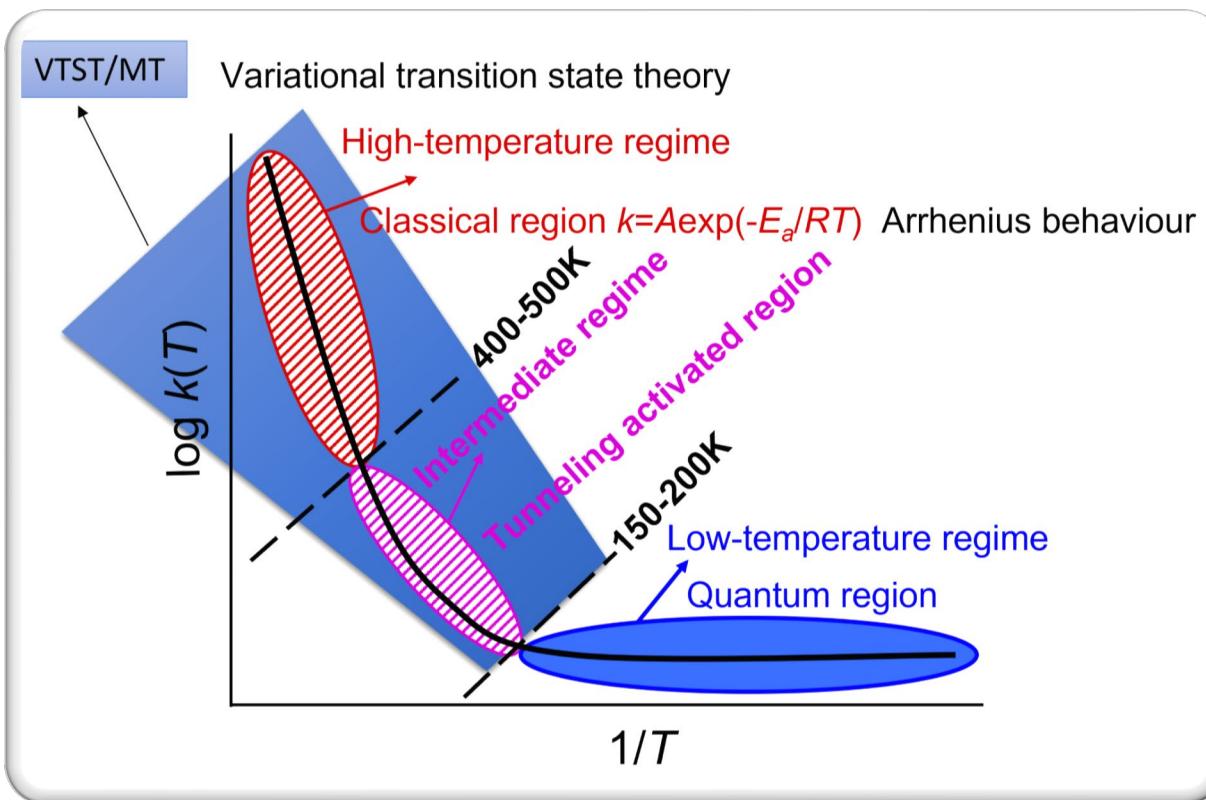
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
SPAIN



School on Kinetics and Dynamics of Chemical Reactions
March 18, 2024 - March 22, 2024



Chemical kinetics

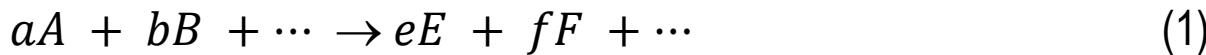


J\J



Basic definitions:

- ✓ Homogenous reactions
- ✓ Closed system



Rate of reaction (r)

$$r = \frac{1}{V} \left(\frac{1}{v_i} \frac{dn_i}{dt} \right) = \frac{1}{v_i} \frac{d[S_i]}{dt} \quad \text{constant } V \quad (2)$$

$$r = -\frac{1}{a} \frac{d[A]}{dt} = -\frac{1}{b} \frac{d[B]}{dt} = \dots = \frac{1}{e} \frac{d[E]}{dt} = \frac{1}{f} \frac{d[F]}{dt} = \dots \quad (3)$$

Example: $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$ $r = -\frac{d[\text{N}_2]}{dt} = -\frac{1}{3} \frac{d[\text{H}_2]}{dt} = \frac{1}{2} \frac{d[\text{NH}_3]}{dt}$

Units for r : chemical kinetics: M s^{-1} ($\text{mol L}^{-1} \text{s}^{-1}$),

chemical dynamics: molecule $\text{cm}^{-3} \text{s}^{-1}$

Rate Law

Relationship between the rate of reaction and the concentrations of species at time t .

$$r = k[A]^\alpha[B]^\beta\dots$$

k is the rate coefficient

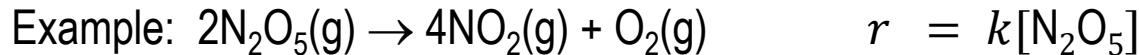
Examples:



Reaction Mechanism (aka reaction network)

Collection of coupled steps involving chemical transformations of molecular species. The different steps are called **elementary reactions**.

A **complex reaction** is formed by two or more elementary steps.



1. $\text{N}_2\text{O}_5 \rightleftharpoons \text{NO}_2 + \text{NO}_3$
2. $\text{NO}_2 + \text{NO}_3 \rightarrow \text{NO} + \text{O}_2 + \text{NO}_2$
3. $\text{NO} + \text{N}_2\text{O}_5 \rightarrow \text{NO}_2 + \text{NO}_2 + \text{NO}_2$

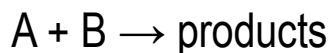
The **molecularity** is the number of molecules that react in an elementary reaction.

Unimolecular reaction



$$-\frac{d[\text{A}]}{dt} = k[\text{A}]$$

Bimolecular reaction



$$-\frac{d[\text{A}]}{dt} = -\frac{d[\text{B}]}{dt} = k[\text{A}][\text{B}]$$



$$-\frac{1}{2} \frac{d[\text{A}]}{dt} = k[\text{A}]^2$$

Differential rate equations (aka master equation)

For a reaction mechanism, we may write the (coupled) differential rate equations. From these equations, we can predict the time evolution of the populations of all the chemical species involved in the mechanism.

Example: $2\text{N}_2\text{O}_5(\text{g}) \rightarrow 4\text{NO}_2(\text{g}) + \text{O}_2(\text{g})$

1. $\text{N}_2\text{O}_5 \rightleftharpoons \text{NO}_2 + \text{NO}_3$
2. $\text{NO}_2 + \text{NO}_3 \rightarrow \text{NO} + \text{O}_2 + \text{NO}_2$
3. $\text{NO} + \text{N}_2\text{O}_5 \rightarrow \text{NO}_2 + \text{NO}_2 + \text{NO}_2$

$$\frac{d[\text{N}_2\text{O}_5]}{dt} = -k_1[\text{N}_2\text{O}_5] + k_{-1}[\text{NO}_2][\text{NO}_3] - k_3[\text{NO}][\text{N}_2\text{O}_5]$$

...

