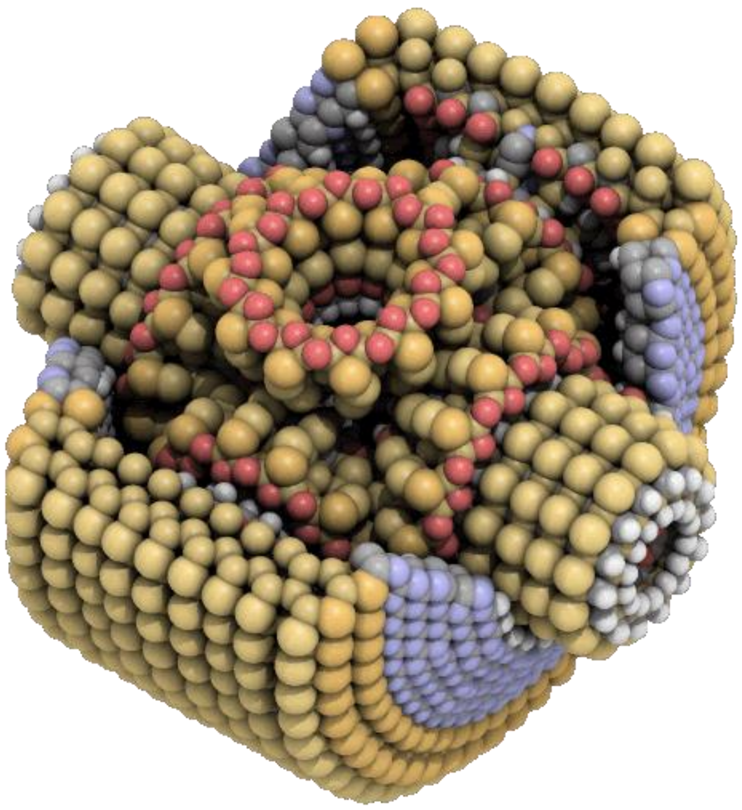
# Les machines moléculaires : concepts et réalisations



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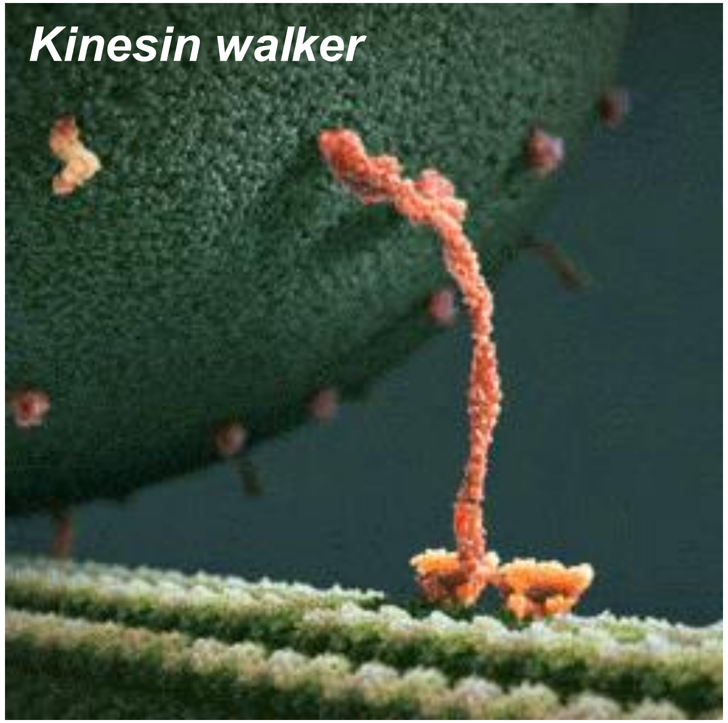
***Congrès national de l'Union des Professeurs de Physique et de Chimie (UdPPC)***
*Université de Strasbourg, 30 octobre 2025*

# Cellules vivantes et machines biomoléculaires

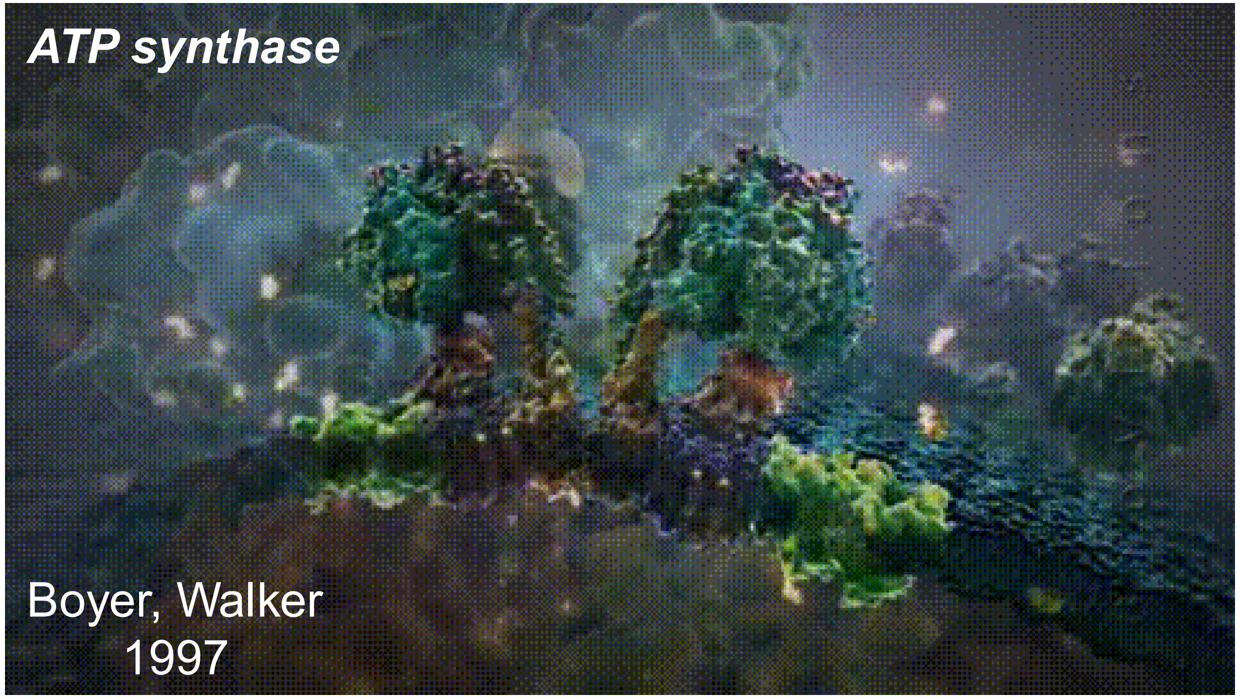



**Sont capables - à l'échelle du nanomètre - de:**

- Produire un travail mécanique
- Utiliser / Convertir / Produire différents types d'énergie

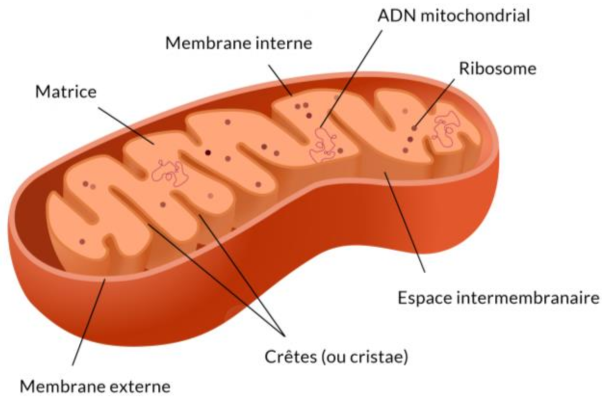
**Supportent les processus clefs du vivant:**

