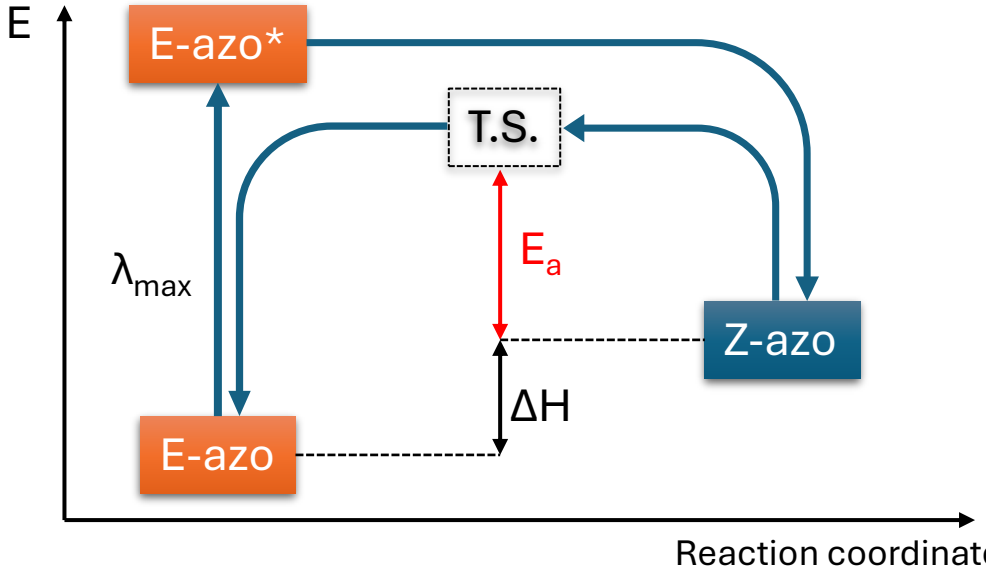
On the determination of the activation energies for the thermal relaxation of photoisomers by state-of-the-art mass spectrometry methods

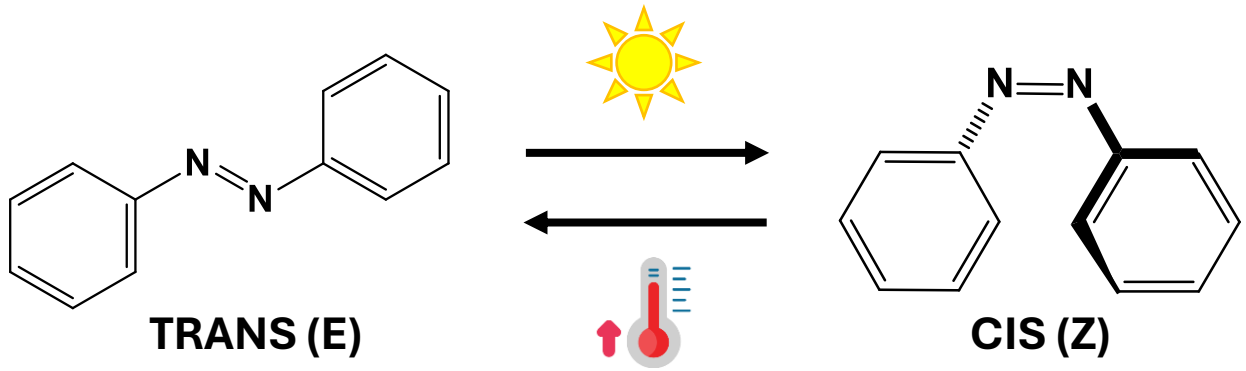
Thomas ROBERT

73rd Conference on Mass Spectrometry and Allied Topics

The authors declare no competing financial interest

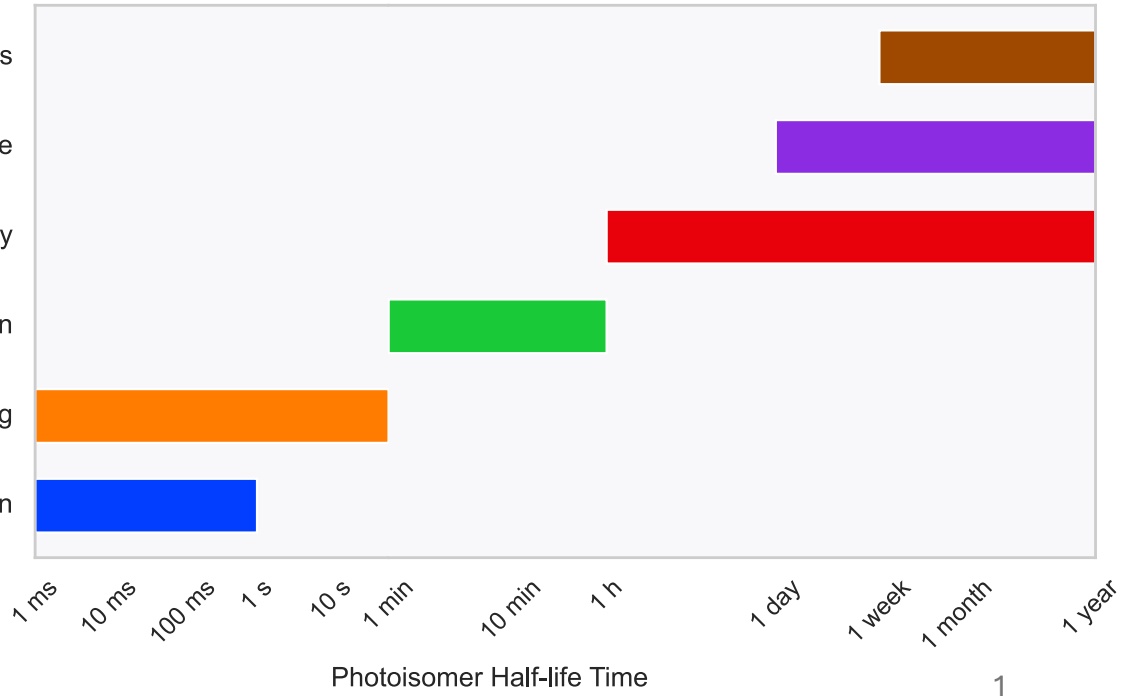
A matter of speed





Key properties :

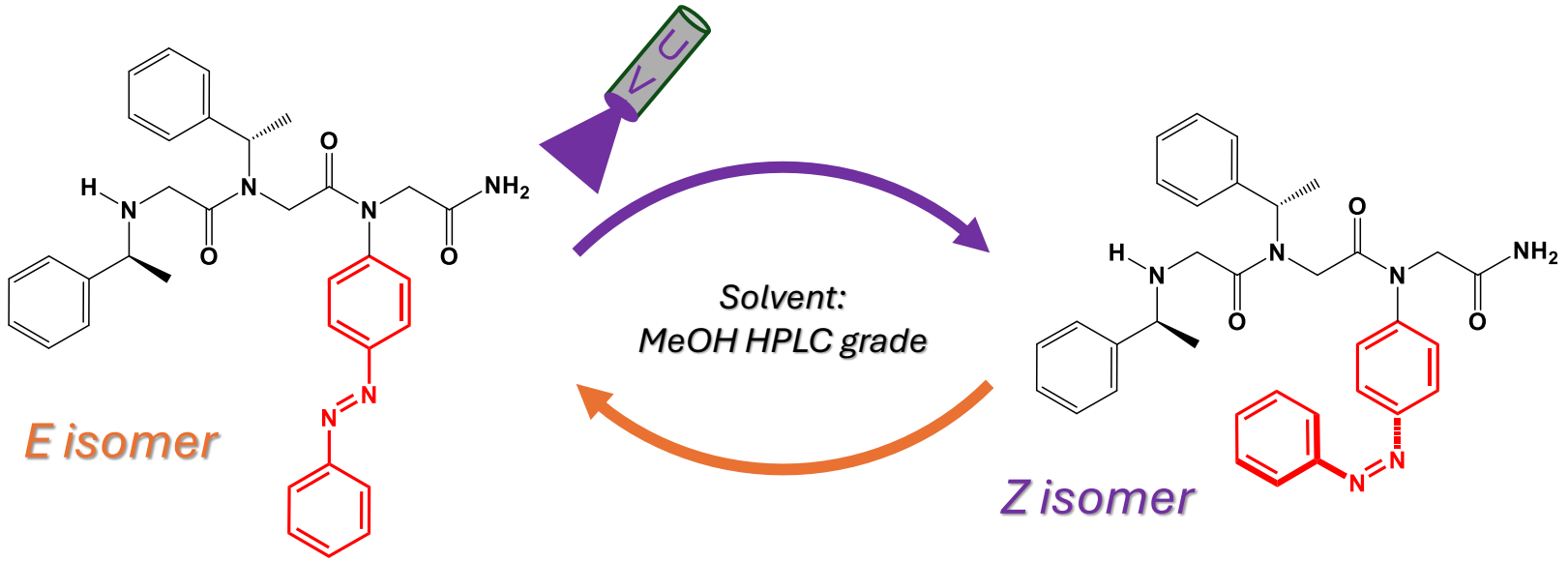
- Light absorption
  → **λ_{max}**
- Energy difference
  → **ΔH**
- Back-isomerization rate
  → **$E_a \leftrightarrow t_{1/2}$**