$$\frac{d[\text{O}_2]}{dt} = k_2[\text{NO}_2][\text{NO}_3]$$

$$\frac{d\mathbf{n}(t)}{dt} = \mathbf{Mn(t)}$$

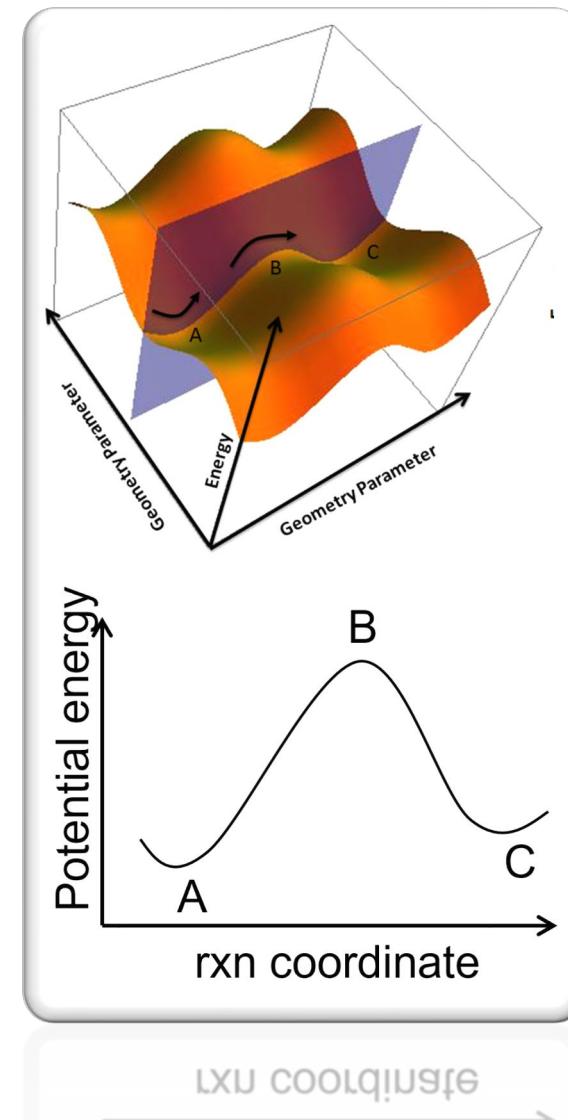
Solution of the ME: Analytical, numerical integration, KMC



Elementary reactions

At the molecular level:

An elementary step involves motion across a single barrier



Not all points matter for chemical kinetics

Important points of the PES: Those in which the gradient is zero (stationary points).

Minima or equilibrium geometries: All the eigenvalues of the Hessian are positive.

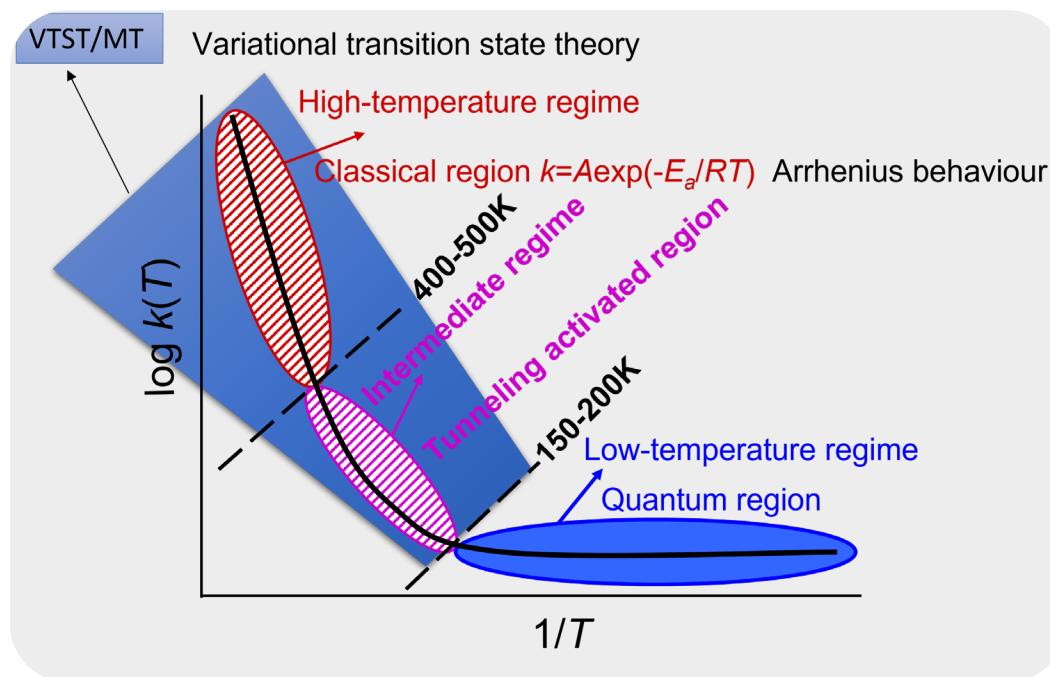
- ✓ *Global*: Lowest potential energy of the PES.
- ✓ *Local*: A point with the lowest potential in a given region.
- ✓ *Reactive intermediate*: Metastable local minimum.
- ✓ *Conformers*: Local minima interconverted by rotations about single bonds.

Saddle points: One or more eigenvalues of the Hessian are negative.

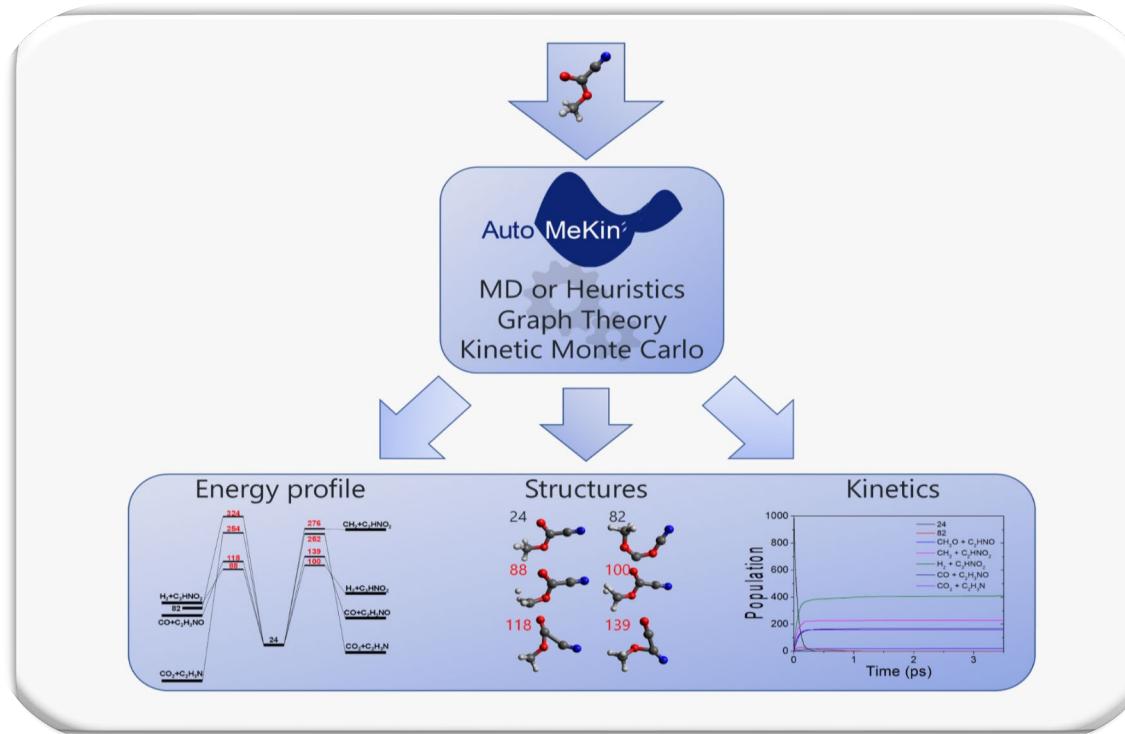
- ✓ *First order*: Only one of the eigenvalues is negative.
- ✓ *Second order*: Two eigenvalues are negative.
- ✓ *Transition state (TS)*: First order saddle point

Note: the Hessian is the matrix of second derivatives of the potential with respect to the coordinates (also called force constant matrix).