- Réplication et traduction du génome
- Transport
- Mouvements
- Biosynthèse

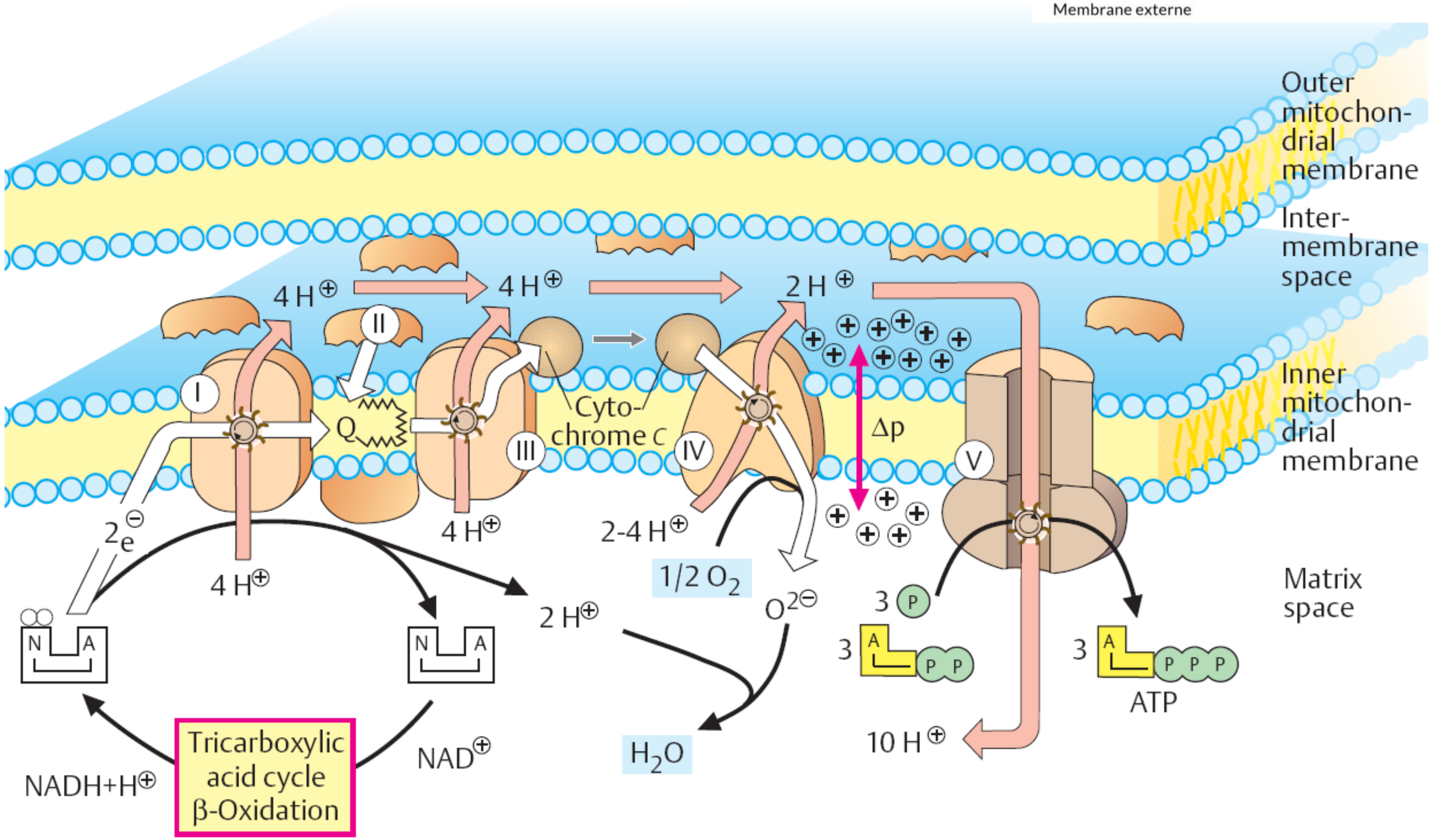


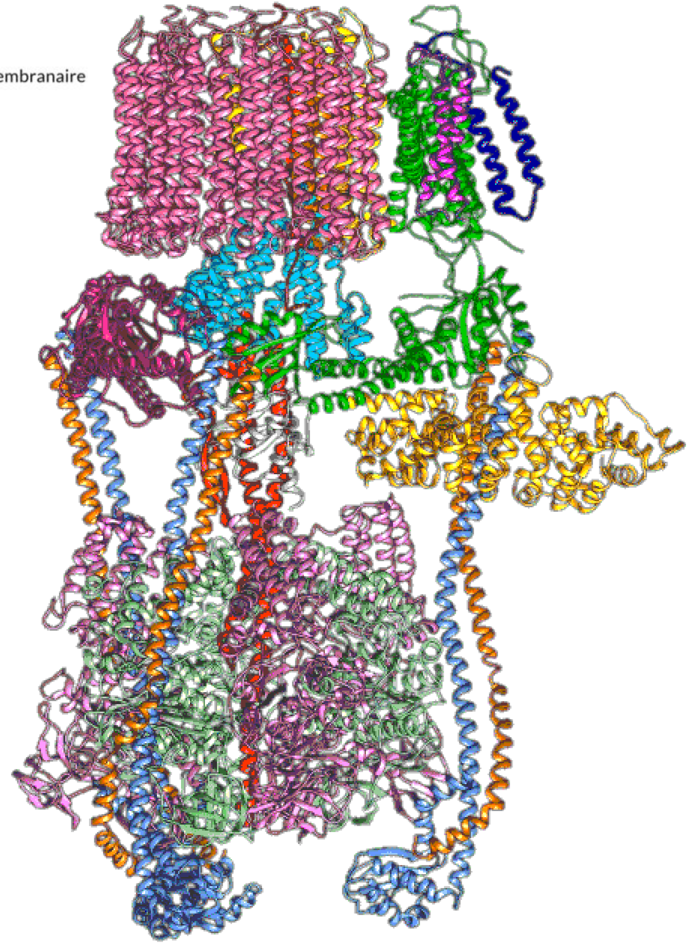

*The Inner Life of the Cell* – Harvard University

# L'exemple de l'ATP synthase




## L'ATP synthase au sein de la chaîne respiratoire:



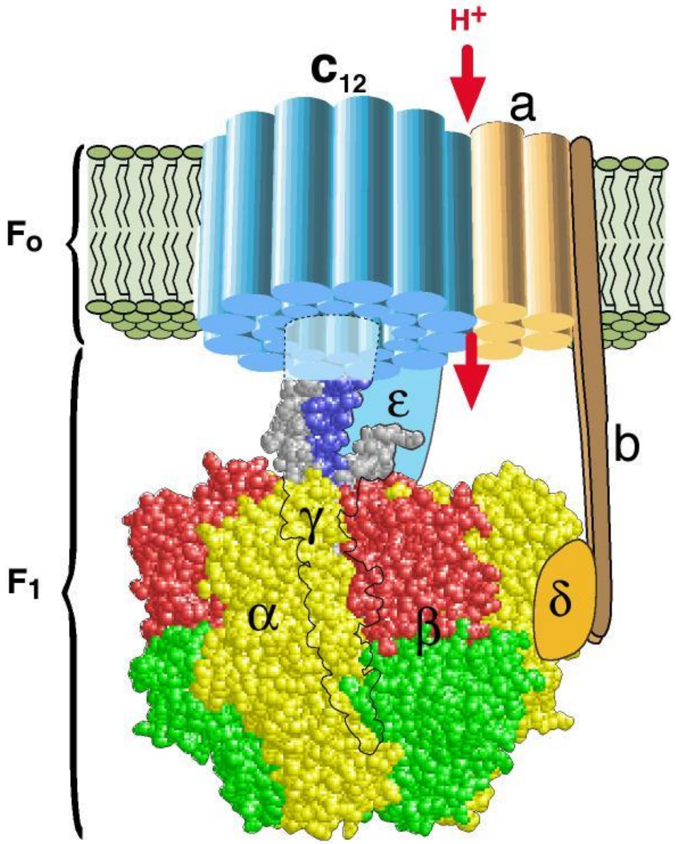



$M_w$ = 600 000 Da
Efficacité ~ 40%
Production ~ ?

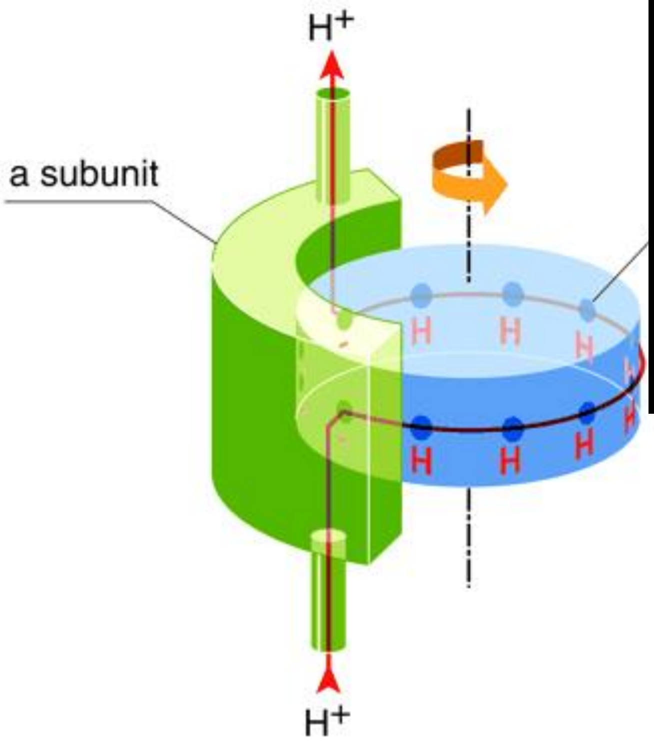
S. Nath, *Biophys. Chem.* **2016**, 69-74.

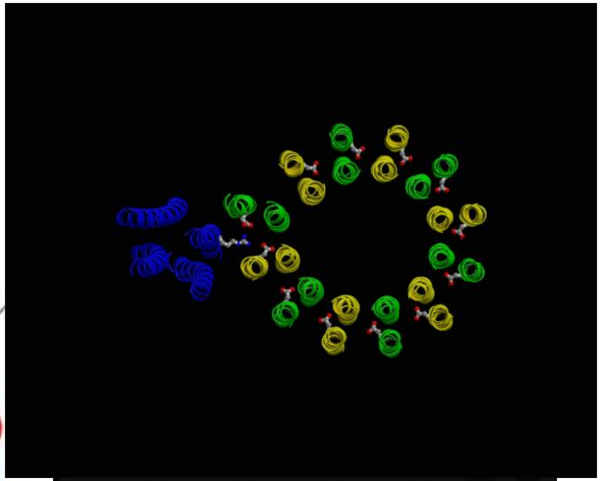
# L’exemple de l’ATP synthase

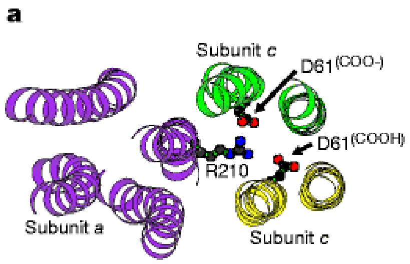
## Un mouvement unidirectionnel
## Un système hors équilibre thermodynamique

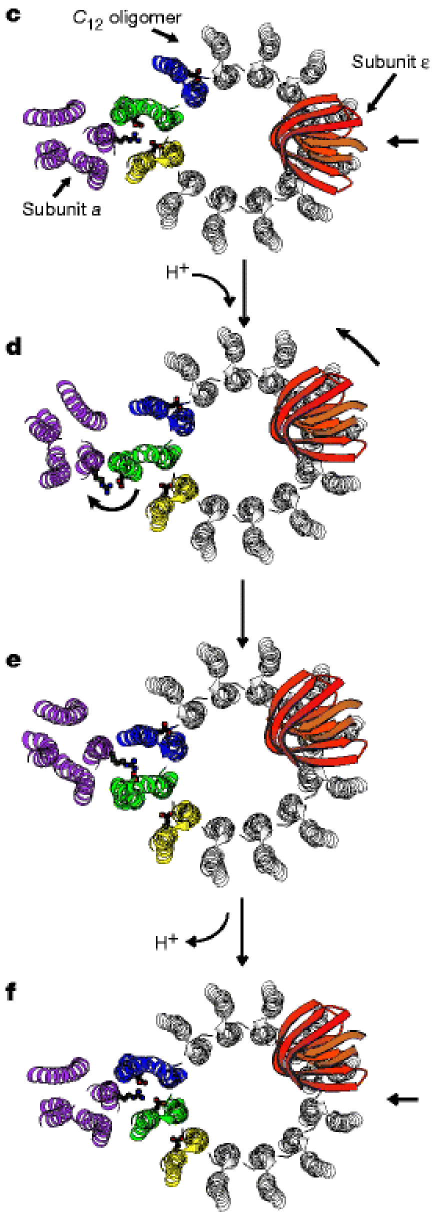



H. Wang and G. Oster (1998). Nature 396:279-282.



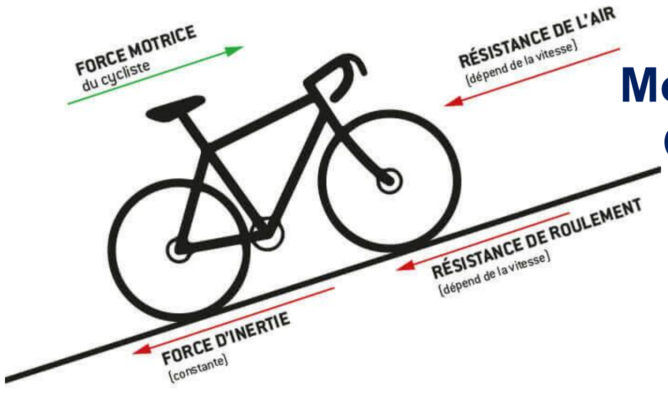





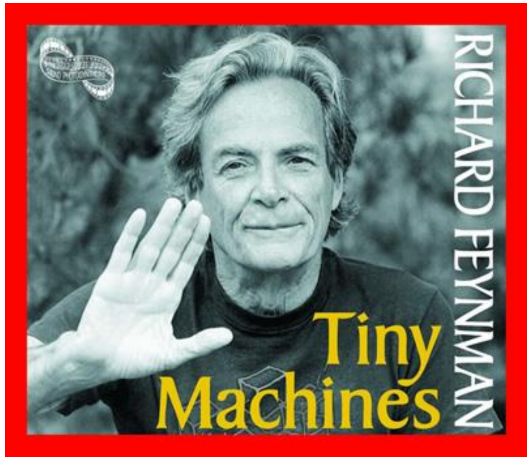

Yoshida et al. *Nature Reviews Molecular Cell Biology* **2001**, 669-677.

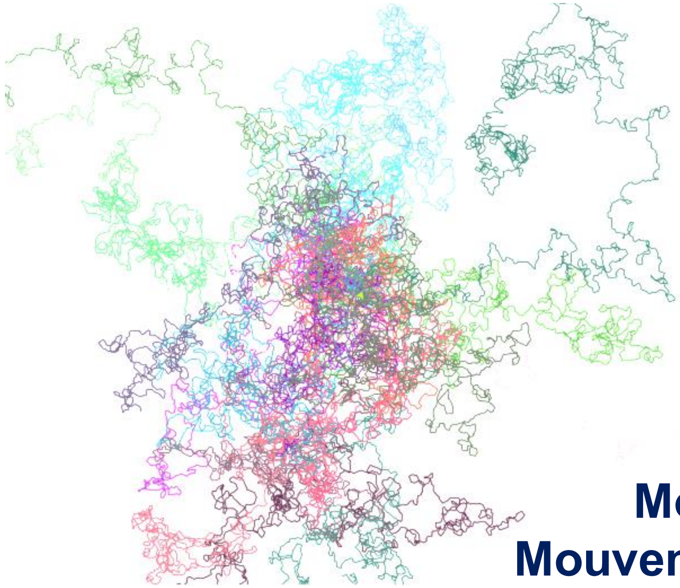
# Production d'un travail à l'échelle du nanomètre