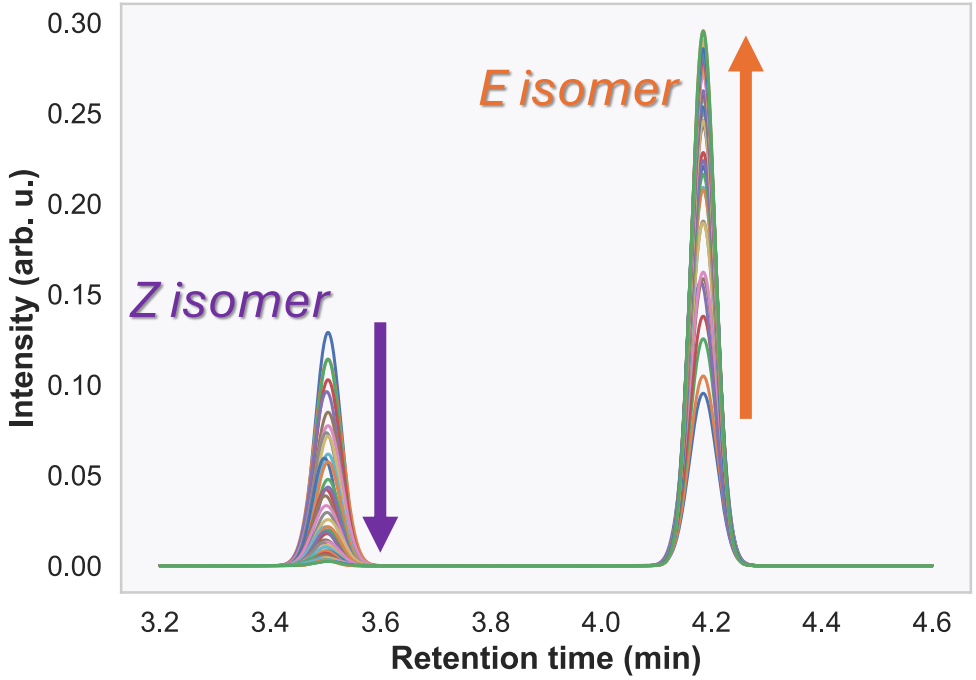
LC-MS to monitor back-isomerization in solution

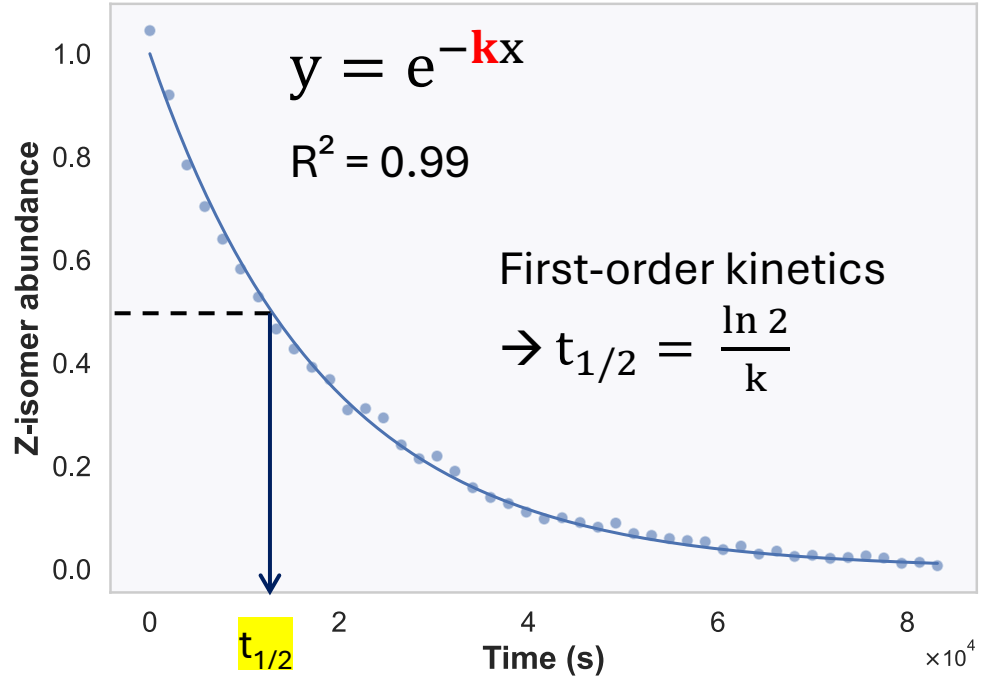
Chem. Eur. J. **2023**, *29* (70)

B Tassignon ***G Henrard***



EIC *m/z* 577 (MH^+) after LC separation





Solution stored in the **dark** at **controlled temperature**

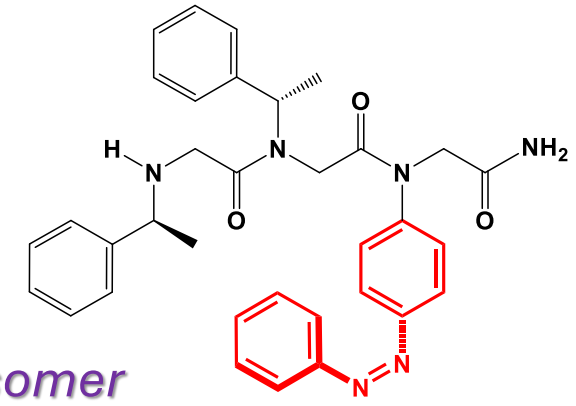
LC-MS analyses at **variable relaxation times**