Dependence on temperature: $k(T)$



AutoMeKin (Automated Mechanisms and Kinetics)



FULL PAPER

WWW.C-CHEM.ORG

Journal of
COMPUTATIONAL
CHEMISTRY

An Automated Method to Find Transition States Using Chemical Dynamics Simulations

Emilio Martínez-Núñez*

PCCP

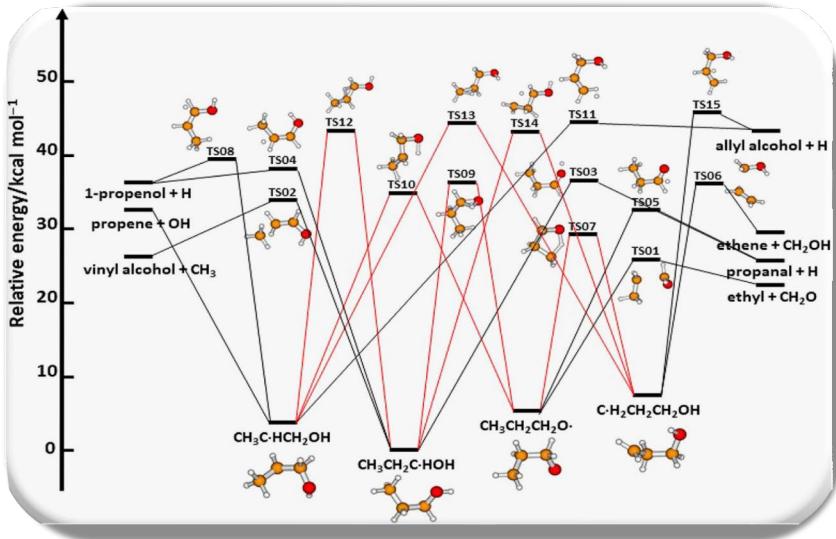
PAPER

Cite this: *Phys. Chem. Chem. Phys.*,
2015, 17, 14912View Article Online
View Journal | View Issue

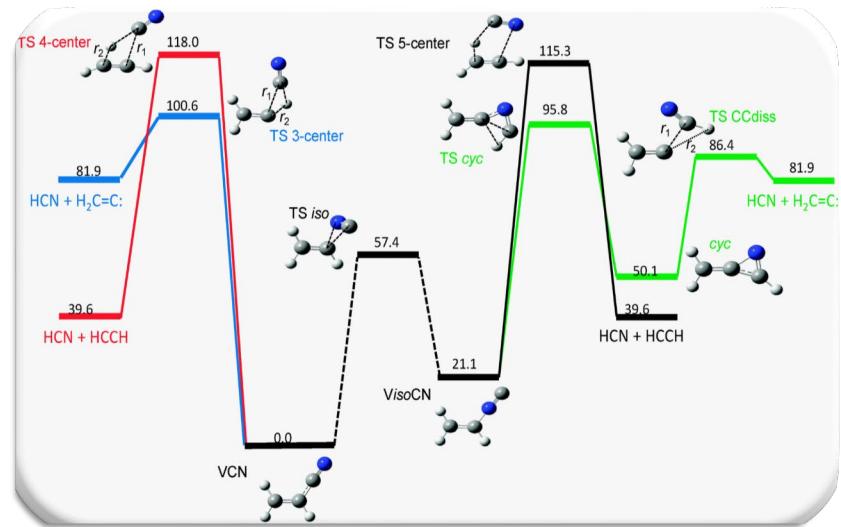
An automated transition state search using classical trajectories initialized at multiple minima†

Emilio Martinez-Núñez

AutoMeKin: Motivation

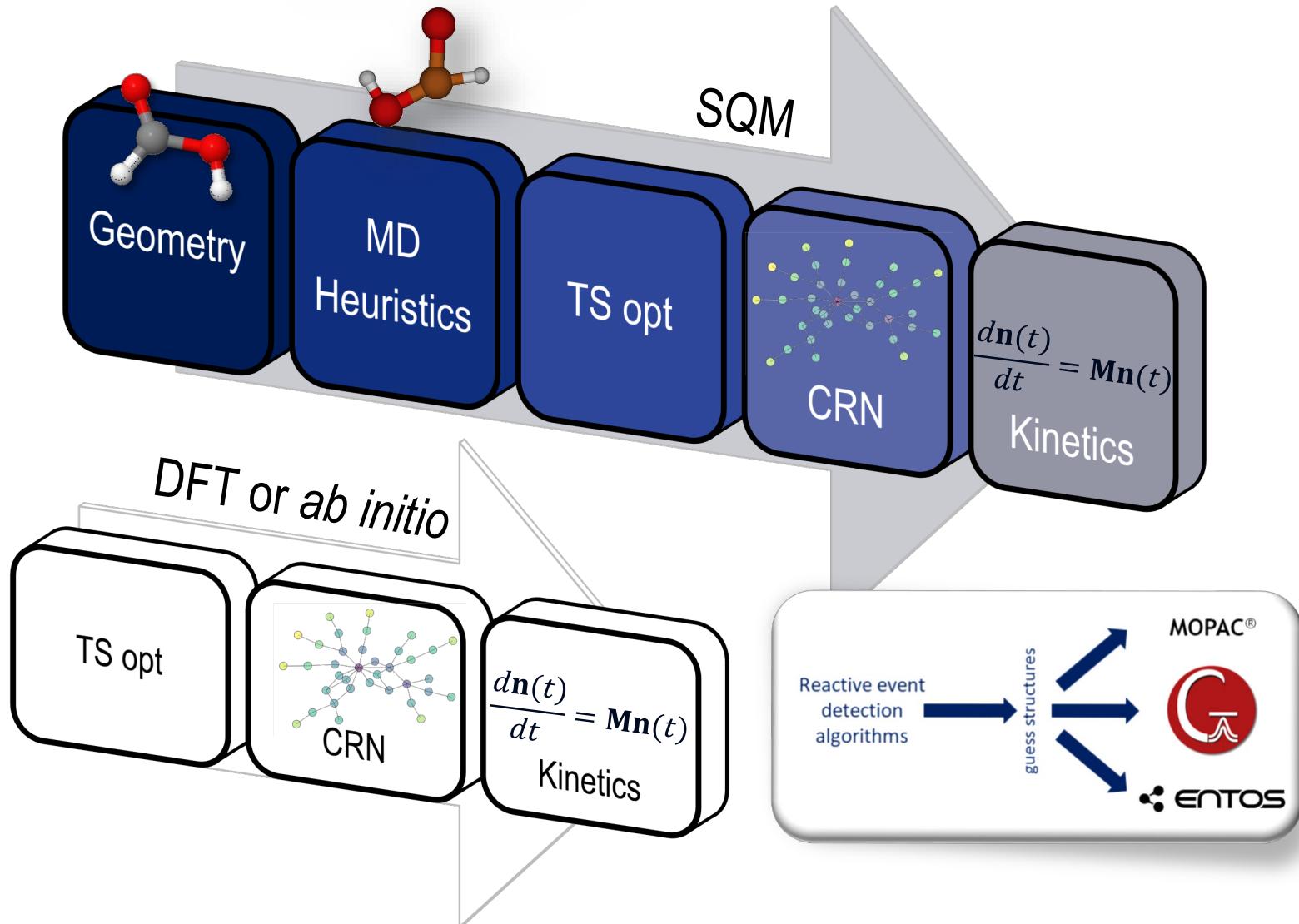


Manual search is not efficient



Possible non-intuitive pathways

AutoMeKin: Workflow

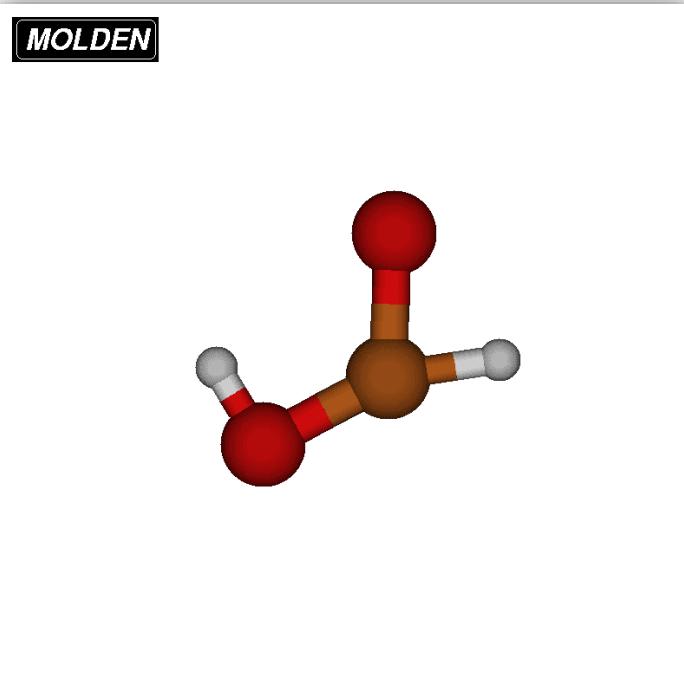


MD simulations

Phys. Chem. Chem. Phys. 2015, 17, 14912

Standard MD: high E or T
and short:

- ✓ QCT
- ✓ Microcanonical/canonical sampling
- ✓ Adaptive energy range
- ✓ Movie: 210 kcal/mol



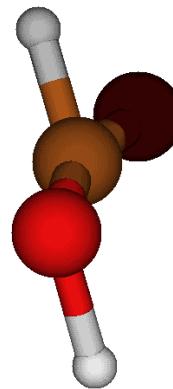
MD simulations

ChemSystemsChem 2020, 152, e19002

Rare-event acceleration
method (BXDE):

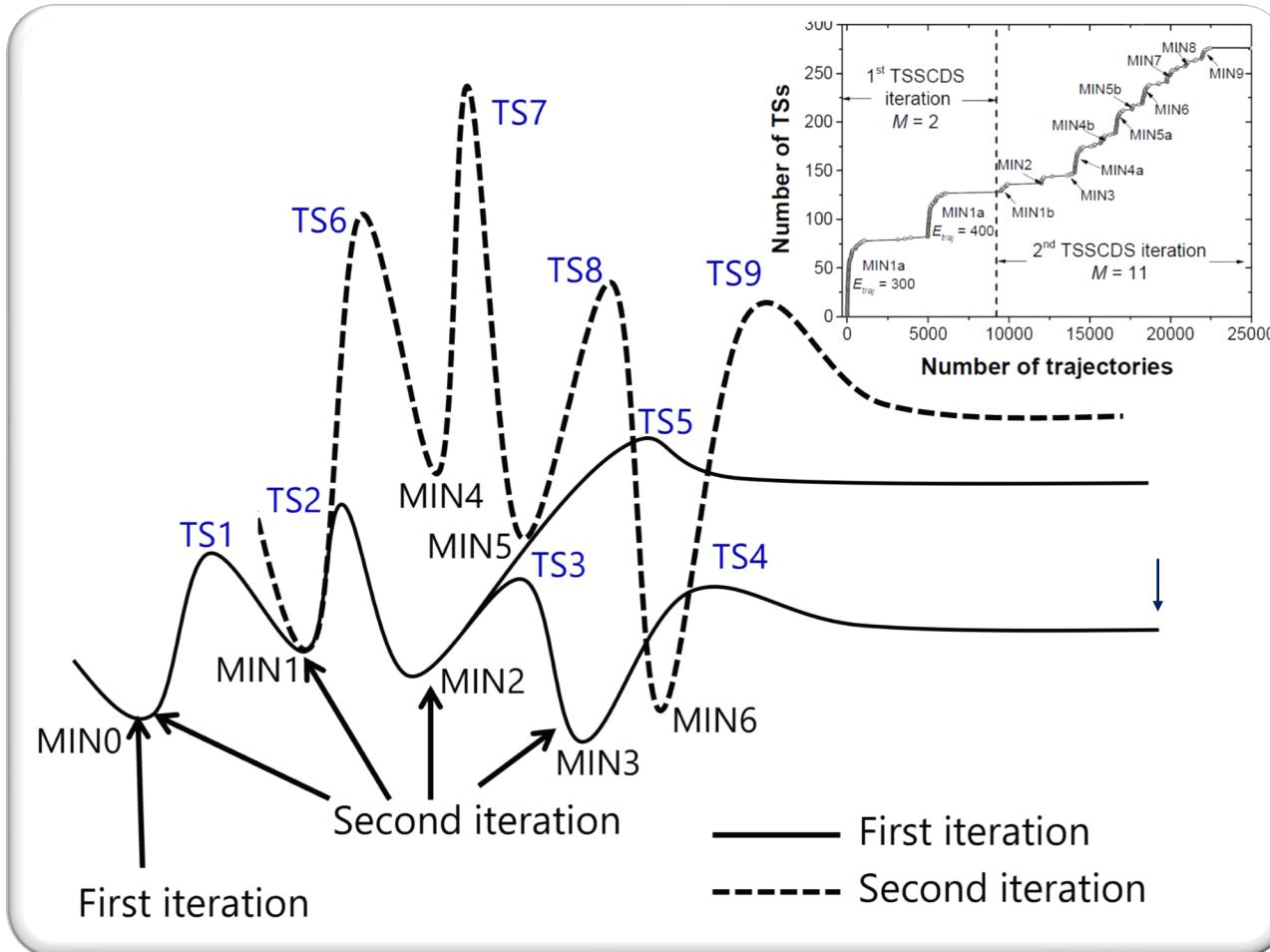
- ✓ Energy boxes
- ✓ More efficient sampling
- ✓ Loose coupling via ASE
- ✓ Movie: Langevin 1000 K

MOLDEN



Sampling from multiple minima

Phys. Chem. Chem. Phys. 2015, 17, 14912



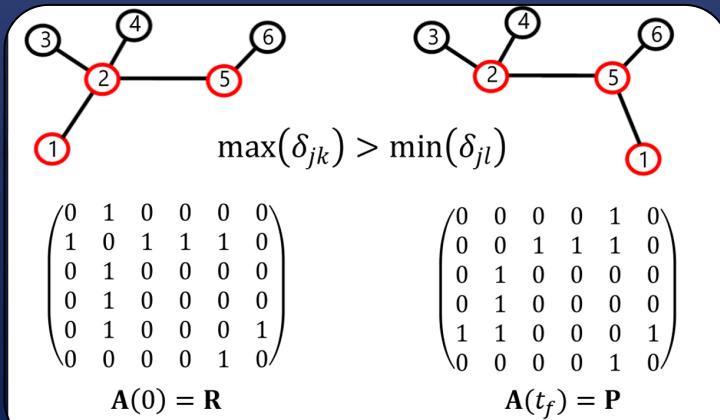


What's different from other methods?