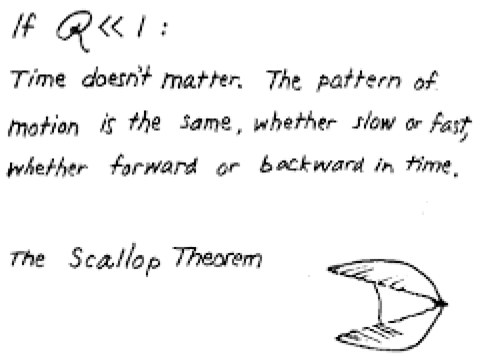


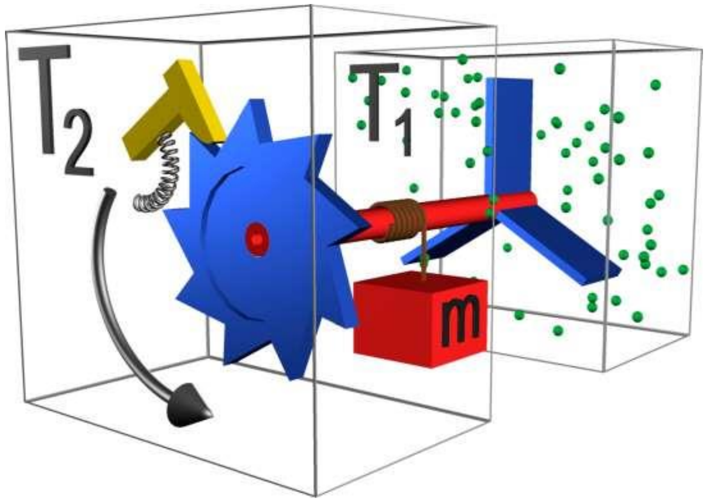

**Monde macroscopique**
**Gravitation / Inertie**

1965





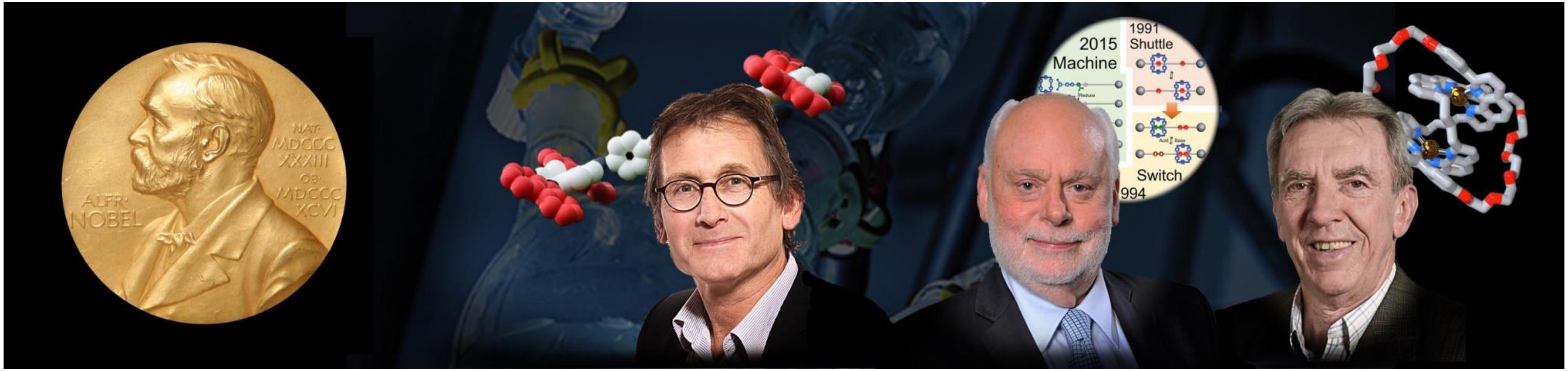




**Monde microscopique**
**Mouvement Brownien / Viscosité**

*There's plenty of room at the bottom*


E. M. Purcell, *Am. J. Phys.* **1977**, 3-11.
R. P. Feynman, *Caltech Eng. Sci.* **1960**, *23*, 22– 36.

# Machines moléculaires artificielles



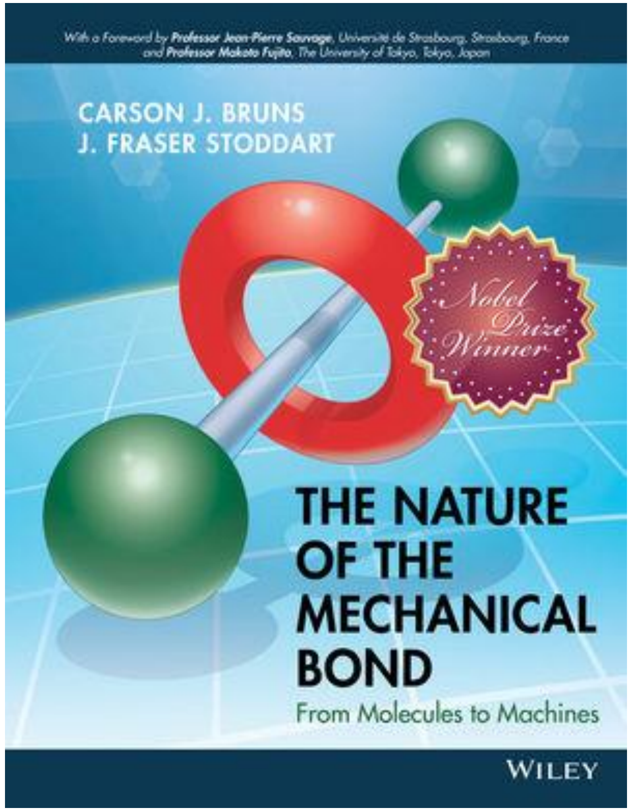

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Chemistry 2016 to

**Jean-Pierre Sauvage**
University of Strasbourg, France
**Sir J. Fraser Stoddart**
Northwestern University, Evanston, IL, USA
**Bernard L. Feringa**
University of Groningen, the Netherlands

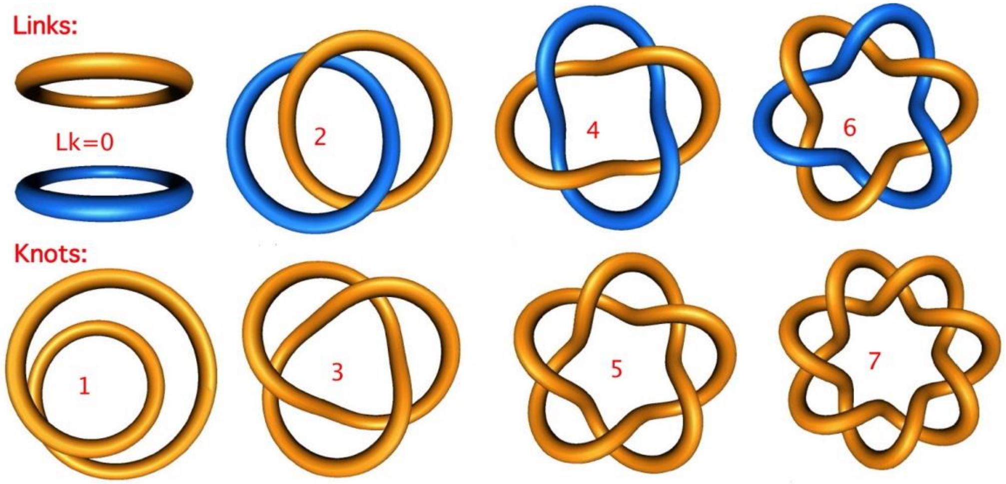
***"for the design and synthesis of molecular machines"***

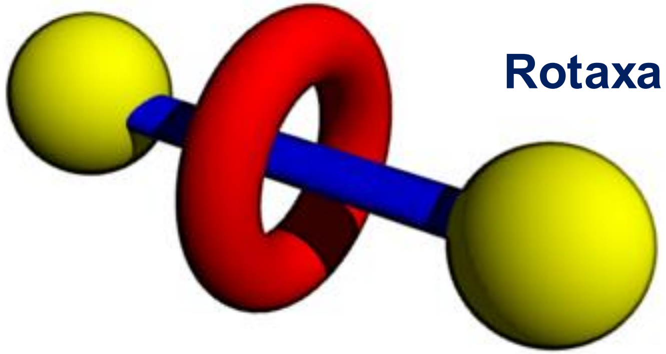
# Introduction de la liaison mécanique

**Topologie des nœuds et entrelacs moléculaires**



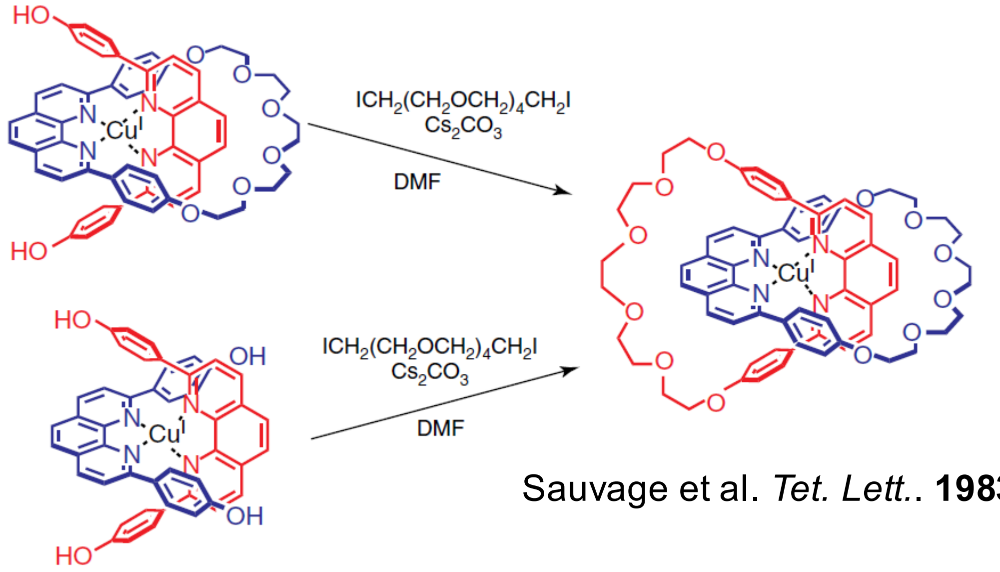

**Caténane**



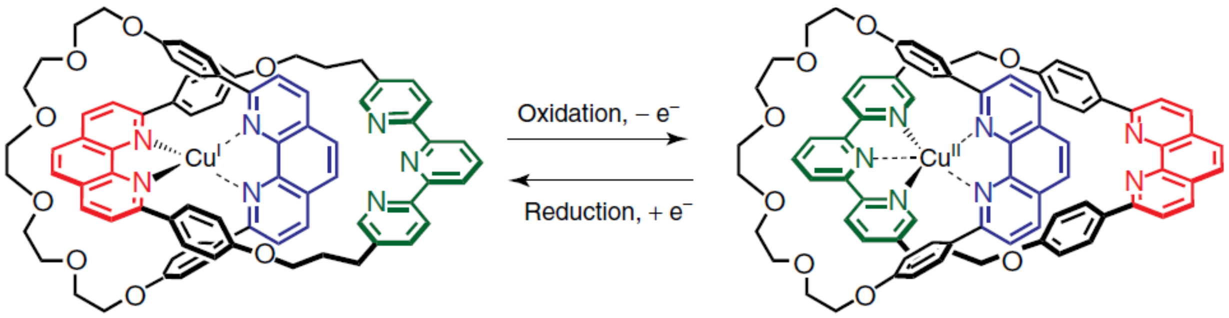



**Rotaxane**

# Les caténanes




Sauvage et al. *Tet. Lett.*. **1983**, *24*, 5095.

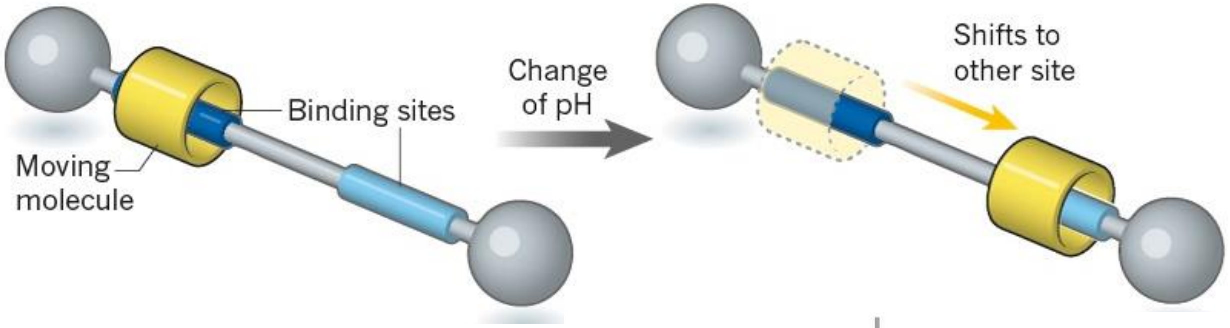



Cu(I)–four coordinate

Cu(II)–five coordinate

Sauvage et al. *J. Am. Chem. Soc.* **1994**, 9399.

# Les rotaxanes



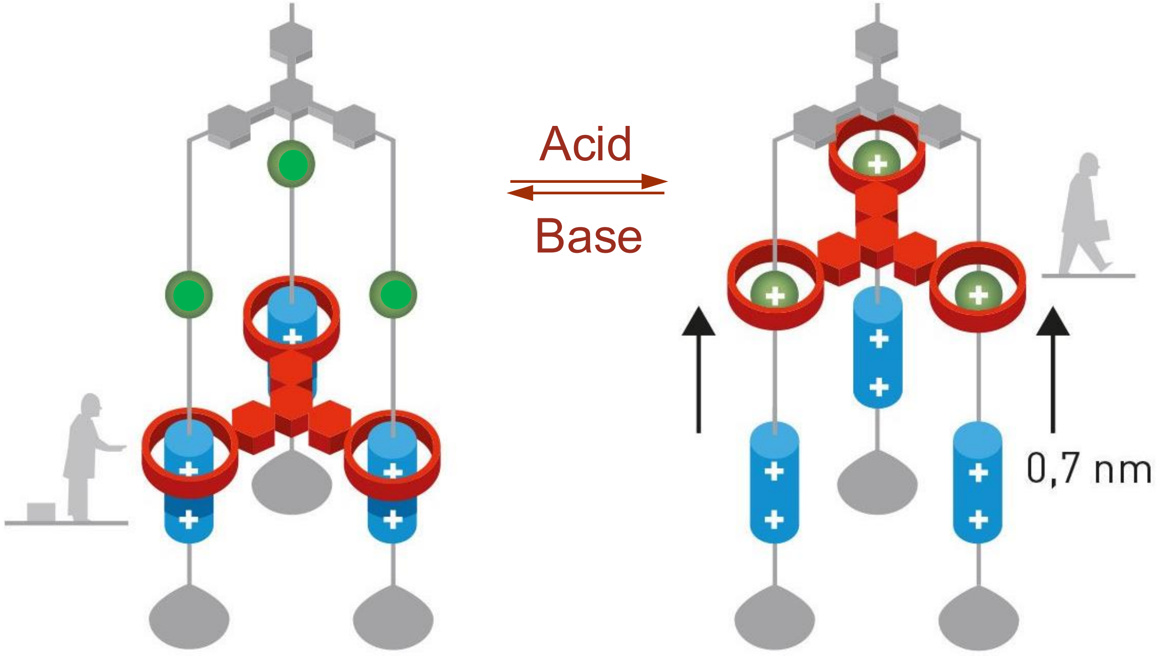

**Bistable rotaxanes**

Stoddart et al.