Z content vs back-isomerization time

Crucial property

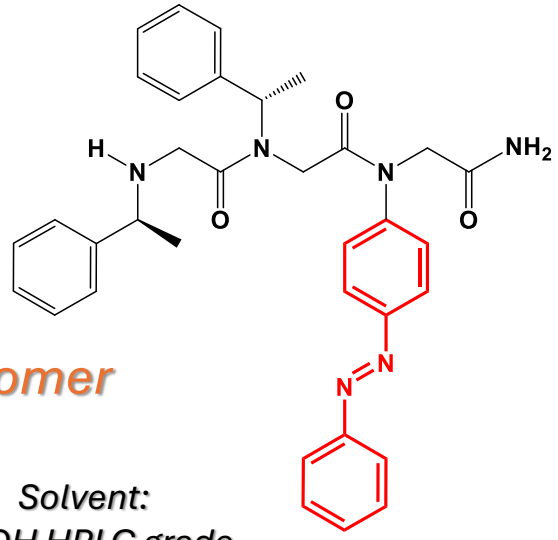
$t_{1/2}$ 2

Characterization of the activation barrier



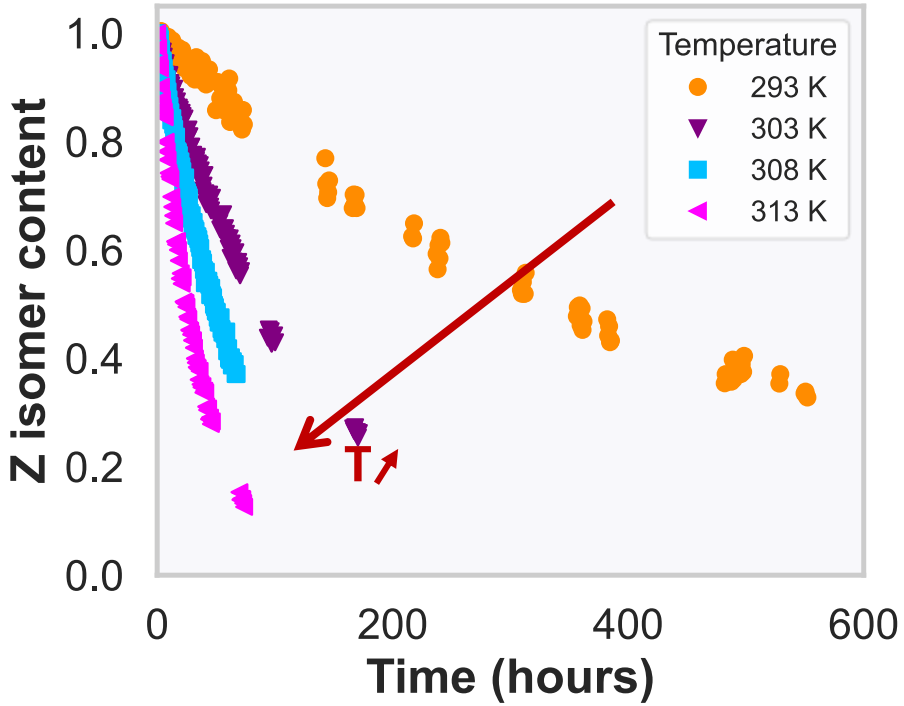
Z isomer

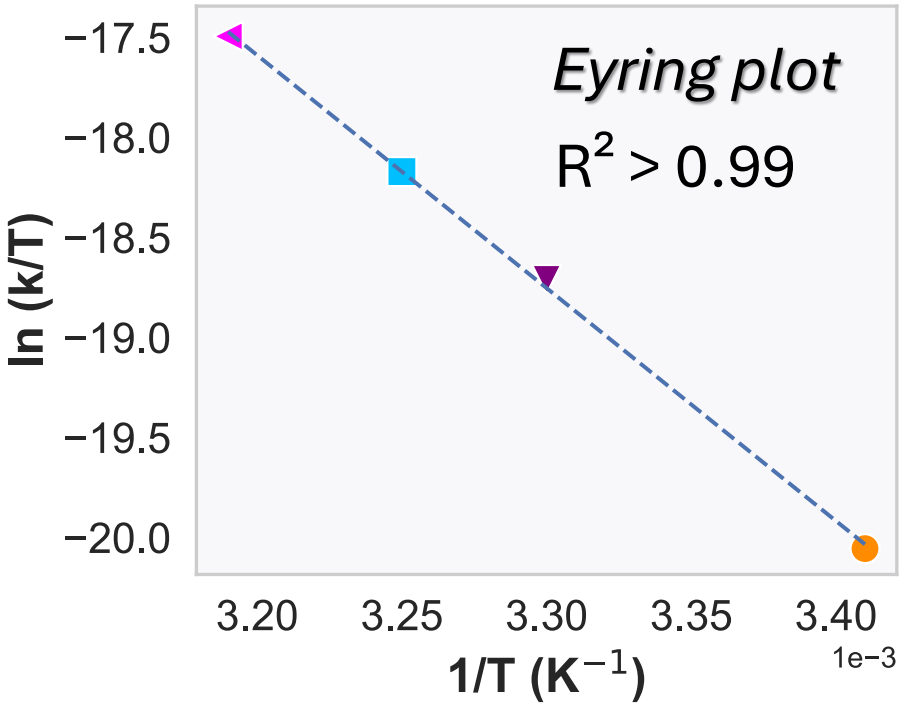
Δ or R.T.



E isomer

Solvent:
MeOH HPLC grade





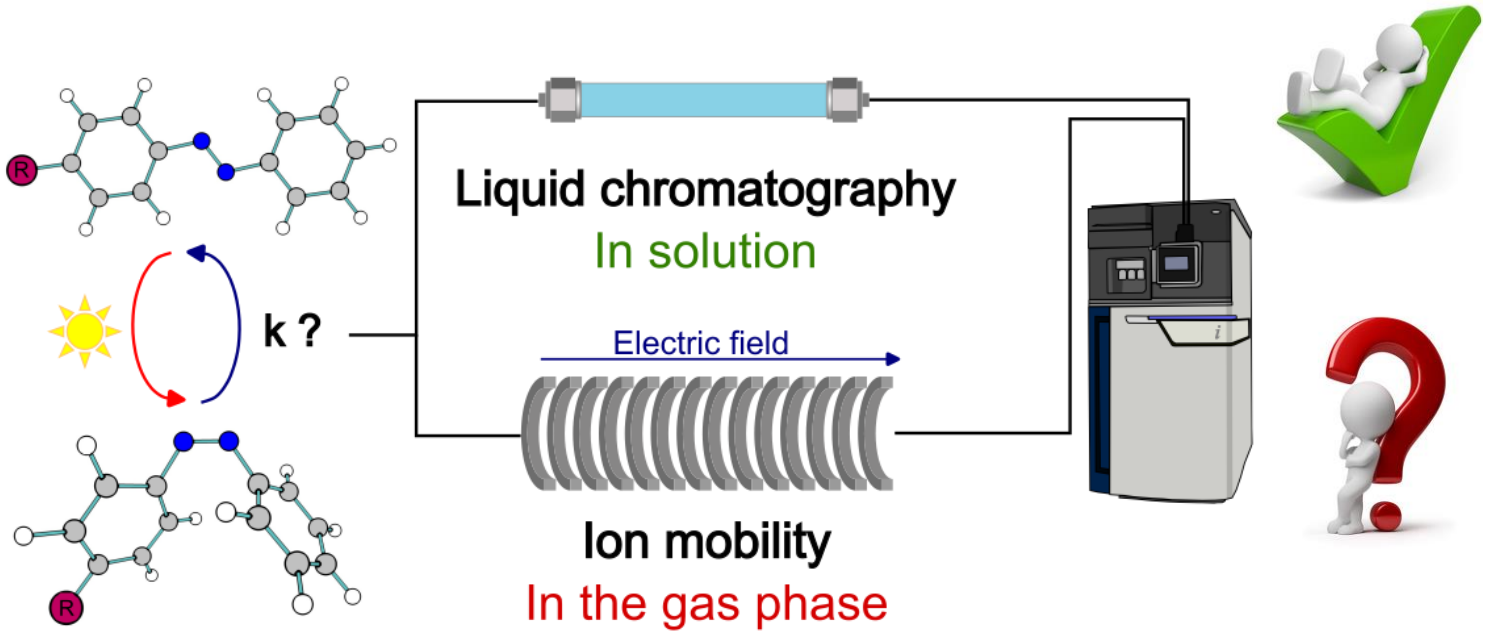
$$\ln\left(\frac{k}{T}\right) = \underbrace{\frac{-\Delta H^{\ddagger}}{R}}_{\text{Slope}}\frac{1}{T} + \underbrace{\ln\frac{k_B}{h} + \frac{\Delta S^{\ddagger}}{R}}_{\text{Intercept}}$$

$\Delta H^{\ddagger}$ = 96.8 kJ.mol^{-1}
$\Delta S^{\ddagger}$ = -34.2 J.mol^{-1}.K^{-1}

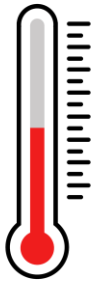
$\Delta G^{\ddagger}$ = 106.9 kJ.mol^{-1} (298 K)

Chem. Eur. J. **2023**, *29* (70)

Objectives



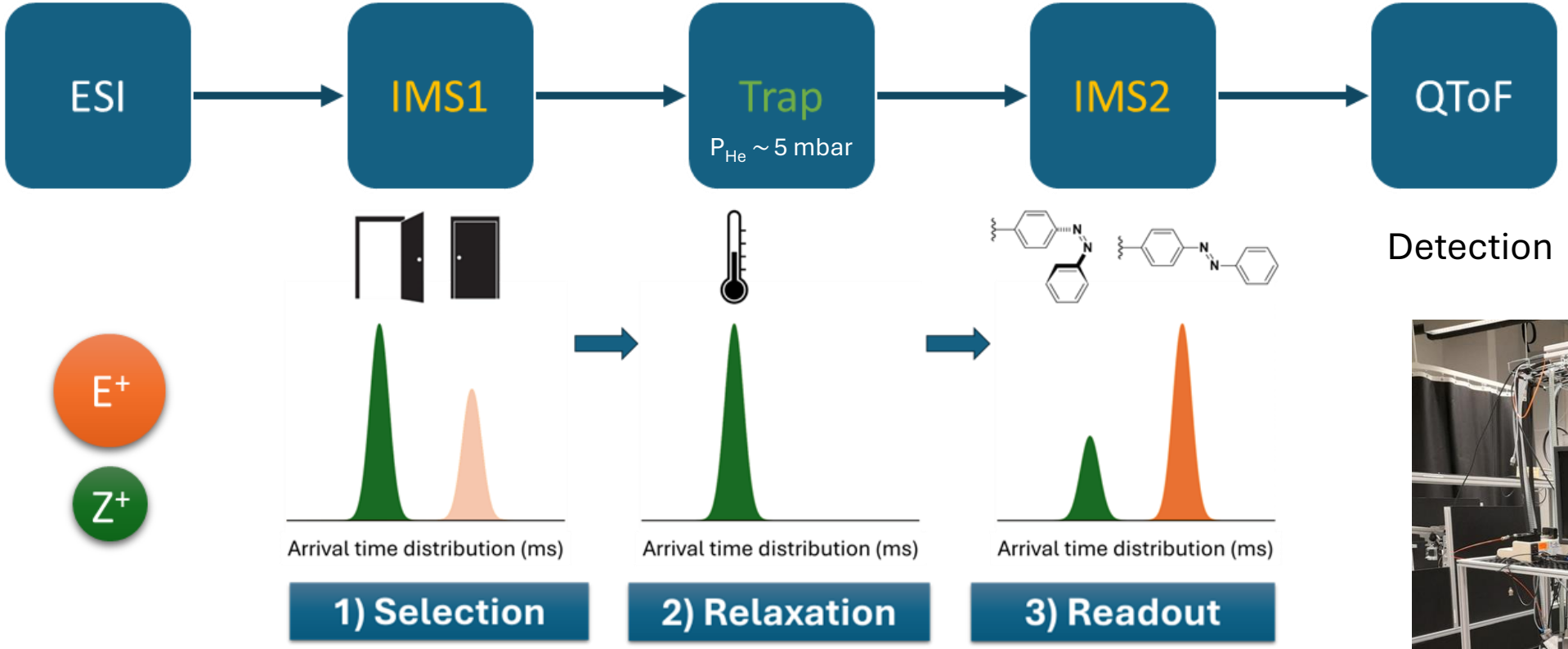
How to measure back-isomerization kinetics in the gas phase ?