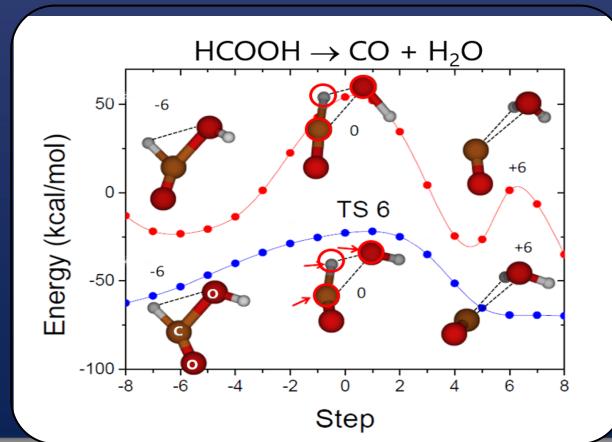
J Comput. Chem. 2015, 36, 222

Detecting Transition States

Graph-based detection step



Relaxation step



$$\text{Laplacian } \mathbf{L} = \mathbf{D} - \mathbf{A}$$

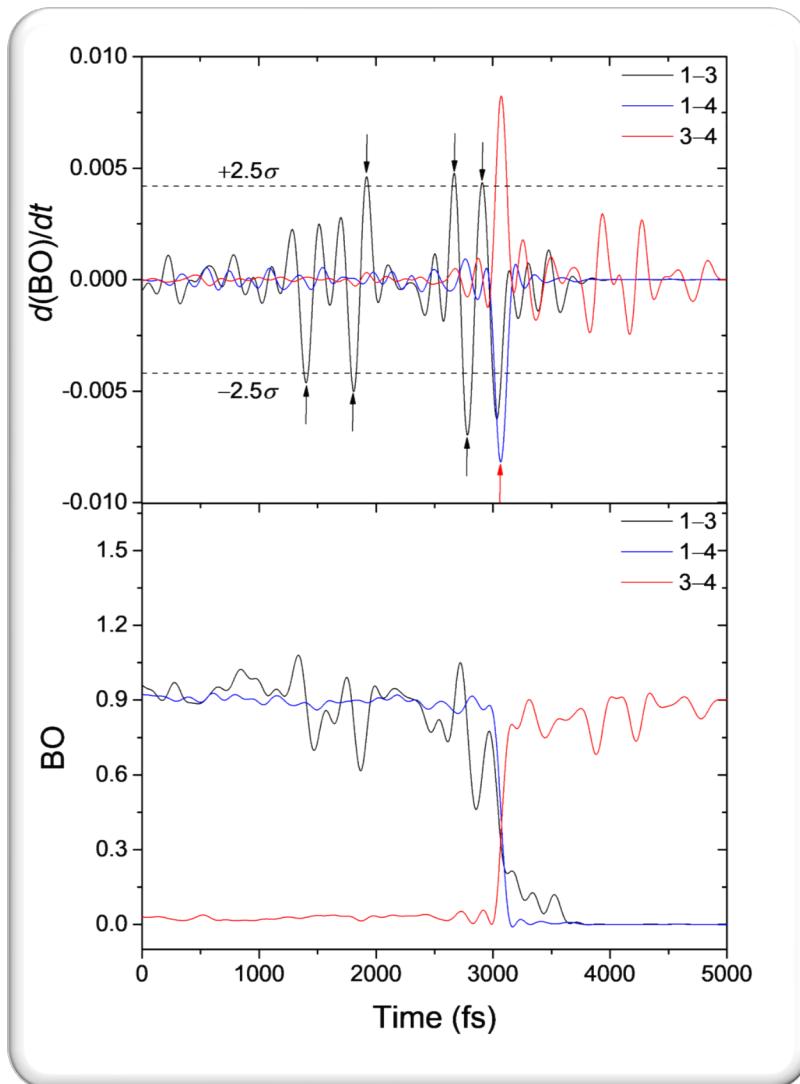
$$\begin{pmatrix} 2 & -1 & -1 & 0 \\ -1 & 2 & 0 & -1 \\ -1 & 0 & 2 & -1 \\ 0 & -1 & -1 & 2 \end{pmatrix}$$

$$\lambda = 0, 2, 2, 4$$

Multiple minima
Spectral Graph Theory
✓ Compare structures
✓ Degree of fragmentation

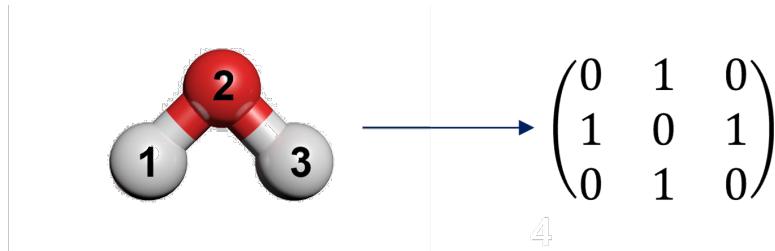
Event detection: Bond orders

JCTC, 2020, 16, 1606

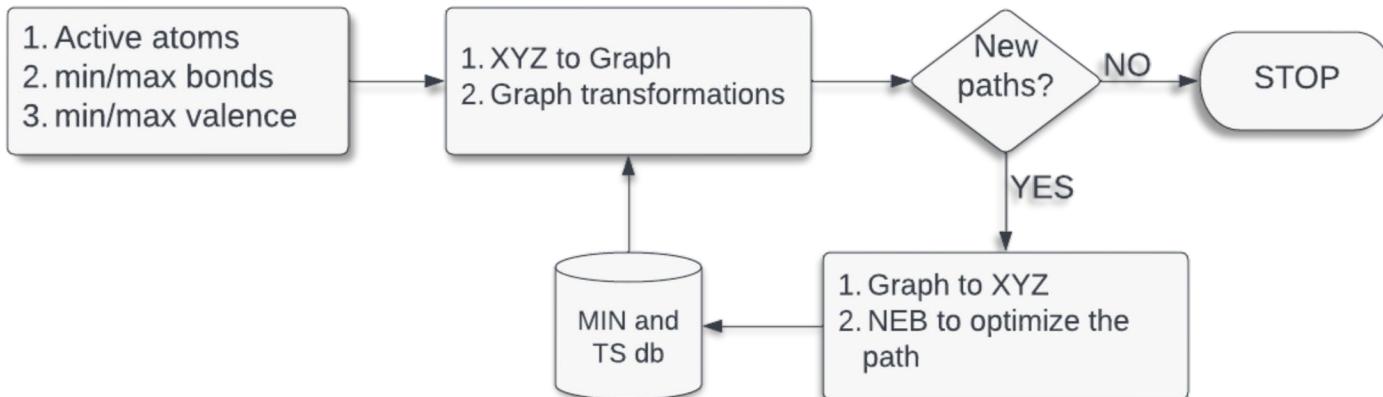


ChemKnow module

J Comput. Chem. 2021, 42, 2036



Graph space



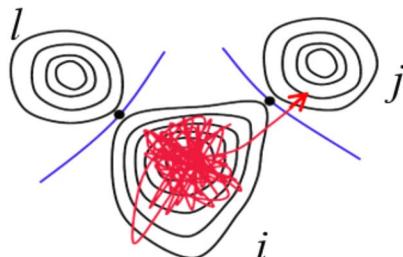
Workflow

Semi-automated kinetics

Automated

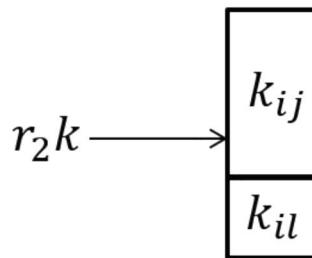
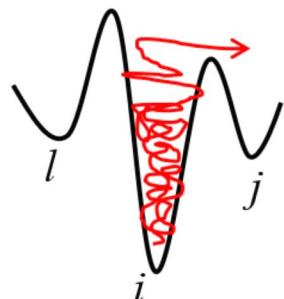
$$k(T) = \sigma \frac{k_B T}{h} e^{-\frac{\Delta G^\ddagger}{RT}}$$

$$\frac{d\mathbf{n}(t)}{dt} = \mathbf{M}\mathbf{n}(t)$$



$$t = -\frac{1}{k} \ln(r_1)$$

$$k = k_{ij} + k_{il}$$



Semi-automated kinetics

Not automated

Pilgrim

<https://github.com/dafarro/Pilgrim>

$$\gamma = \Gamma \kappa$$

$$\Gamma = \frac{Q(T, s^*)}{Q^\dagger(T)} e^{-\beta \Delta E(s^*)}$$

$$\kappa = \frac{\beta \int_0^\infty dE \exp(-\beta E) P(E)}{\exp(-\beta V^{\text{AG}})}$$