***Symmetric***
*J. Am. Chem. Soc.* **1991**, *113*, 5131.

***Non symmetric***
*Nature* **1994**, *369,* 133.

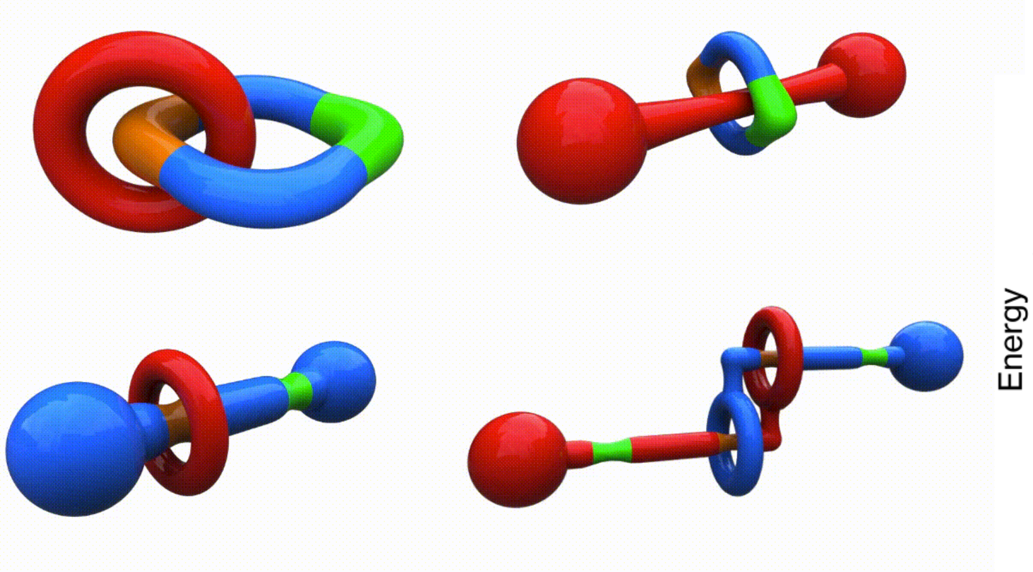
**States 0 / 1**

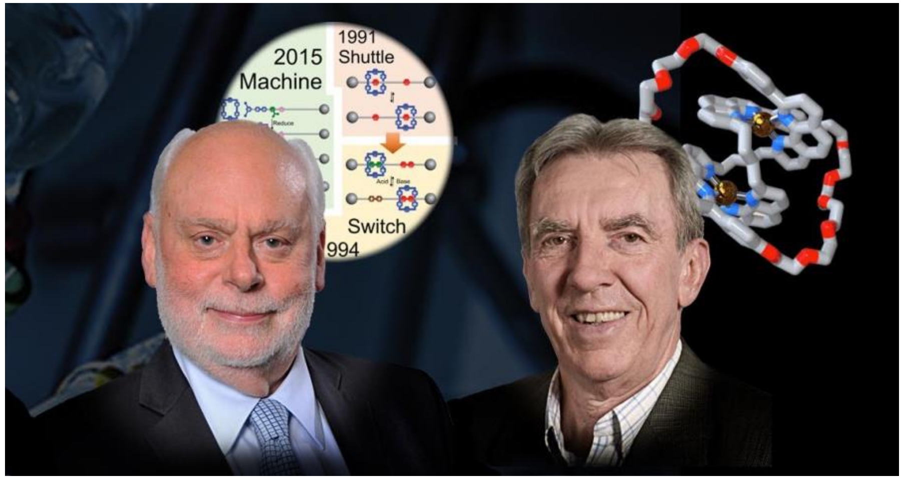


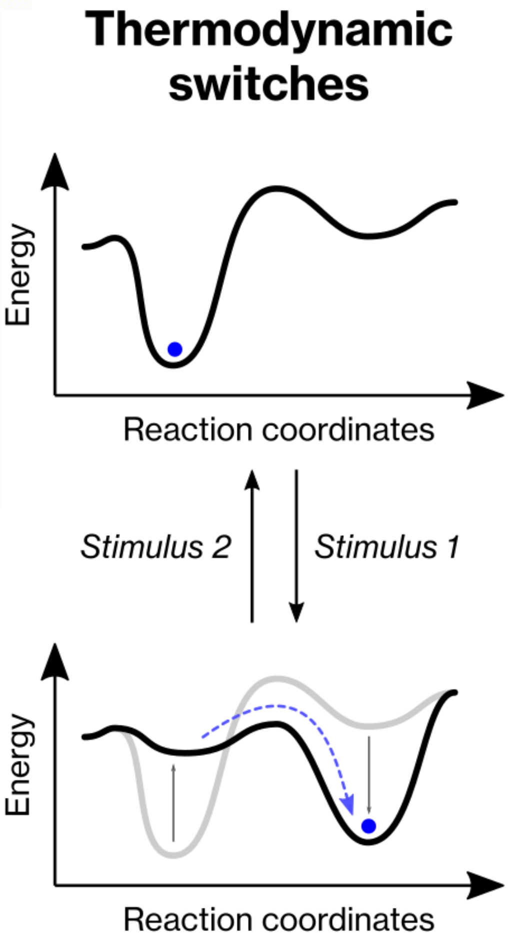

**Molecular elevator**

Stoddart et al.
*Science* **2004**, *303,* 1845.

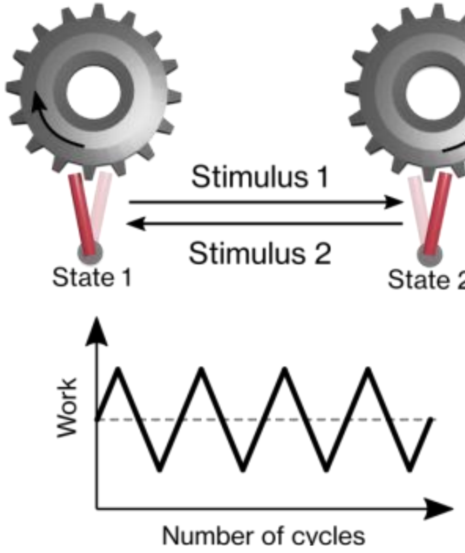
# Liaison mécanique – Travail mécanique?