- **Home-built tandem IMS device**
- **Thermal activation**
- **Waters Synapt G2-S*i***
- **Collisional activation**

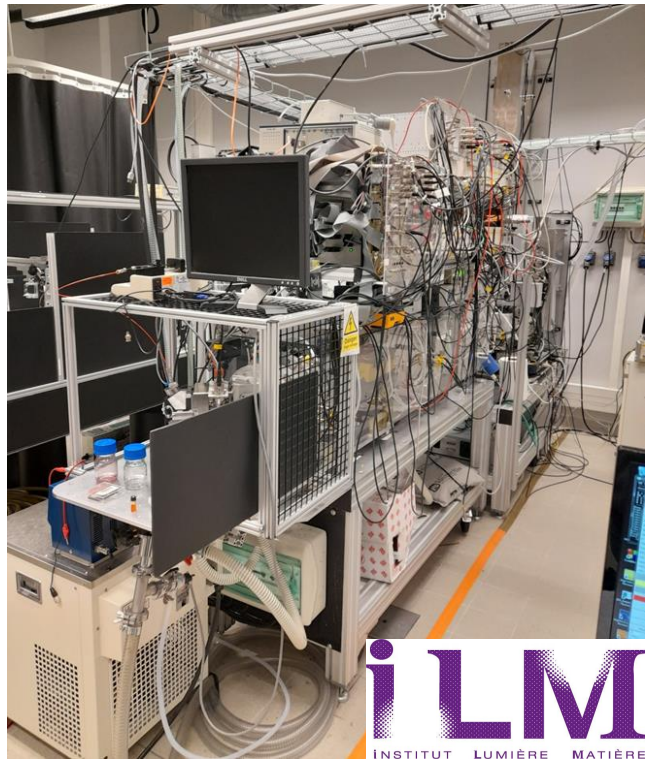
Gas phase thermal back-isomerization kinetics study by a home-built IMS device

F Chirot



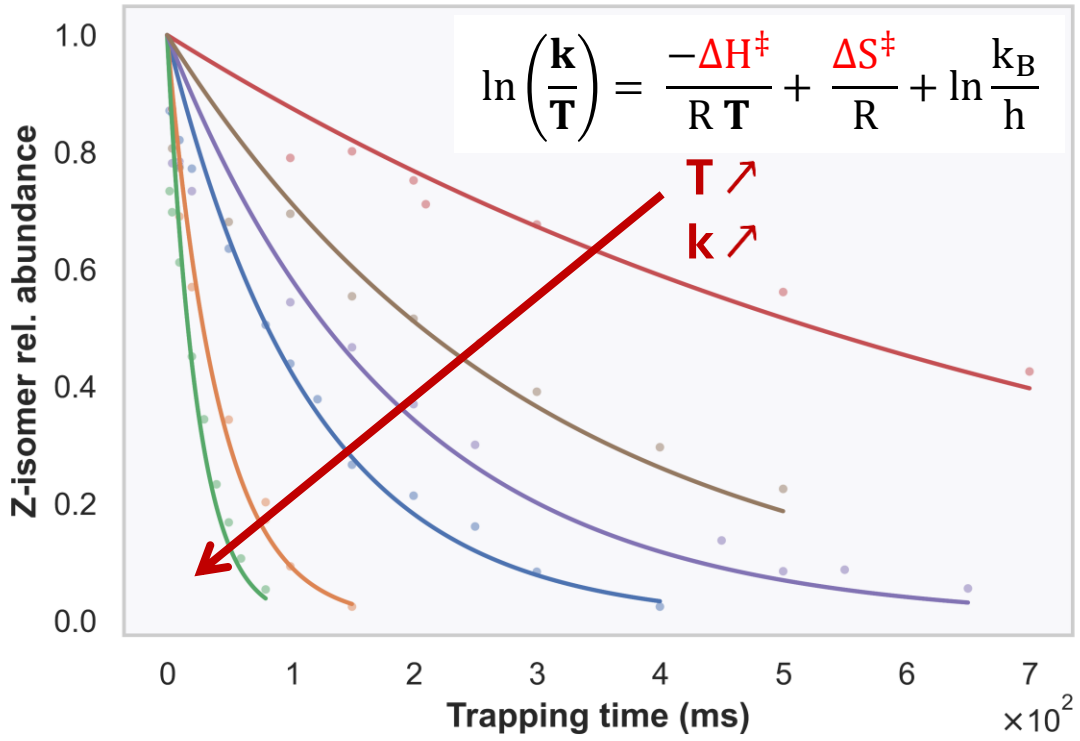
1) Z-photoisomer selection in **IMS1**
2) Trapped ion relaxation at a **controlled temperature** for a **variable time**

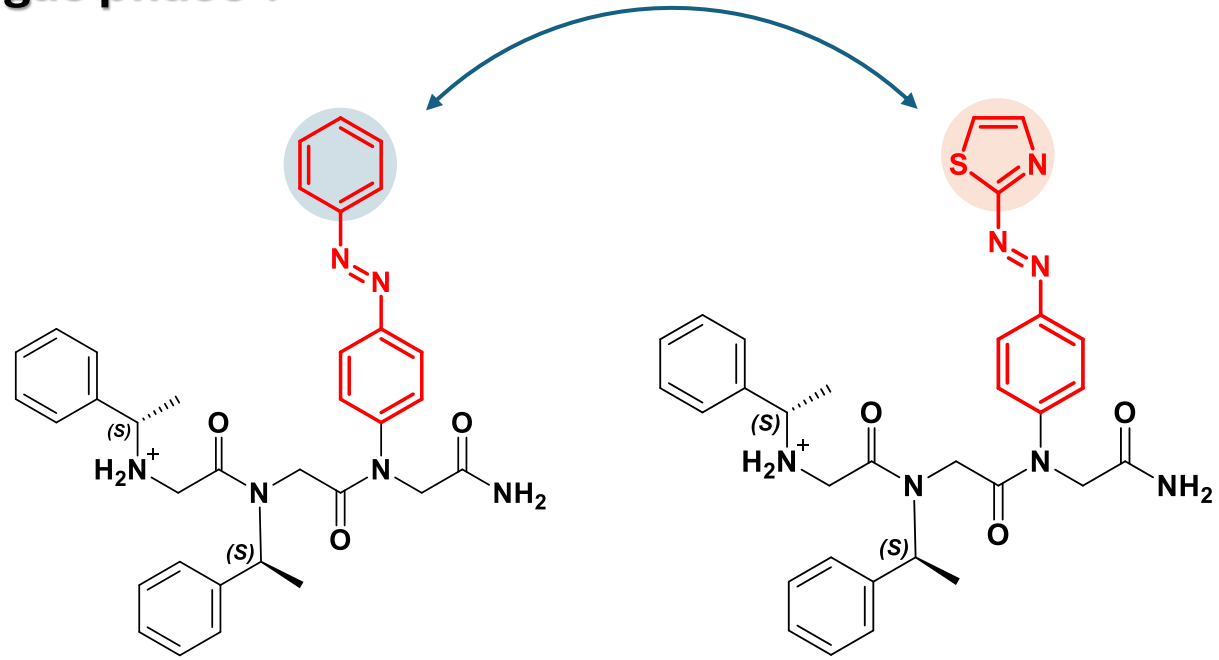
   = **kinetic monitoring** (different **T**)
3) Photoisomer population sampling by **IMS2**



Rev Sci Instrum. **2023**, *29* (70), 094101

How to monitor thermal back-isomerization in the gas phase ?