amk_tools

ACS Phys. Chem. Au **2022**, 2, 225



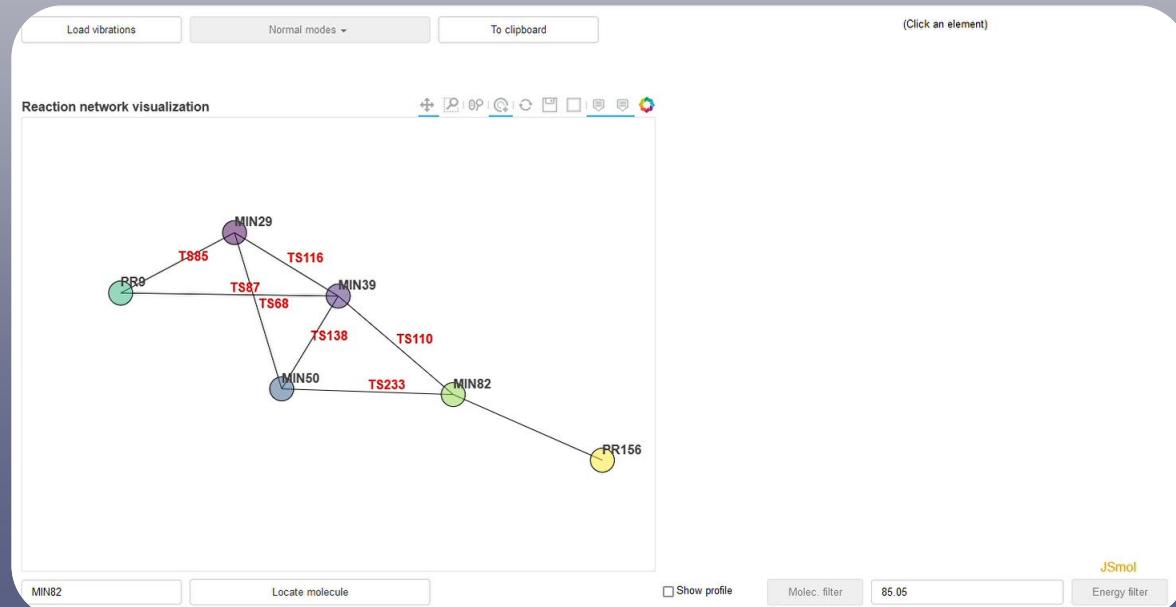
Carles Bo



Diego Garay

- ✓ Interactive HTML
- ✓ Visualize the CRN and energy diagrams

https://github.com/dgarayr/amk_tools



Last version: 2021.1137

J. Comput. Chem. 2021, 42, 2036



Pablo
Tahoces



Roberto
Rodríguez

- ✓ GitHub & syllabs
- ✓ Web site
- ✓ Notebook



Aurelio
Rodríguez

<https://github.com/emartineznunez/AutoMeKin>

The screenshot shows a table of jobs with columns: Id, Description, Status, Graph, Report, Data, and Delete. There are two rows:

Id	Description	Status	Graph	Report	Data	Delete
1952	FA	✓	🕒	🕒	🕒	🕒
1959	your job description here	✓	🕒	🕒	🕒	🕒

At the bottom left is a "New Job" button. At the bottom right is a "Completed" status indicator.

Acknowledgements



The screenshot shows a browser window with the URL <https://catal-research.google.com/github/emartineznunez/AutoMeKin/blame/master/AutoMeKin.ipynb?raw=true&t=202208090242>. The page title is "AutoMeKin.ipnb".

The content includes:

- Making the input files**: A section with instructions and a code editor containing Python code for generating input files.
- Building the molecule**: A section with instructions and a code editor containing Python code for building molecules.
- Installing third-party packages**: A section with instructions and a code editor containing Python code for installing packages.

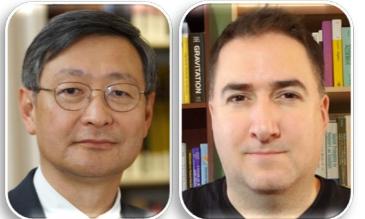
AutoMeKin: Applications

System	Reference
Pyrolysis of isoprene	Combust. Flame 2022 , 242, 112206
Fragmentation of indole	ACS Phys. Chem. Au 2022 , 2, 225
Diglycine and dialanine	JCTC 2021 , 17, 5556
Photoisomerization of a charged styryl dye	J. Am. Soc. Mass. Spectrom. 2021 , 32, 284
Formation of formaldehyde in cold astrophysical regions	A&A 2021 , 656, A148
Fragmentation of octaazapentalene	Monatsh Chem. 2021 , 152, 421
Syngas oxy-combustion in supercritical CO ₂	J. CO ₂ Util 2021 , 49, 101554
Electron-transfer-induced cleavage in Tryptophan	JPCA 2021 , 125, 2324
Cycloaddition of cyclic nitrone	Tetrahedron 2020 , 76, 130764
Ozonolysis of α -pinene	ChemSystemsChem 2020 , 152, e19002.
vdW interactions	IJQC 2019 , 119, e26008
Fragmentation of L-Cysteine	JPCA 2019 , 123, 3685
Thermal decomposition of 1-propanol	JPCA 2018 , 122, 4790
Tetrahydrofuran oxidation	Combust Flame 2018 , 191, 252
Photolysis of methyl cyanoformate	ApJ 2017 , 849, 15
Hydroformylation of ethylene	Chem. Sci. 2017 , 8, 3843
Fragmentation of protonated uracil	PCCP 2016 , 18, 22712
Photolysis of acryloyl chloride	PCCP 2016 , 18, 5019
Photolysis of propenal	PCCP 2015 , 17, 14912
HCN elimination from vinyl cyanide	PCCP, 2015 , 17, 6948

- ✓ Atmospheric chemistry.
- ✓ Astrochemistry.
- ✓ Non-covalent interactions.
- ✓ Homogeneous catalysis.