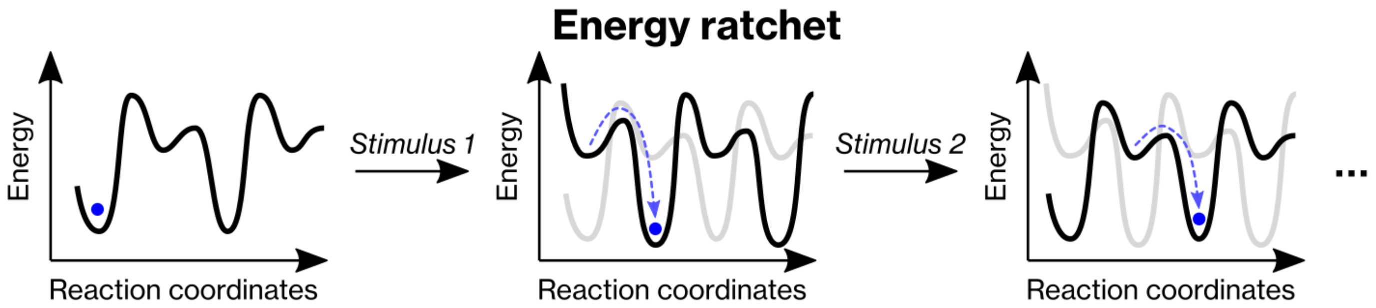



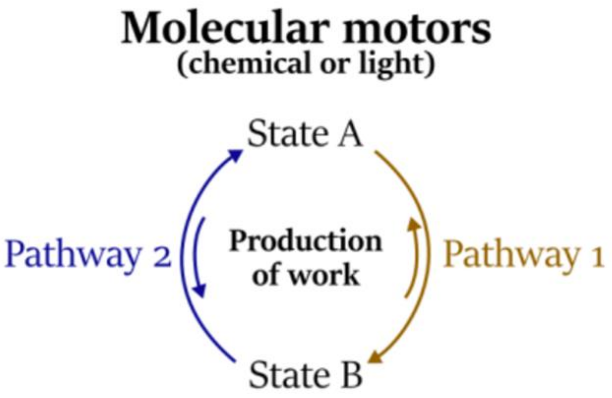

**Back and Forth Motions (microscopic reversibility)**



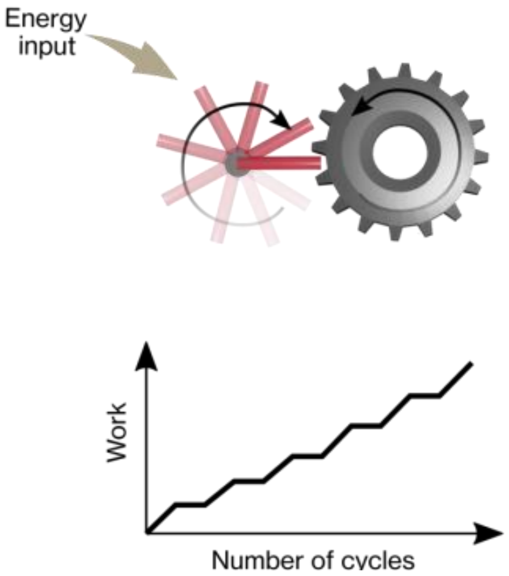

**Switches (*state*)**

# Unidirectionnalité du mouvement – Travail mécanique!



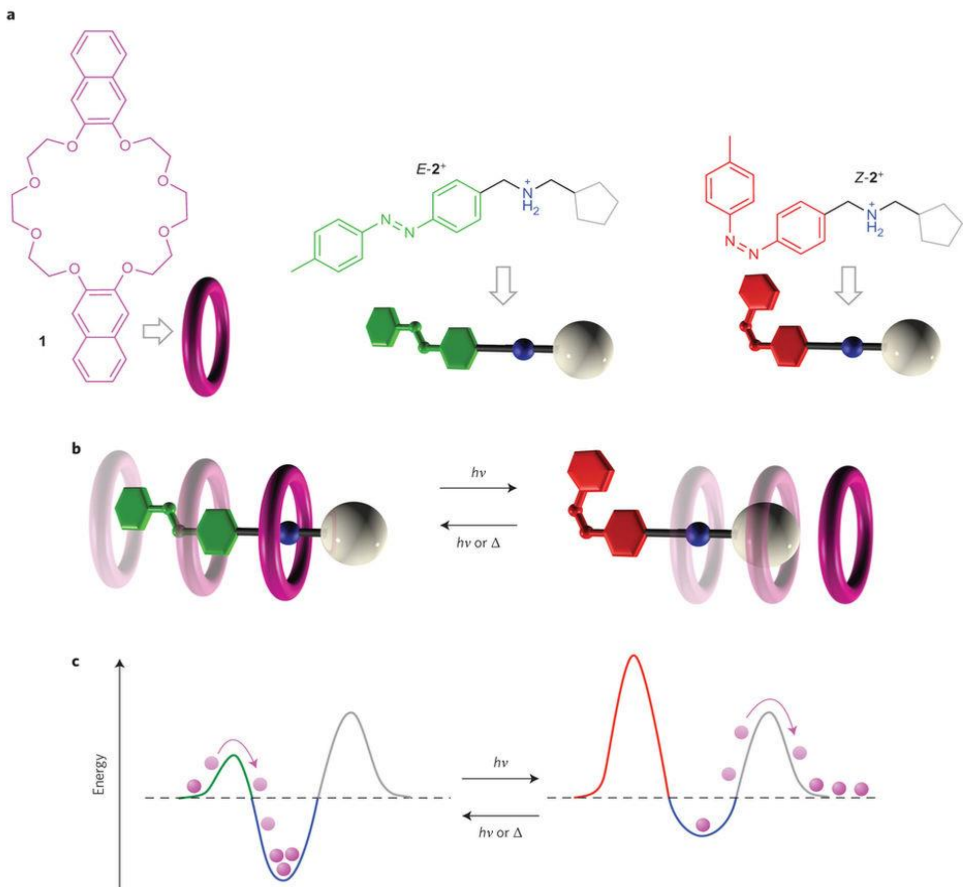

**Unidirectional Cyclic Motions (molecular ratchet)**

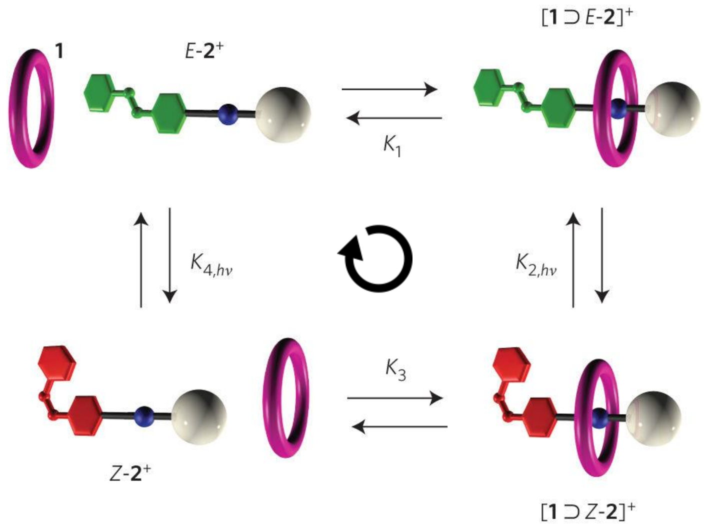



**Motors (*trajectory*)**

A. Perrot, N. Giuseppone, et al, *Trends in Chem.* **2021**, 926.

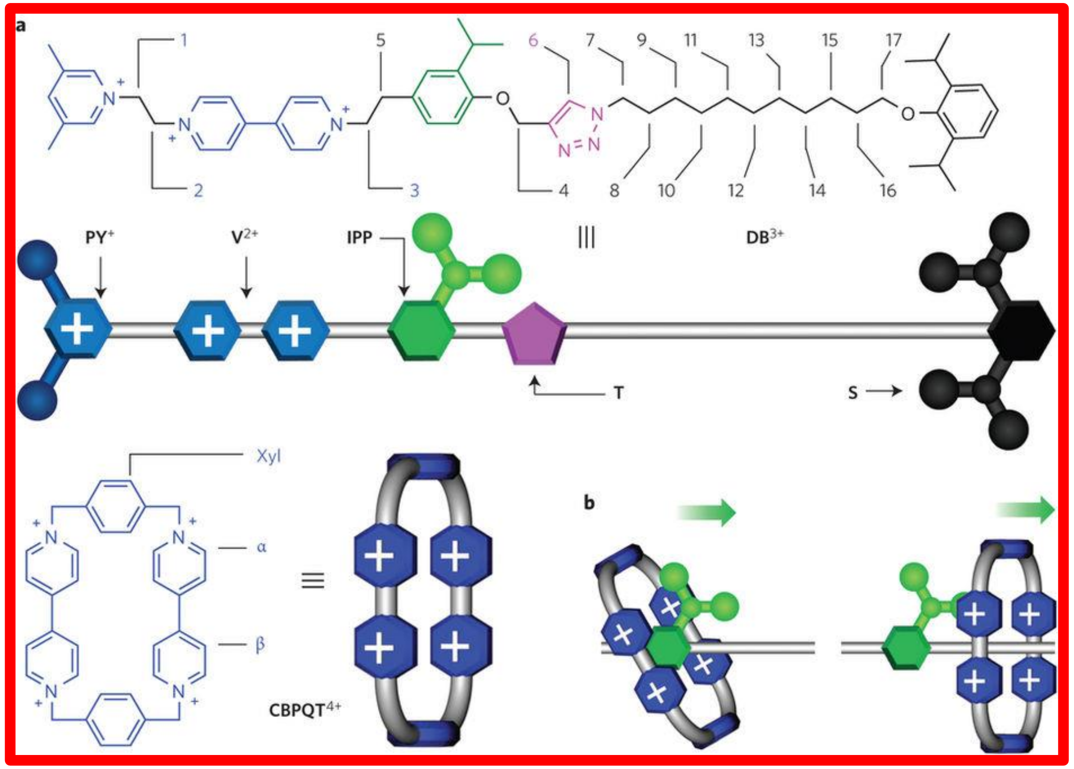
# Couplages rotaxanes et photocommutateurs

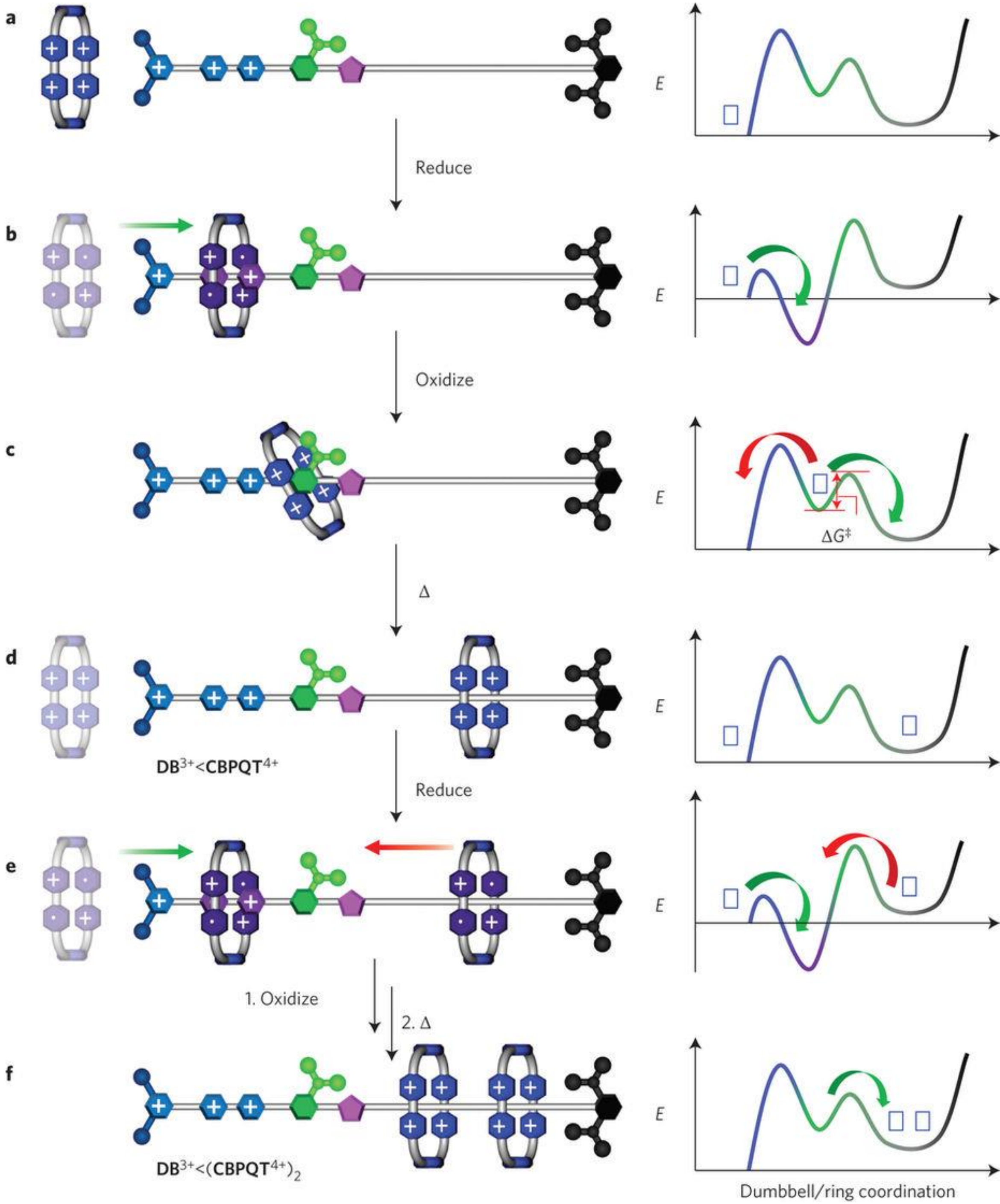



Credi et al. *Nature Nanotech.* **2015**, *10,* 70.

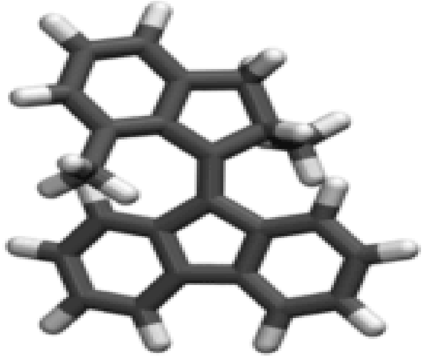
# Couplages rotaxanes et processus redox

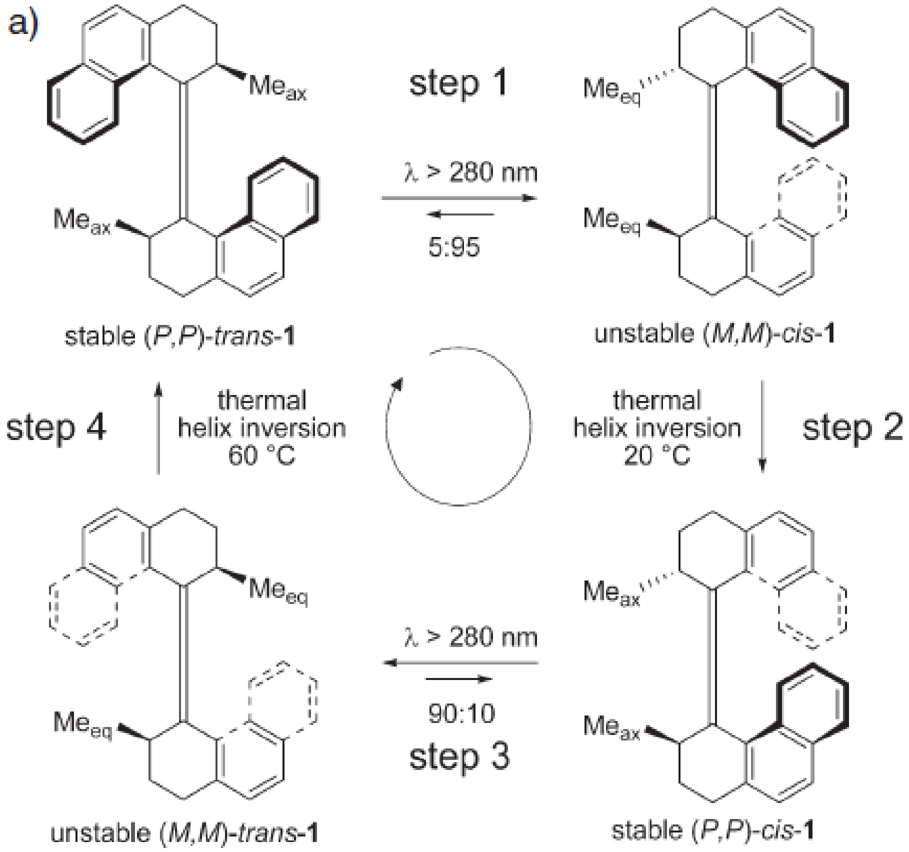


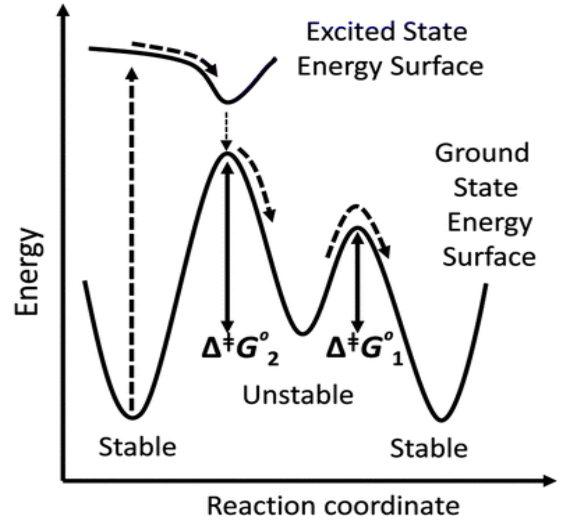



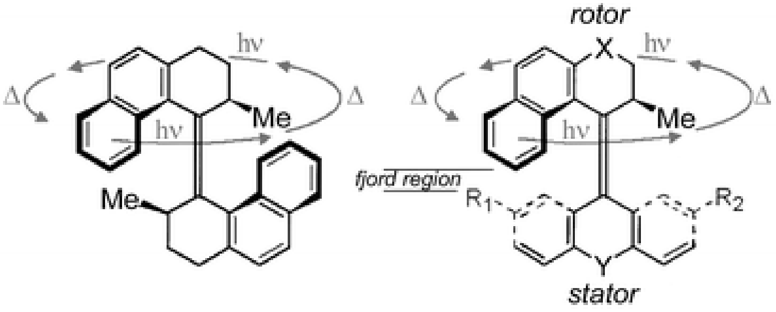

Stoddart et al. *Nature Nanotech.* **2015**, *10,* 547.