In gas phase: Tandem IMS

$\Delta H^{\ddagger}$ = 101.6 kJ mol^{-1}

$\Delta S^{\ddagger}$ = -25.4 J mol^{-1} K^{-1}

→

$\Delta H^{\ddagger}$ = 93.1 kJ mol^{-1}

$\Delta S^{\ddagger}$ = 9.9 J mol^{-1} K^{-1}

In solution: Liquid Chromatography

$\Delta H^{\ddagger}$ = 96.8 kJ mol^{-1}

$\Delta S^{\ddagger}$ = -34 J mol^{-1} K^{-1}

→

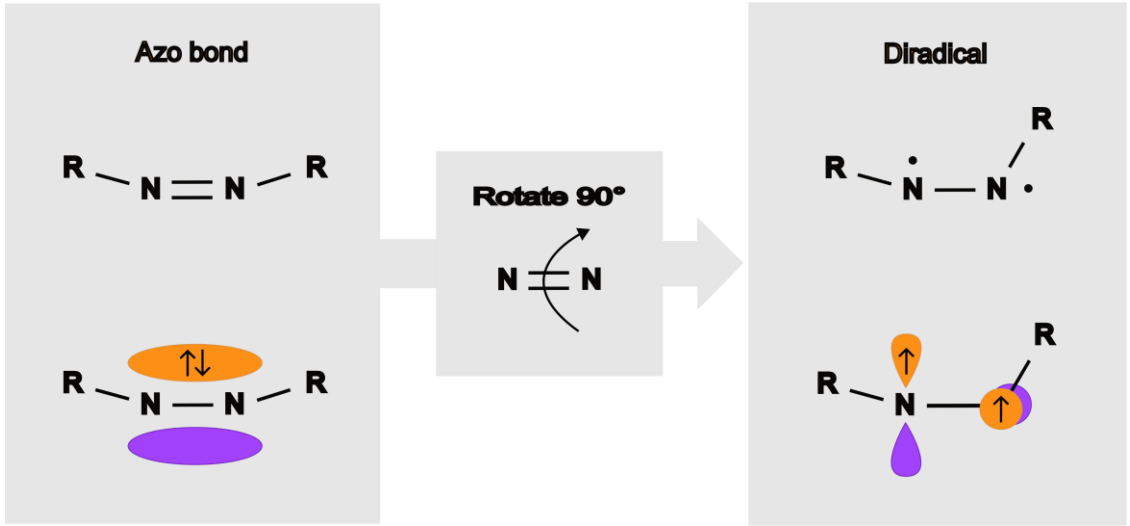
$\Delta H^{\ddagger}$ = 94.9 kJ mol^{-1}

$\Delta S^{\ddagger}$ = -2.9 J mol^{-1} K^{-1}

→ Activation entropy is a key factor in understanding back-isomerization process

The entropy puzzle: back-isomerization by rotation

What does happen when the N=N bond rotates ?

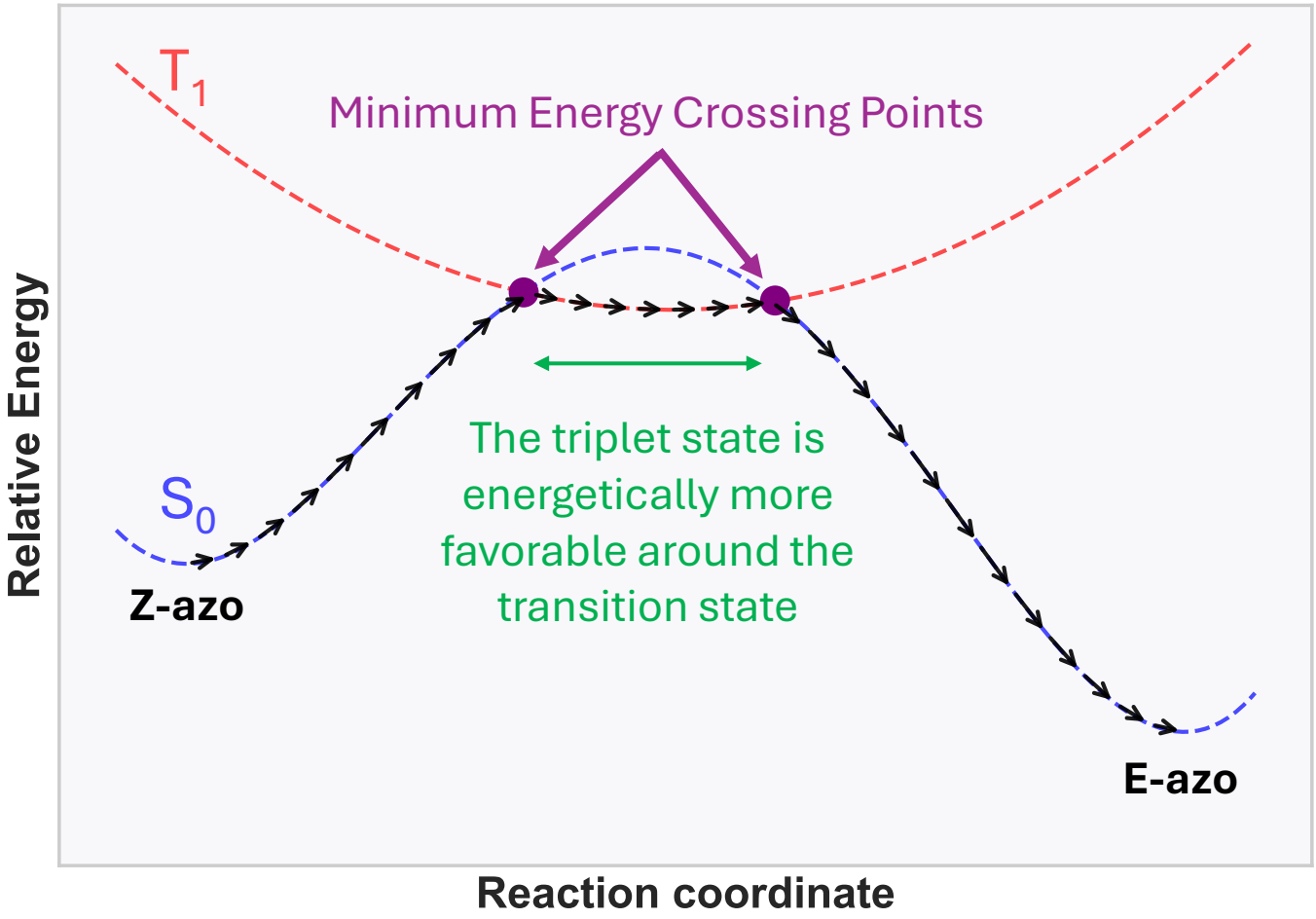


$$k = \gamma \cdot \frac{k_B T}{h} e^{-\left(\frac{\Delta H^{\ddagger} - T\Delta S^{\ddagger}}{RT}\right)}$$

Transmission coefficient, traditionally ≃ 1 but...

$$\Delta H^{\ddagger}_{measured} = \Delta H^{\ddagger}_{Eyring}$$

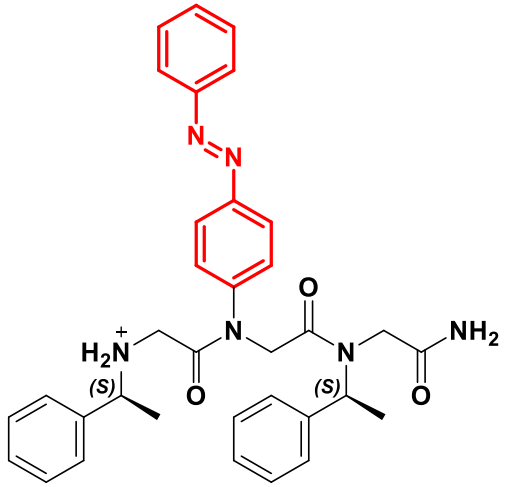
$$\Delta S^{\ddagger}_{measured} = \Delta S^{\ddagger}_{Eyring} + R \ln(\gamma)$$



ISC ⇔ spin-forbidden process ⇔ $\gamma << 1$ ⇔ $\Delta S^{\ddagger}_{measured} << 0$