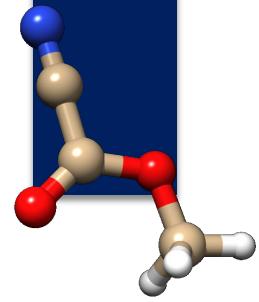
Hai-Lung Dai

Michael Wilhelm

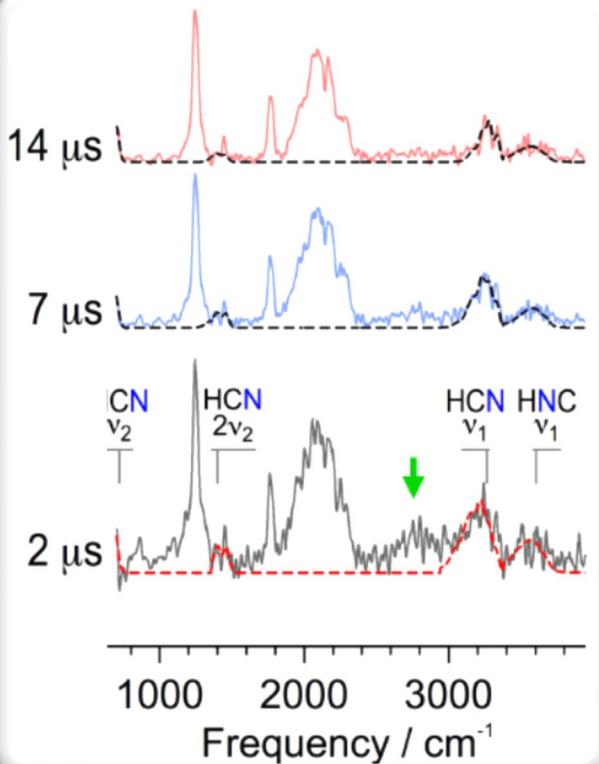


Photolysis of methyl cyanoformate

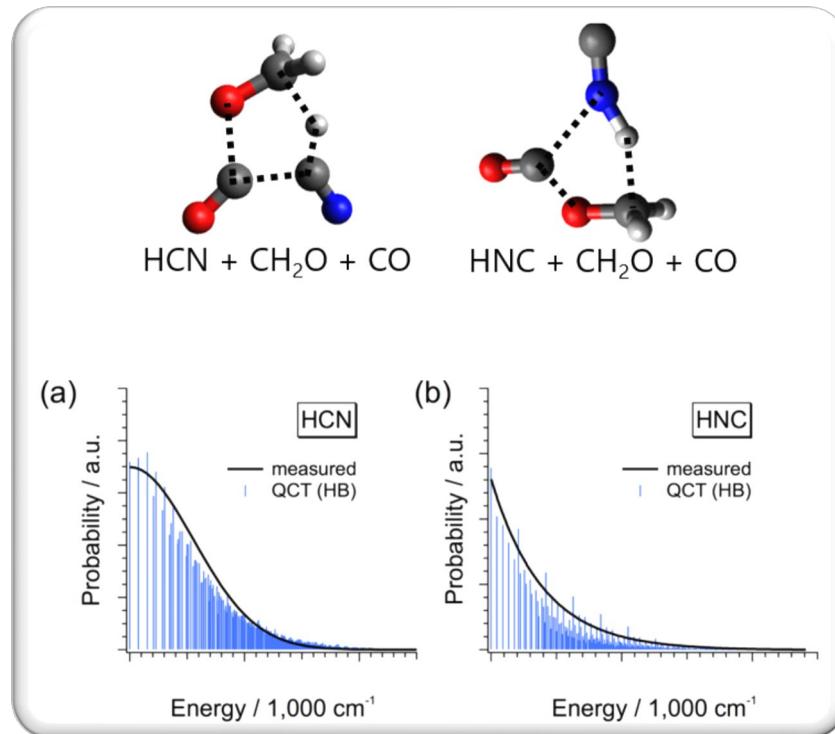
ApJ. 2017, 849, 15



Time-resolved IR spectra
Evidence of HCN(HNC) formation



AutoMeKin & QCT
TSs & Vibrational distros



Dani
Peláez

vdW interactions

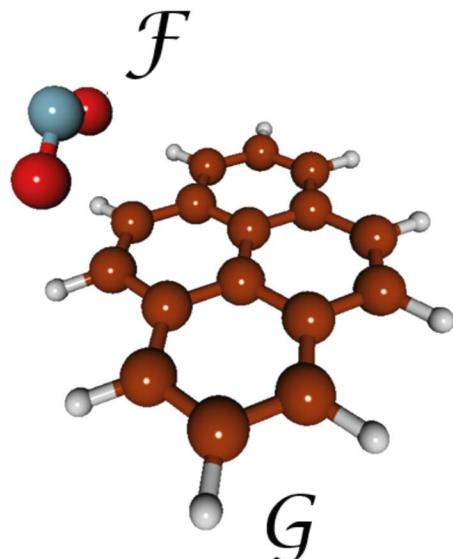
Int. J. Quantum Chem. 2019, 119, e26008

New A matrix

F: Molecule F

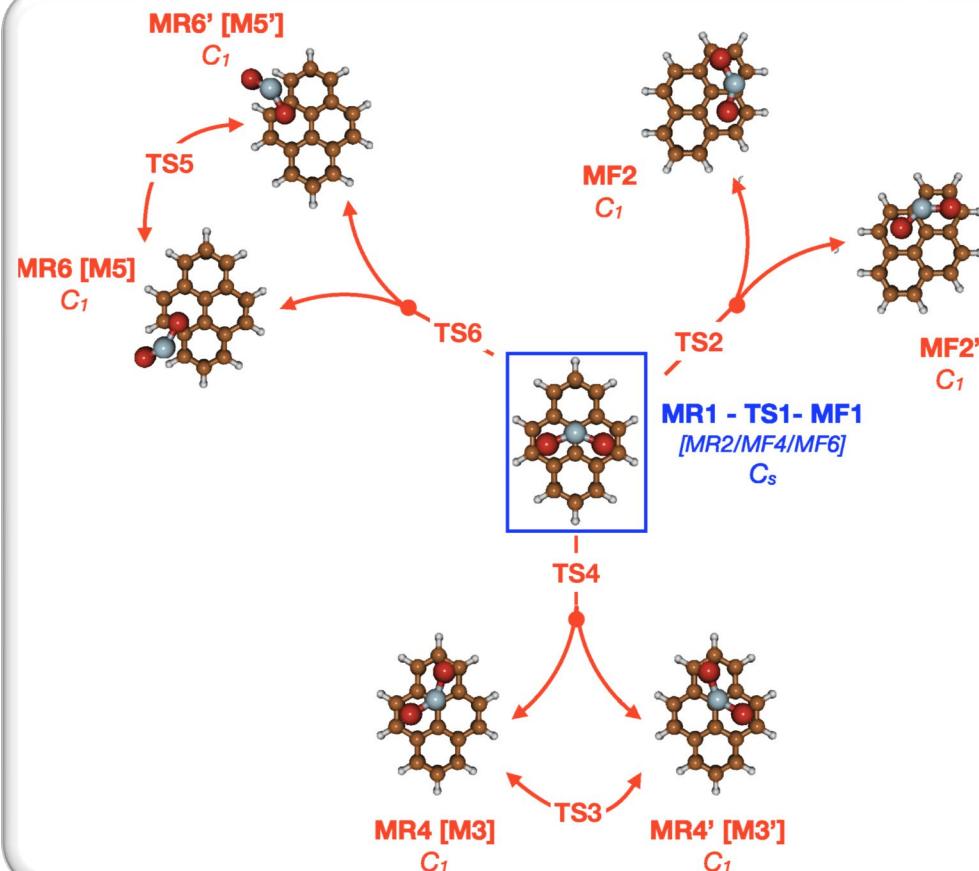
G: Molecule G

$$A = \begin{pmatrix} F & FG \\ FG & G \end{pmatrix}$$



NO₂-pyrene

Most stable minimum-energy structures



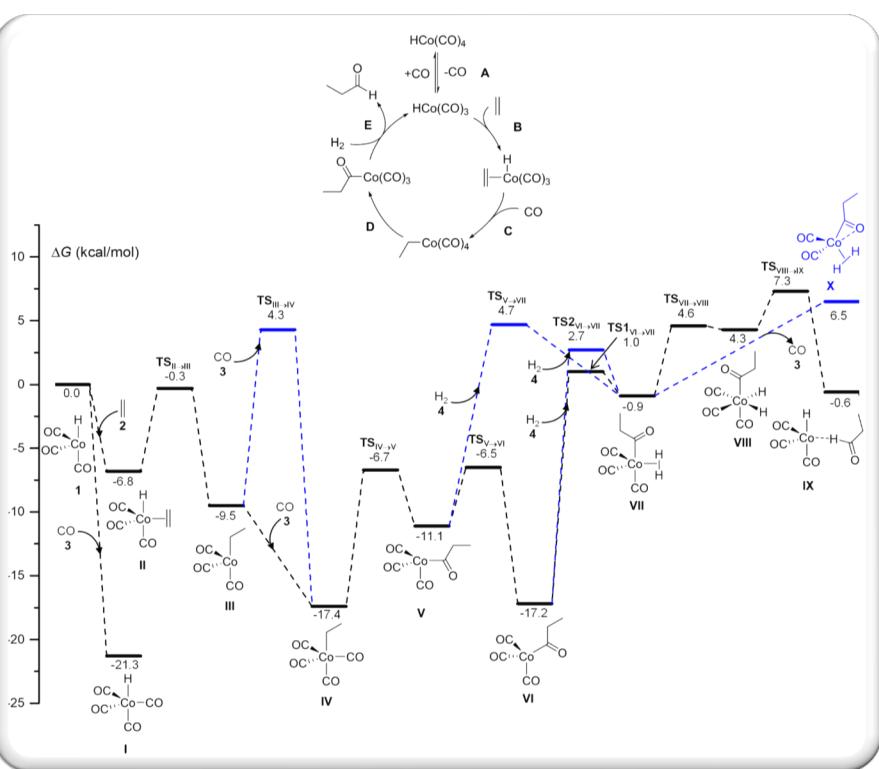


Jesús
Varela

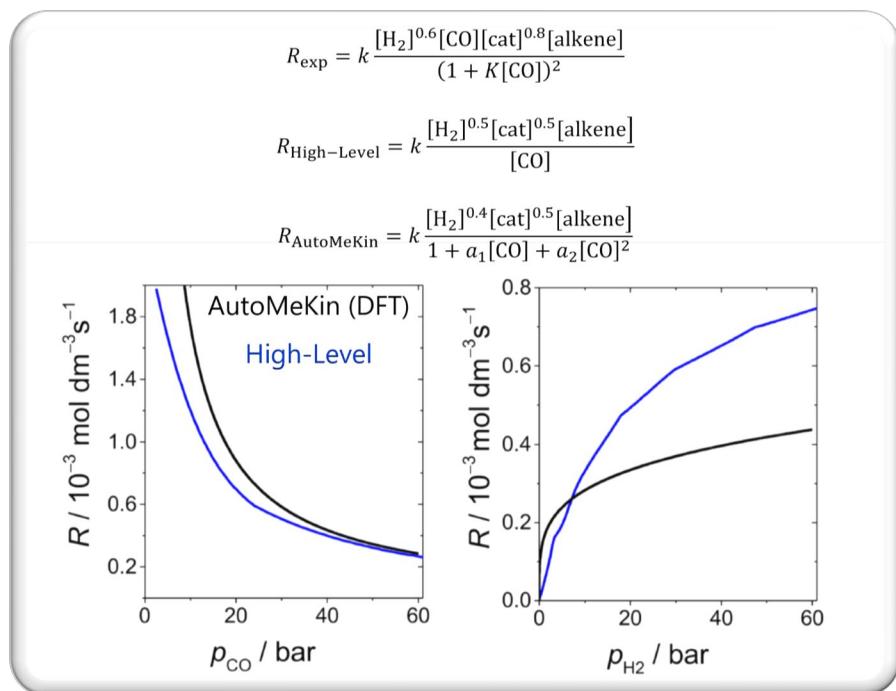
Hydroformylation of ethylene

Chem. Sci. 2017, 8, 3843

Reaction mechanism



Rate law



Dimerization of C₆₀

Carbon 2023, 213, 118209

C₆₀+C₆₀ molecular bonding revisited and expanded

Jorge Laranjeira,^{1,*} Karol Strutyński,² Leonel Marques,¹ Emilio Martínez-Núñez,³ and Manuel Melle-Franco^{2,†}