# Moteur moléculaire rotatif photoactivable





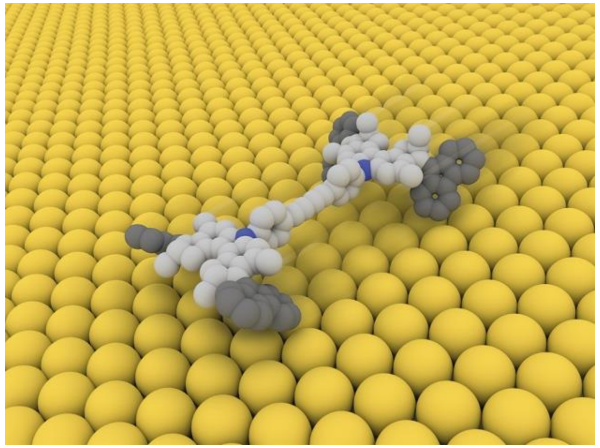



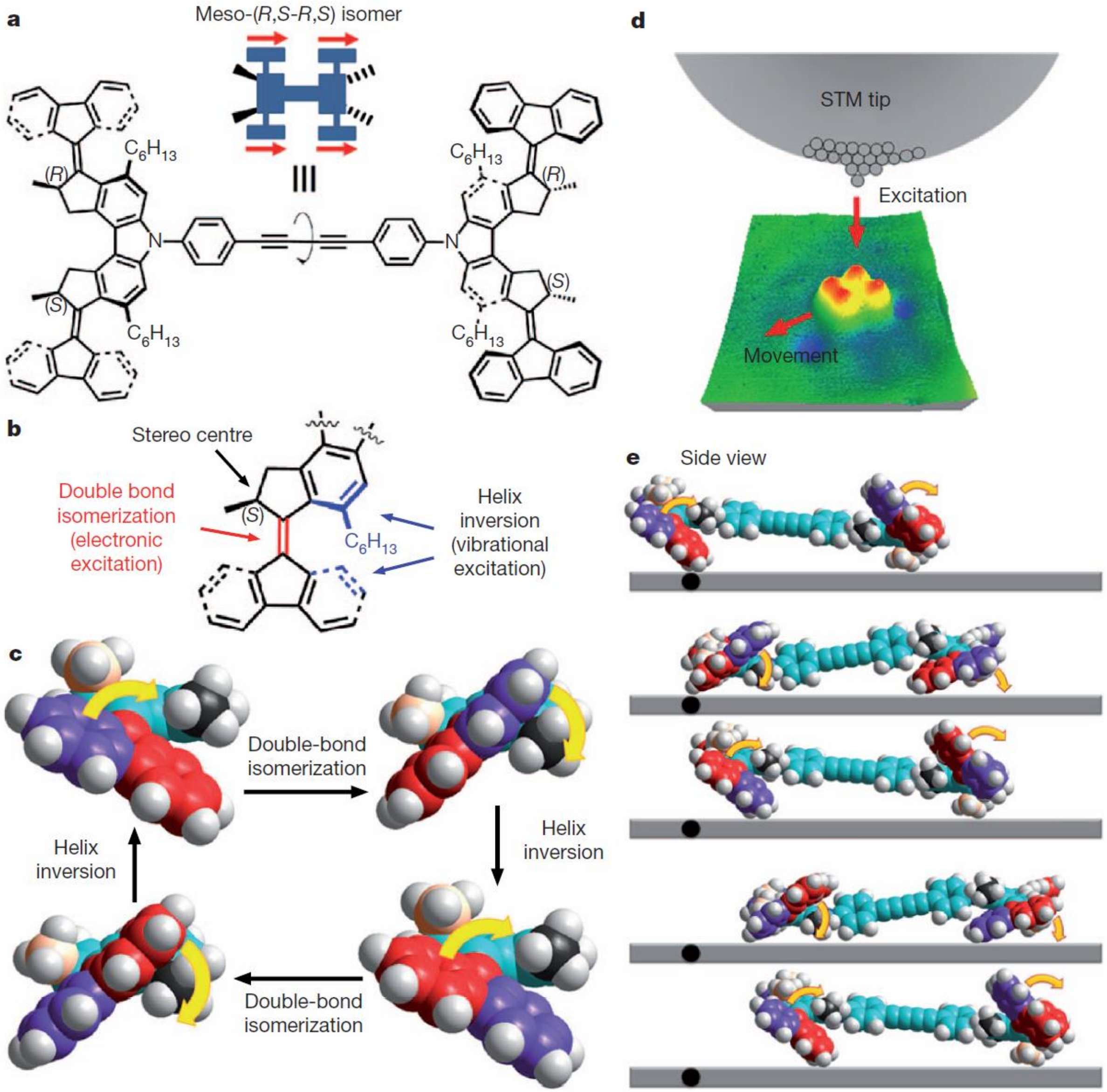




$2^{nd}$ generation
up to MHz frequencies

Ben L. Feringa et al. *Nature* **1999**, *401*, 152-154

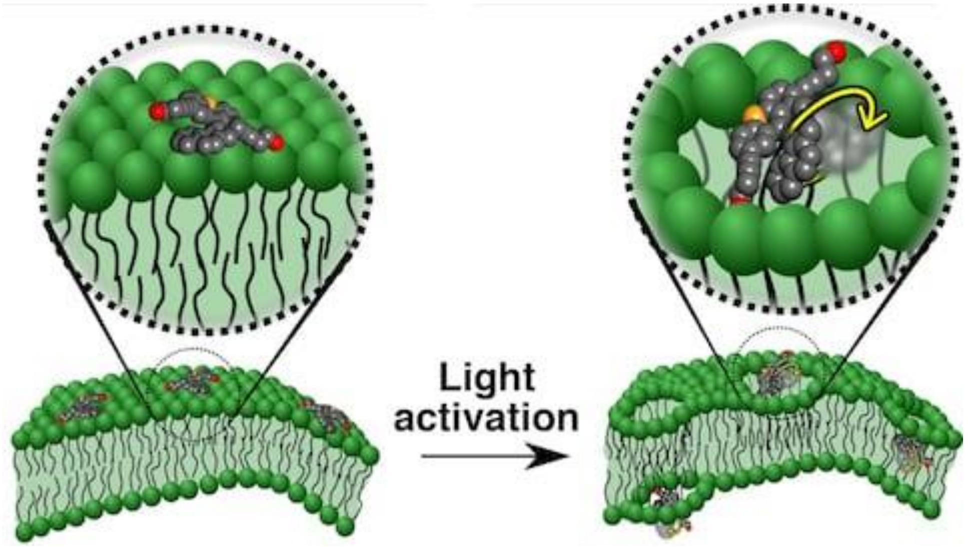
# Nanovoiture motorisée

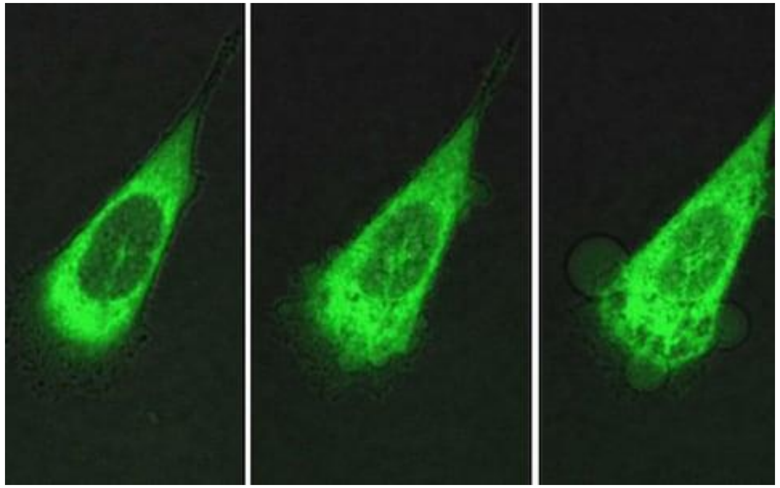



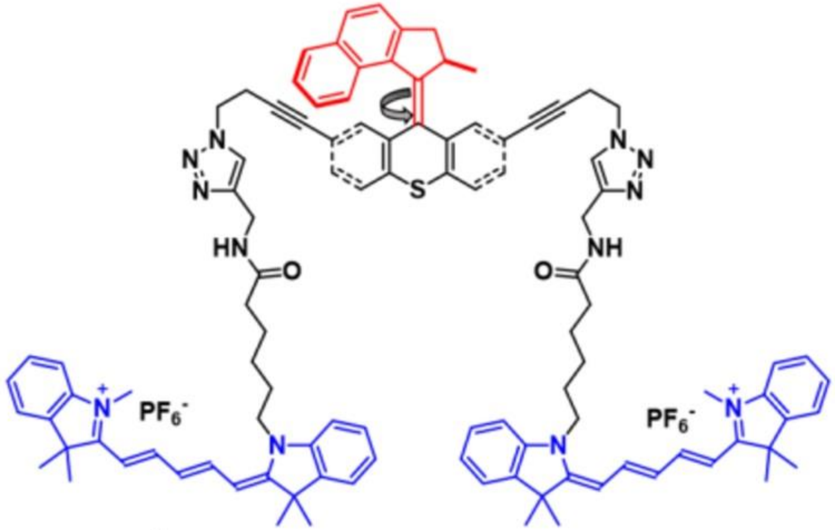


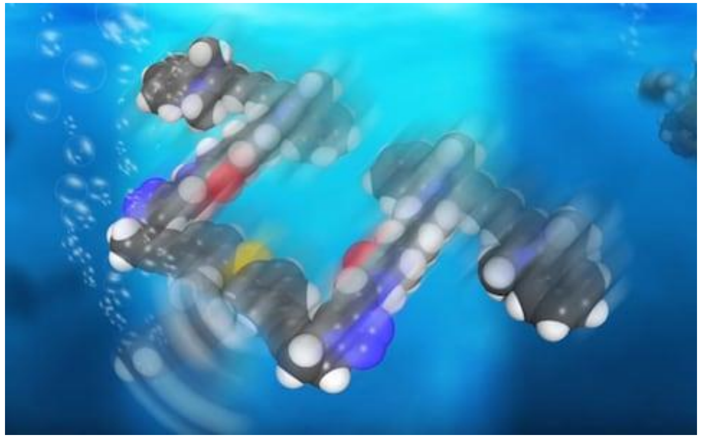

Feringa, et al. *Nature* **2011**, *479,* 208.

# Destruction de cellules cancéreuses par perforation



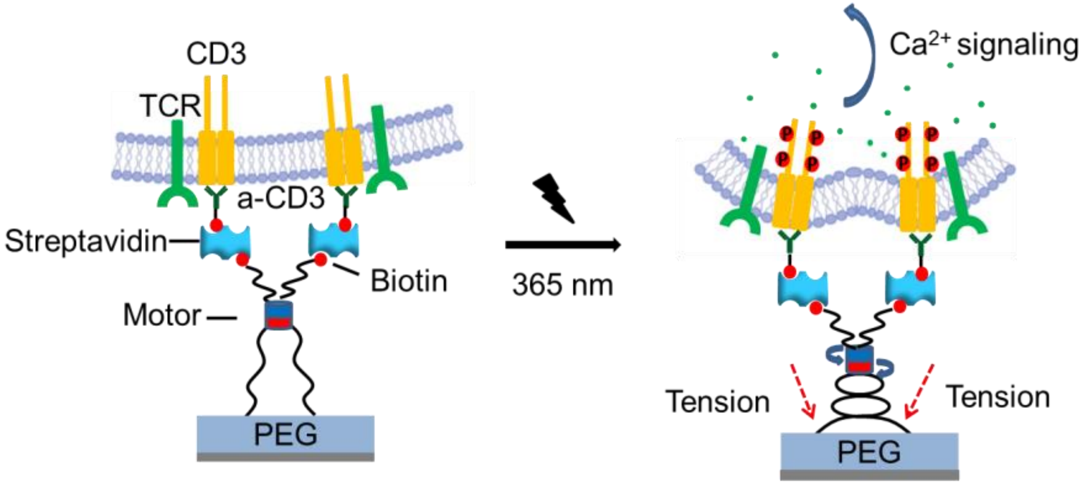


Tour, et al. *Nature* **2017**, *548,* 569.