J. Phys. Chem. Lett., **2022**, *13(46), 10882-10888*

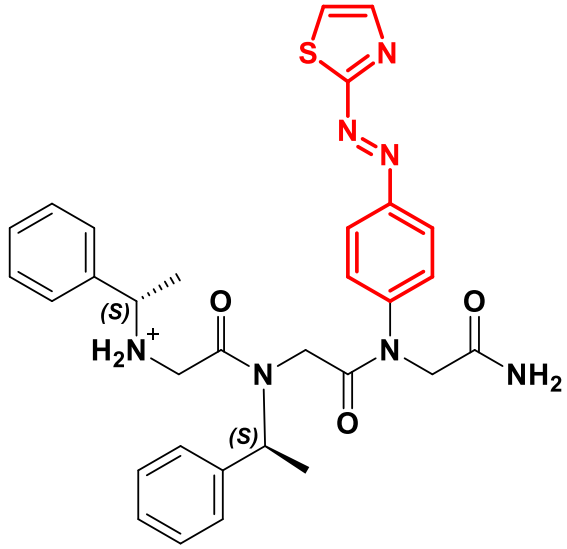
Experimental evidence of the inter-system crossing

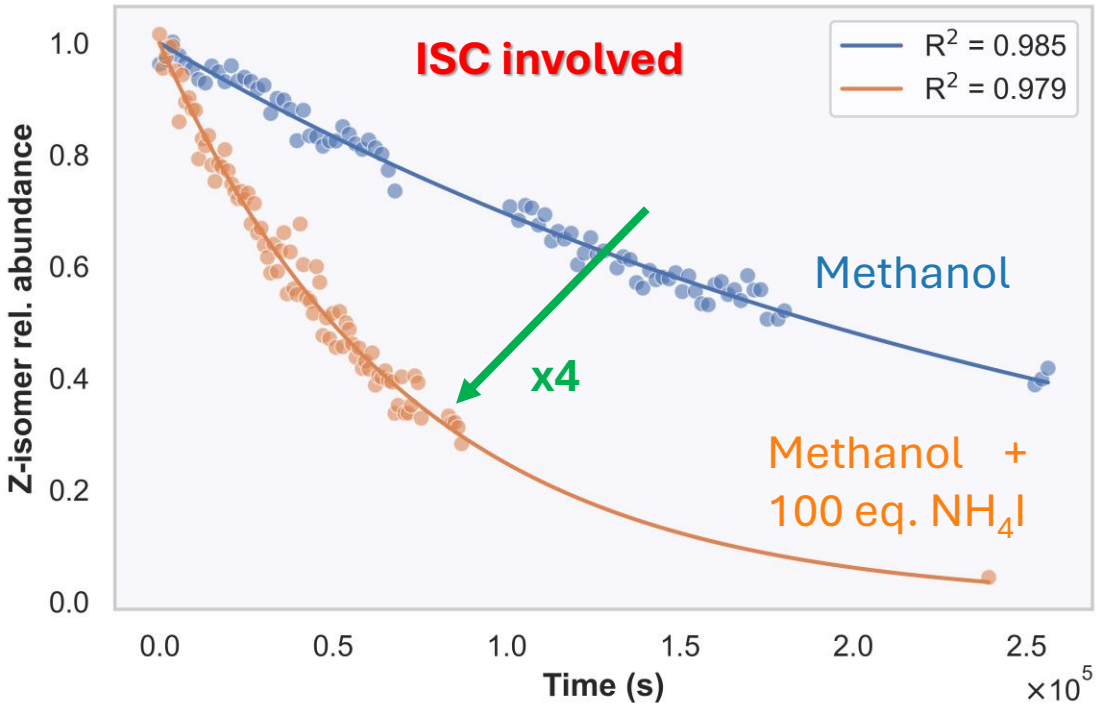


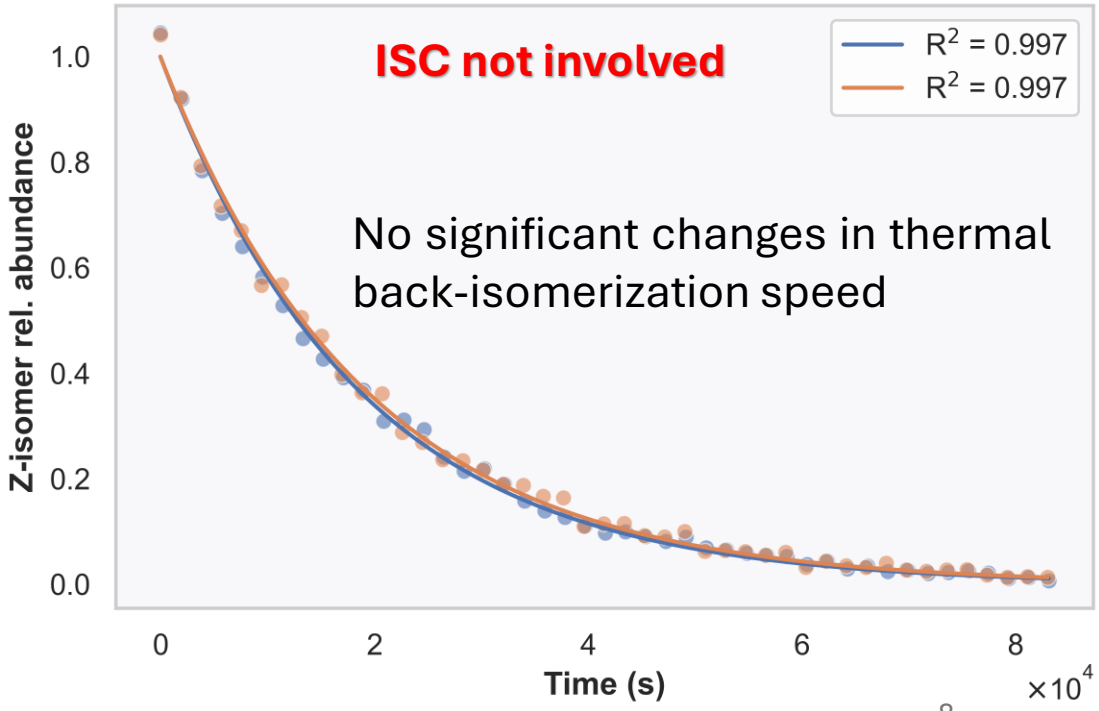
Presence of iodide ions

Spin-orbit coupling ↗

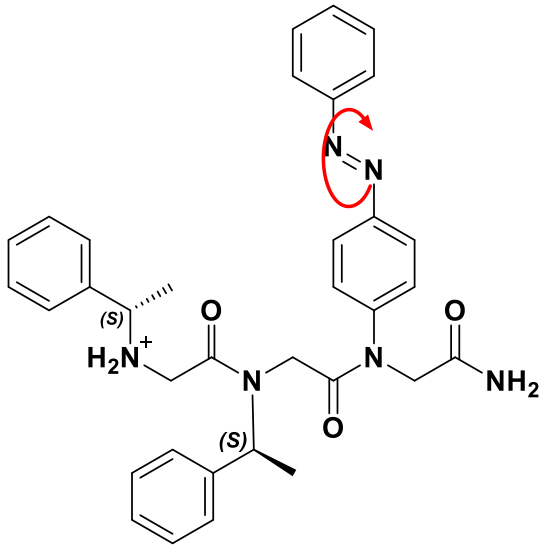
k_{ISC} ↗





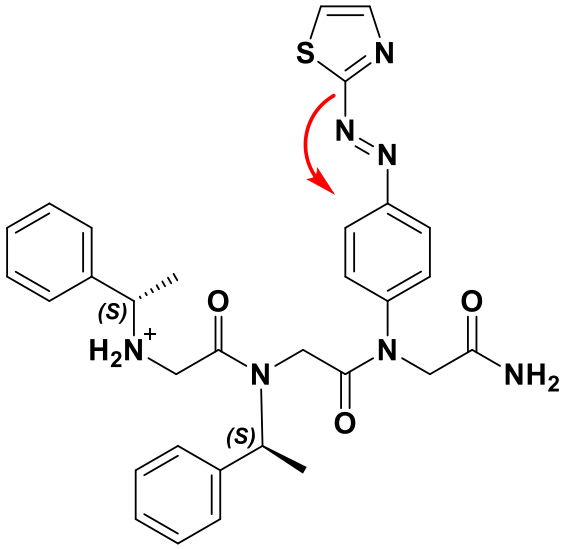


Insights from kinetic measurements by tandem IMS



Back-isomerization by **rotation**

$\Delta S^{\ddagger}$ = -25.4 J mol^{-1} K^{-1}



Back-isomerization by **inversion**

$\Delta S^{\ddagger}$ = 9.9 J mol^{-1} K^{-1}

- Measurement of activation parameters in the gas phase
- Thermal back-isomerization mechanism elucidation based on activation entropy