¹Departamento de Física and CICECO, Universidade de Aveiro, 3810-193 Aveiro, Portugal

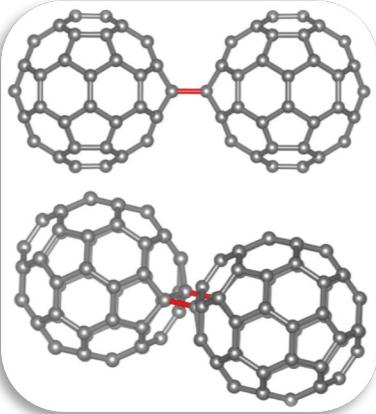
²Departamento de Química and CICECO, Universidade de Aveiro, 3810-193 Aveiro, Portugal

³Departamento de Química Física, Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Spain

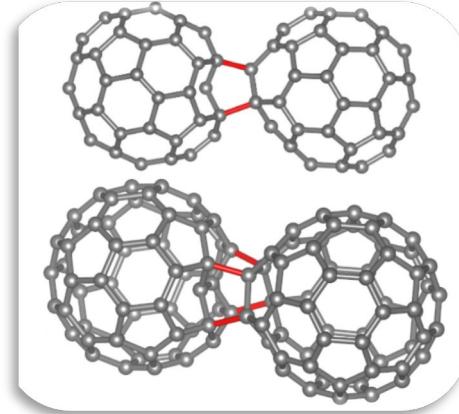
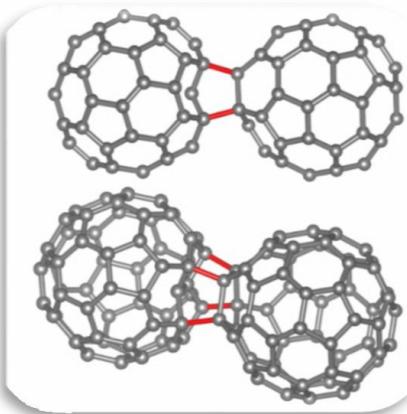


- ✓ DFT with dispersion: TPSS-Def2-TZVPP-D3BJ/B3LYP-6-31G(d,p)-D3BJ
 - ✓ 41 dimers (previously 12).
 - ✓ At 298 K C₆₀ is a van der Waals solid
 - ✓ Subjected to HPHTs molecules bond to each other covalently.

< 8 GPa



> 8 GPa



Integration within the Cathedral package

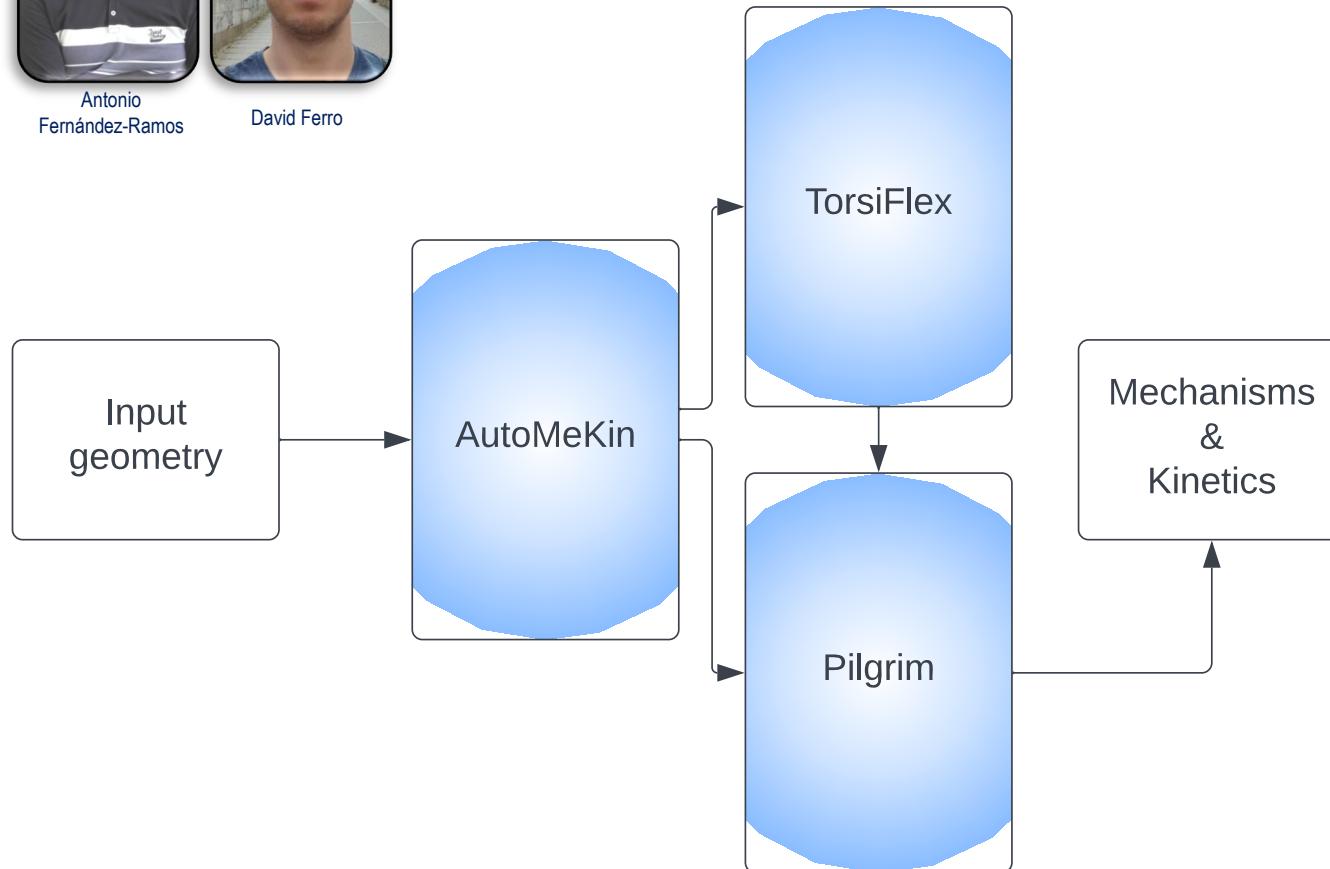


Antonio
Fernández-Ramos



David Ferro

<https://github.com/cathedralpkg>



Acknowledgements



George Barnes



Carles Bo



Antonio
Fernández-Ramos



David Ferro



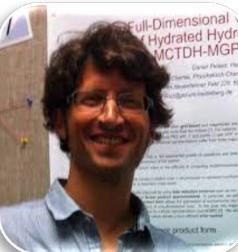
Diego Garay



Dave Glowacki



Sabine Kopec



Dani Peláez



Aurelio Rodríguez



Roberto Rodríguez



Robin Shannon



Pablo Tahoces



Saulo Vázquez