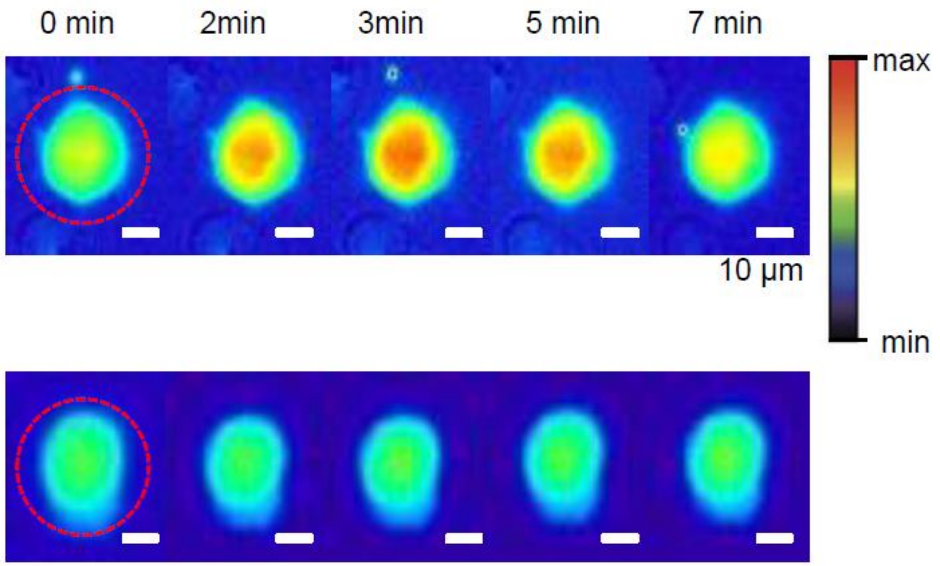
# Mécanotransduction motorisée dans des cellules vivantes

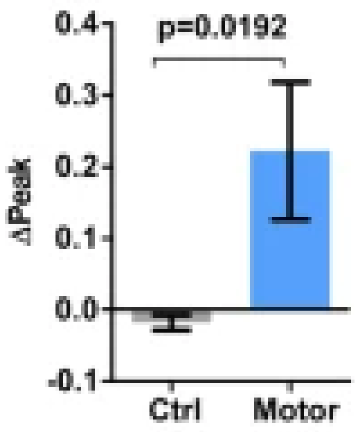
**Human T Cell**




**Motor**

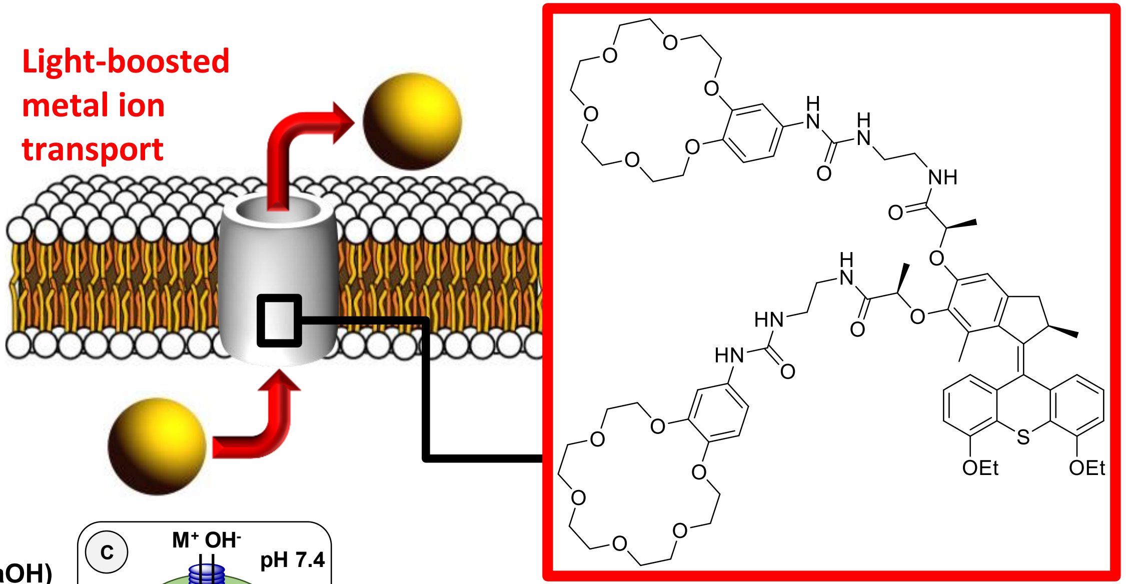
**Locked Motor**

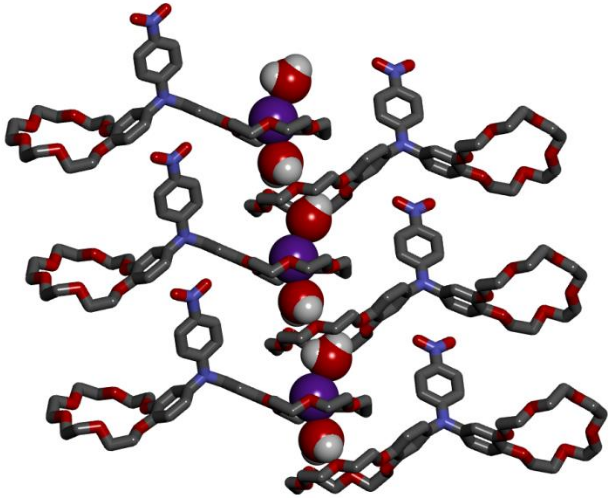


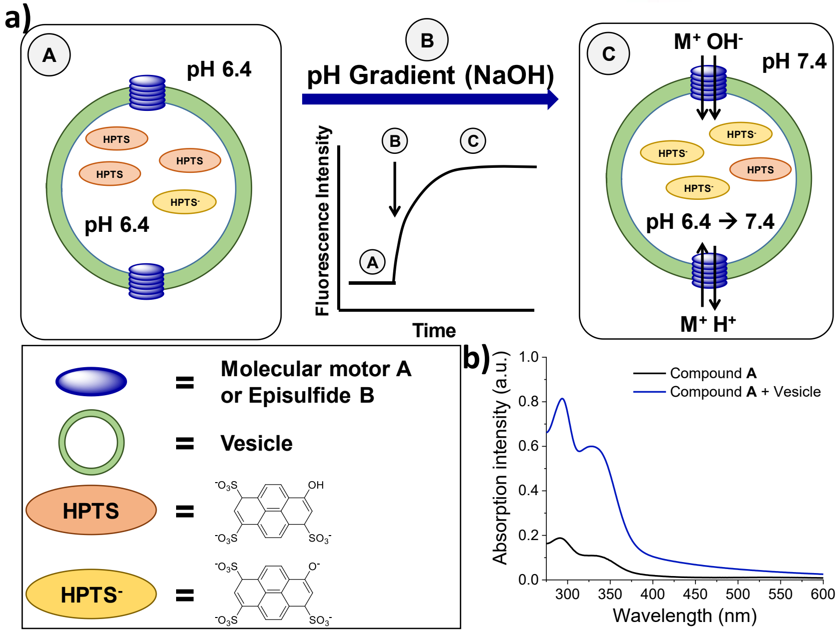



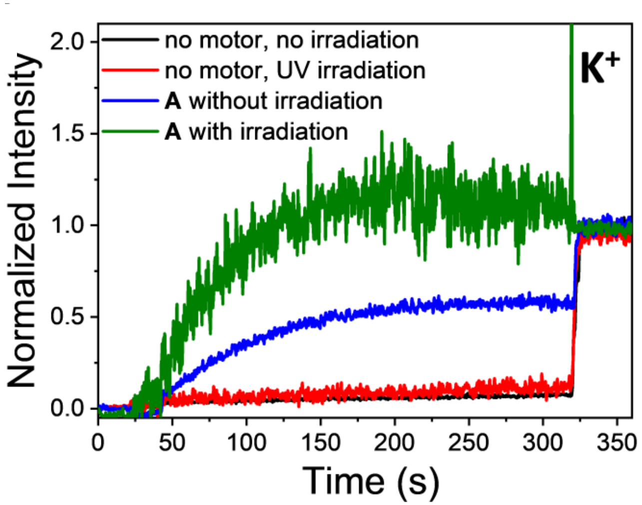

Zheng, Y., de Campo, A., Giuseppone, N. *et al. Nature Commun*. **2021**, *12*, 3580 .

# Transport d'ions motorisé





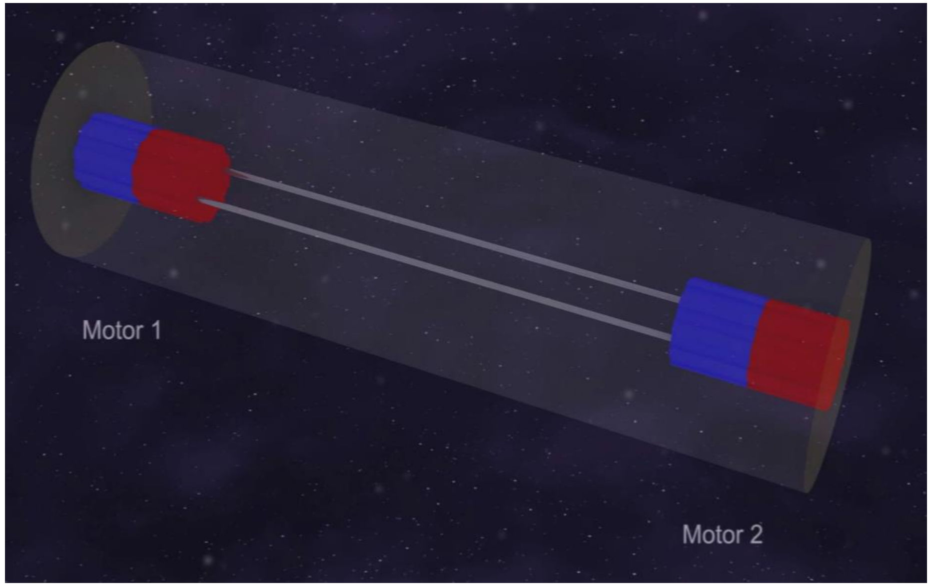

Wang, W., Barboiu, M., Giuseppone, N., *et al.* *J. Am. Chem. Soc.* **2021**, *143*, 15653.

# Couplage et amplification du mouvement

**Comment coupler des moteurs moléculaires rotatifs?**

**Comment utiliser leur travail à plus grandes échelles?**

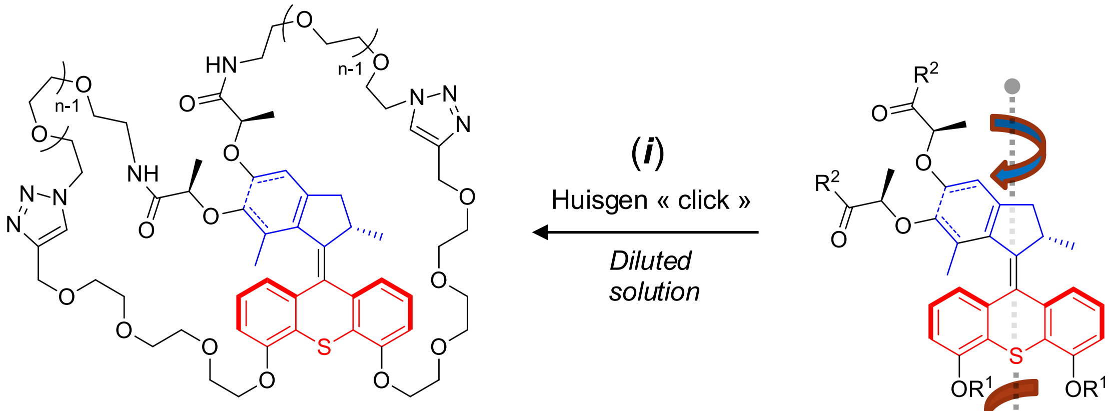
**Transmission par des chaînes polymères**





D. Dattler, G. Fuks, J. Heiser, E. Moulin, A. Perrot, Y. Xuyang, N. Giuseppone, *Chem. Rev.* **2020**, *120*, 310.
Moulin, E., Faour, L., Carmona-Vargas, C., Giuseppone, N., *Adv. Mat.* **2020**, *32*, 1906036.