Anal. Chem. **2025**, *97(17), 9405–9413*

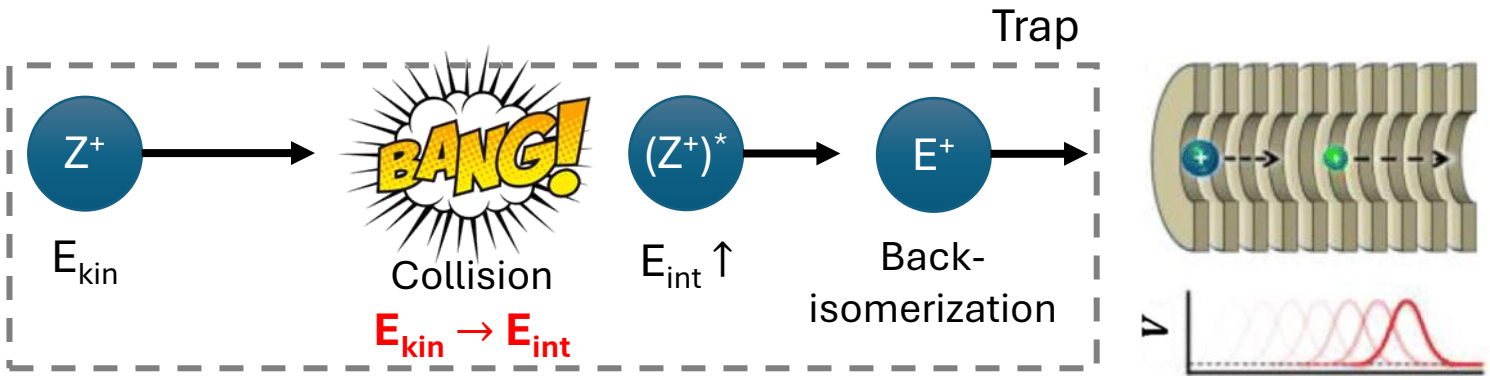
Back Isomerization Kinetics of Molecular Photoswitches : Complementary Insights from liquid chromatography and Ion Mobility Measurements

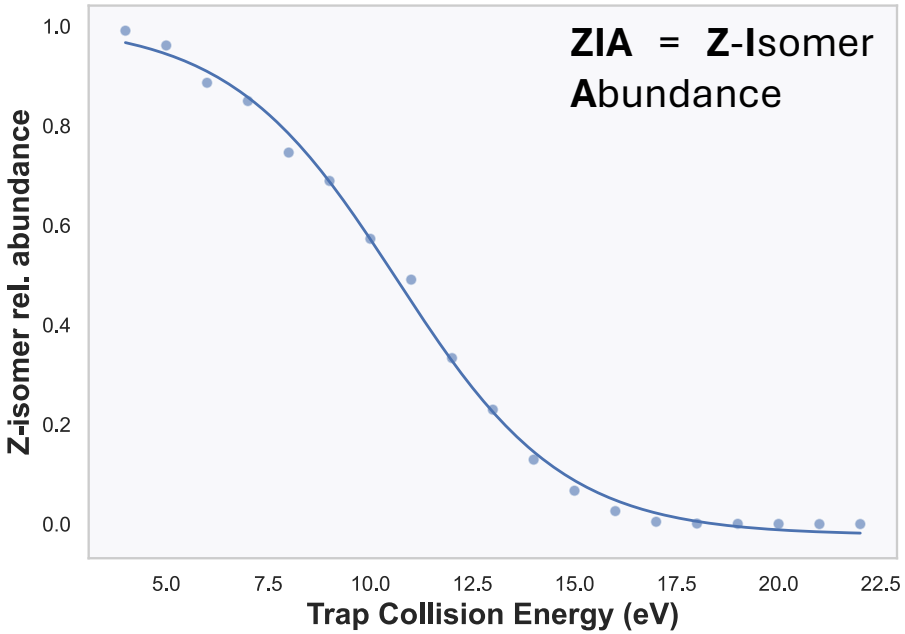
Thomas Robert, Gwendal Henrard, Benjamin Tassignon, Ari Serez, Julien De Winter, Philippe Dugourd, Jérôme Cornil, Fabien Chirot and Pascal Gerbaux

What about collisional activation on a commercial instrument ?

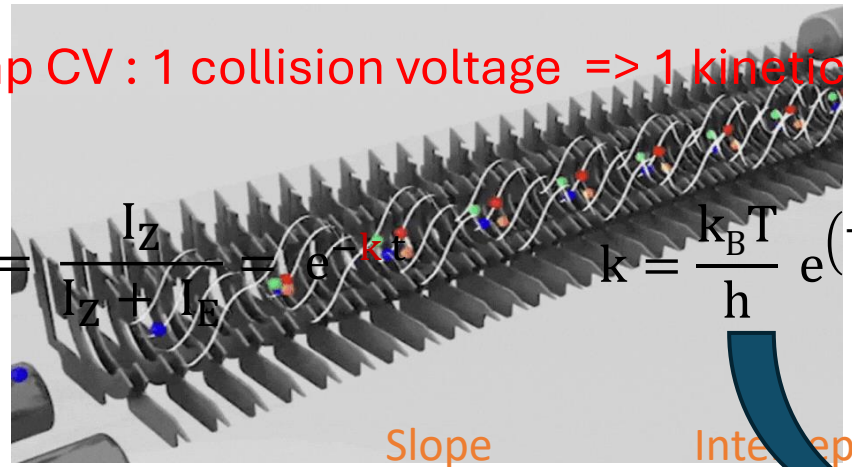
Collisional activation: a fast and widespread activation technique in mass spectrometry

Collision-**I**nduced **D**issociation → **C**ollisional-**I**nduced **I**somerization





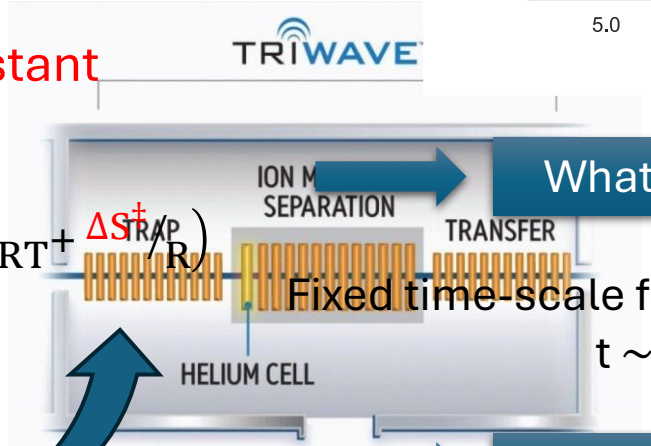
Trap CV : 1 collision voltage => 1 kinetic constant



$$ZIA = \frac{I_Z}{I_Z + I_E} = e^{-kt} \qquad k = \frac{k_B T}{h} e^{\left(-\Delta H^{\ddagger}/RT + \Delta S^{\ddagger}/R\right)}$$

Slope Intercept

$$\ln\left(\frac{-\ln(ZIA)}{T}\right) = \frac{-\Delta H^{\ddagger}}{R}\frac{1}{T} + \ln\frac{k_B}{h} + \ln t + \frac{\Delta S^{\ddagger}}{R}$$



What about the reaction time ?

Fixed time-scale for the back-isomerization reaction

$t \sim 650\ \mu s$ (TW speed)

What about the ion temperature ?

Calibration ?

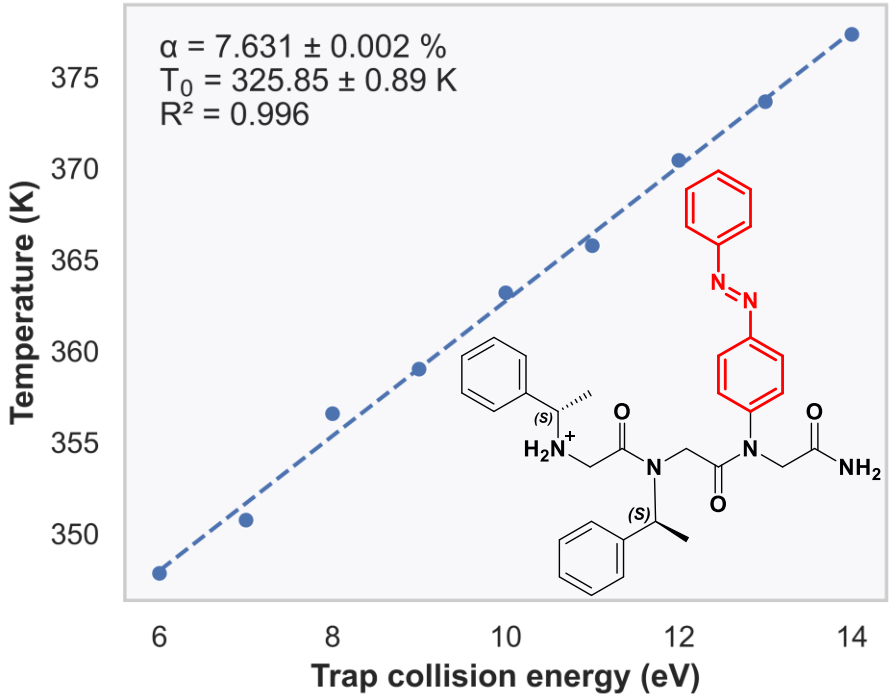
Calibration in temperature

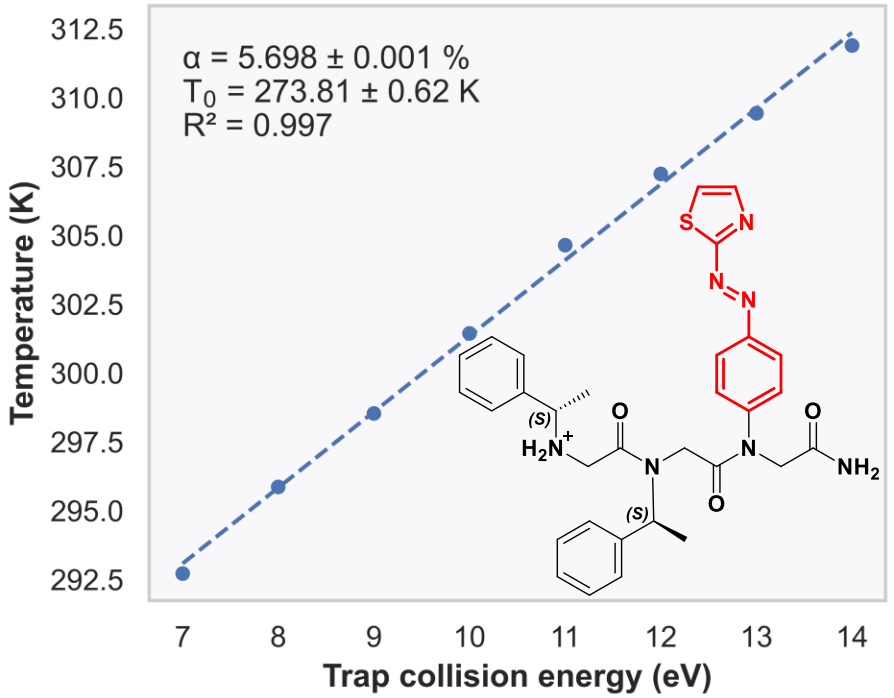
α and T_0 are system-dependent !

Collision energy

Kinetic constant

Temperature





Temperature calibration as proposed by the Prell Lab

$$T_{eff} = T_0 + \frac{\alpha \, ze \, CVtrap}{3 \, N_{at} \, k_B}$$

Chem. Sci., **2019**, *10* (14), 4097-4106; *J Am Soc Mass Spectrom.*, **2020**, *31* (3), 602-610

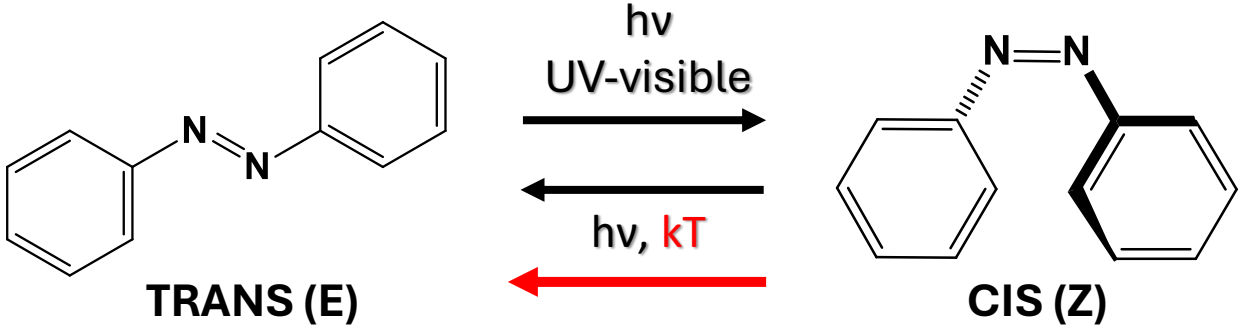
Need of « reference systems » to determine the α and T_0 parameters

Injection of the kinetic parameters determined by tandem IMS

$$\ln\left(\frac{-\ln(ZIA)}{T_{eff}}\right) = \frac{-\Delta H^{\ddagger}}{R}\frac{1}{T_{eff}} + \ln\frac{k_B}{h} + \ln t + \frac{\Delta S^{\ddagger}}{R}$$

Conclusions

- LC-MS method to measure back-isomerization kinetics in solution
- Measurement of activation parameters in the gas-phase by direct heating using an original tandem IMS instrument
  - ➢ Gas phase kinetics with insights about the back-isomerization mechanism (rotation or inversion)
- Temperature calibration of the Synapt G2-S*i* to use collisional activation to measure activation barriers of photoswitches



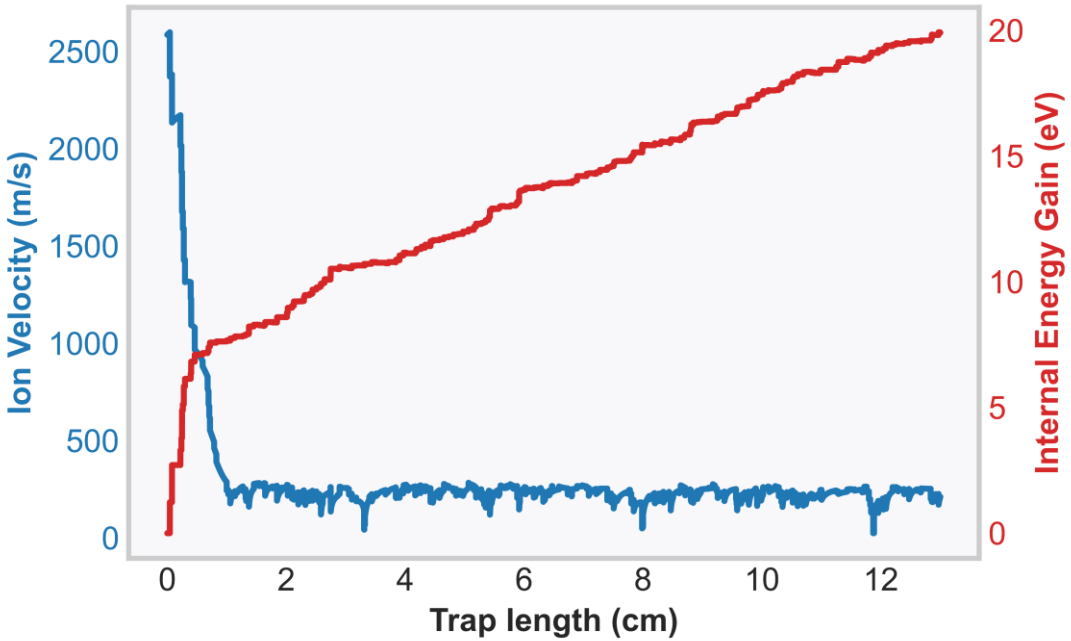
$$T_{eff} = T_0 + \frac{\alpha \, ze \, CV_{trap}}{3 \, N_{at} \, k_B}$$

	Back-isomerization	Fast	Commercially available
LC-MS	In solution	✗	✓
Tandem IMS	In gas phase	✓	✗
Collisional activation	In gas phase	✓	✓

Perspectives : understanding α and T_0 is the key

- Extension of the photoswitches library + machine learning to calibrate α and T_0

- Monte-Carlo simulations with advanced mathematical description of the collisional activation to understand what is behind α



Int. J. Mass Spec., ***2024***, *504, 117290*

Based on dice rolls and models taking into account both heating and cooling by collisions

Monte Carlo (python)

P (Ar) = 2.6 10^{-2} mBar

CV_{trap} = 20 eV

Wave velocity : 200 m/s

J Cornil

A Serez

- Development of a Spin Flip-TDDFT method for an advanced computational method to describe thermal back-isomerization

To Be Continued

Acknowledgments

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Dr. Benjamin Tassignon
Louis Groignet
Gwendal Henrard
Ari Serez
Emma Piplart
Ruth Kamguem Kamga
and all the other group members

The partners :

Jérôme Cornil (UMONS)
Fabien Chirot (ILM)

Special thanks to the organizers

and you for your attention !

UMONS Université de Mons

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