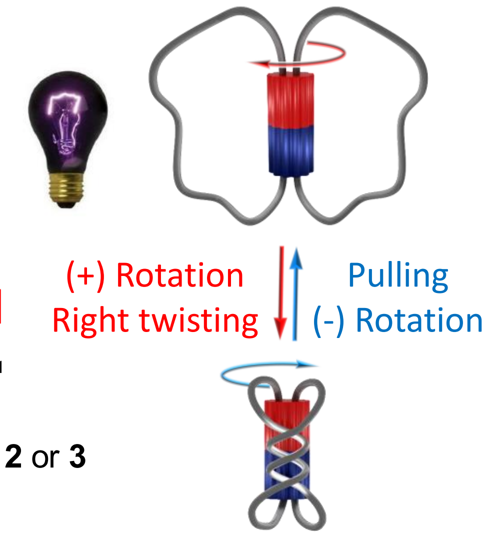
# Enchevêtrement de chaînes polymères



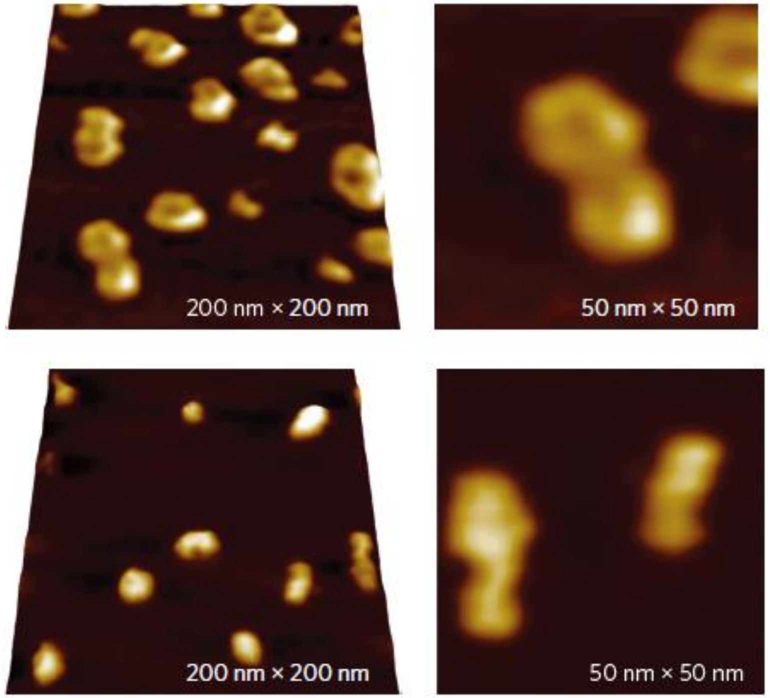

Yields 60-80%

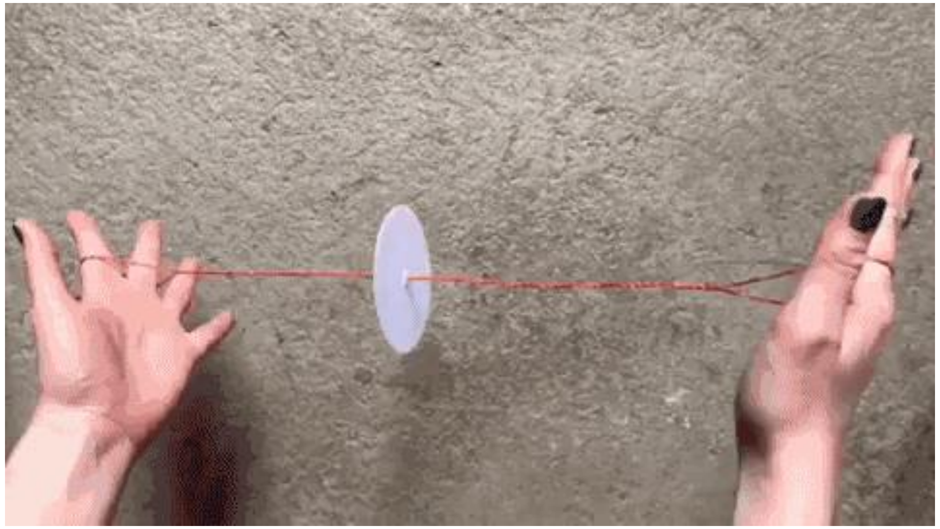
8-shaped-**4**: n=108
8-shaped-**5**: n=238

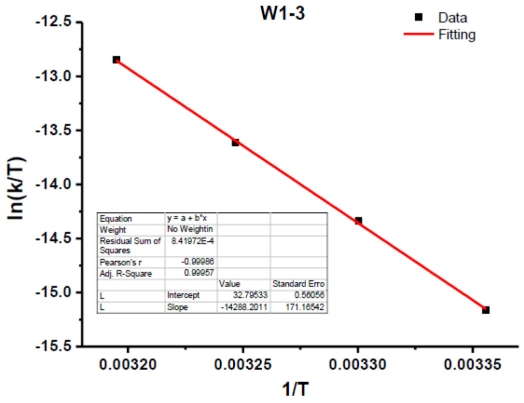
**2** or **3**




*Molecular whirligig*



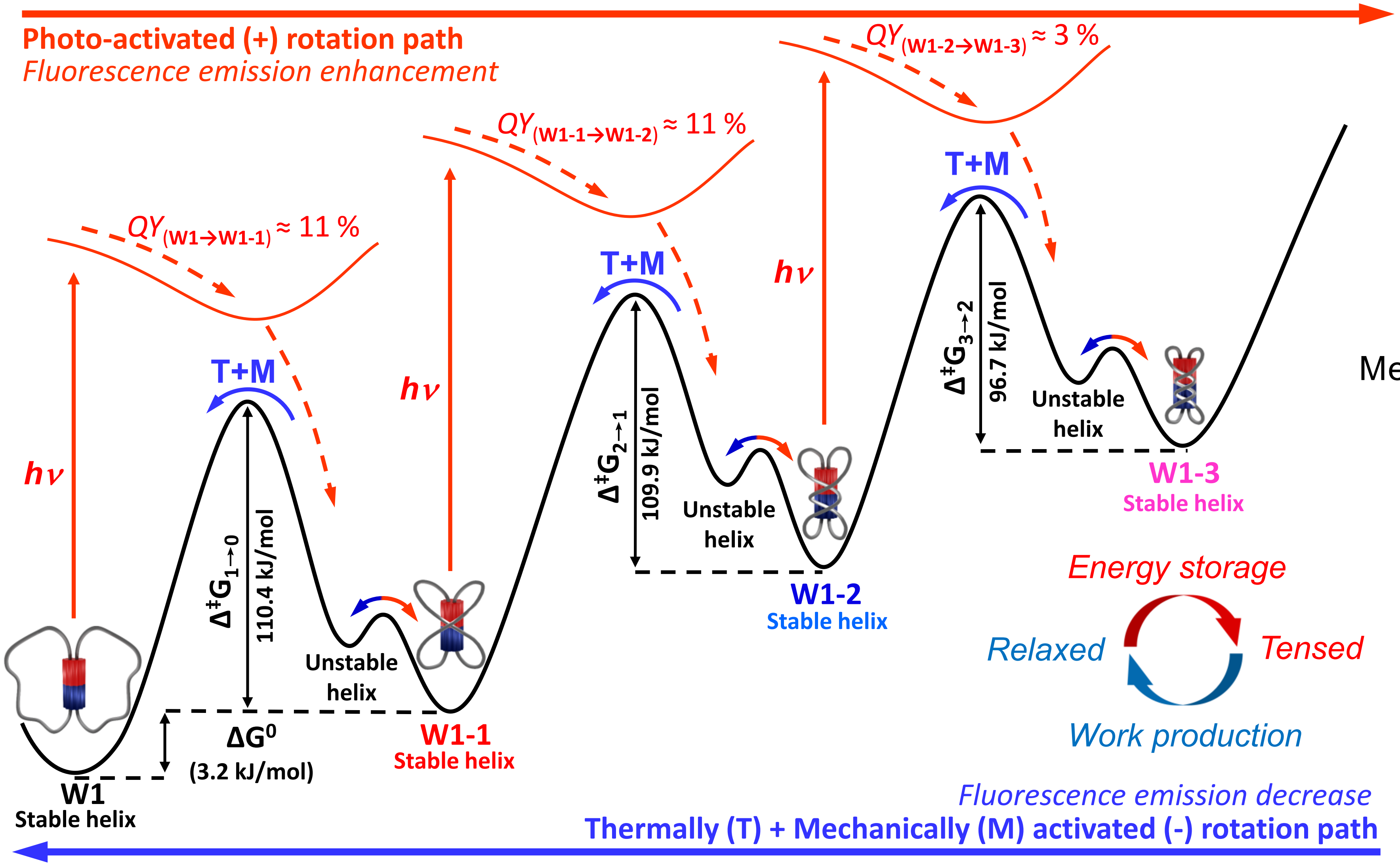






Li, Q., Giuseppone, N. *et al. Nature Nanotech*. **2015**, *10*, 161-165.

Activation parameters: $\Delta^{\ddagger}G_{3\rightarrow 2}$ (293 K) = 96.7 kJ mol$^{-1}$, $\Delta^{\ddagger}H$ = 118.8 kJ mol$^{-1}$, $\Delta^{\ddagger}S$ = 75.1 J mol$^{-1}$ K$^{-1}$, rate constant $k$ (293 K) = $3.398\times10^{-5}$ s$^{-1}$, $t_{1/2}$ (293 K) = 5.7 h.

# Stockage d'énergie et mesure du travail d'un nanomoteur

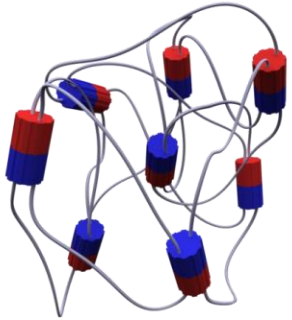


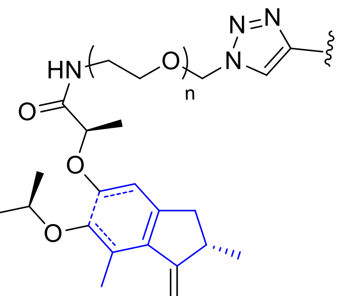

Mechanical energy density
≈12 kJ.kg$^{-1}$

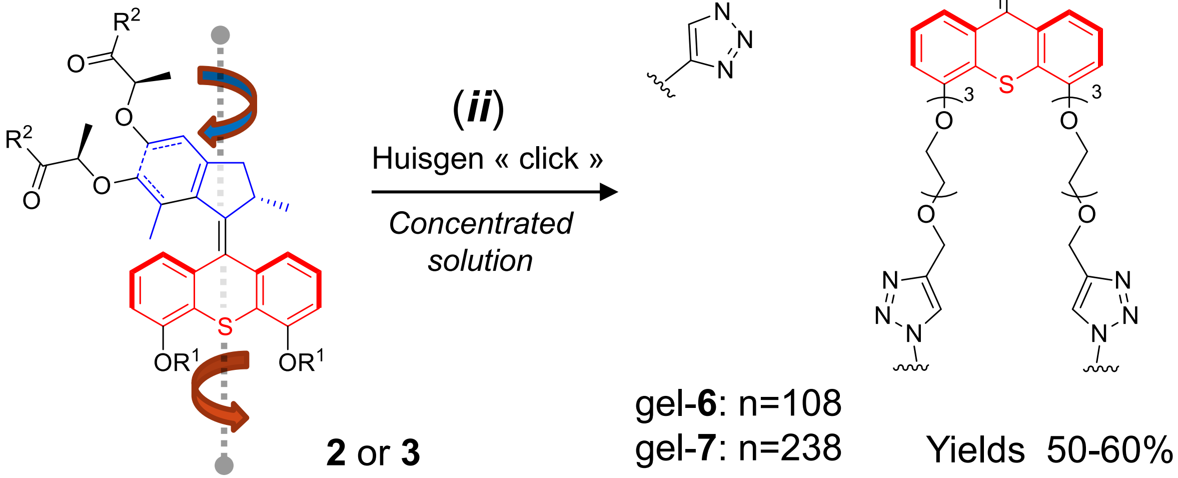
Torque ATP synthase
≈ 40 pN.nm

Gao., C., Giuseppone, N. *et al. J. Am. Chem. Soc.*, **2022**, *144*, 9845-9852.

# Hydrogels motorisés



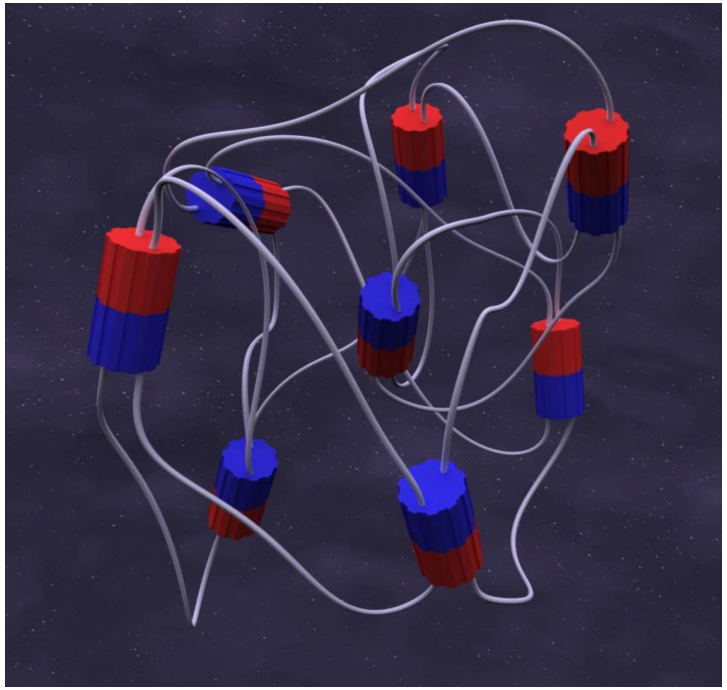





**2** or **3**

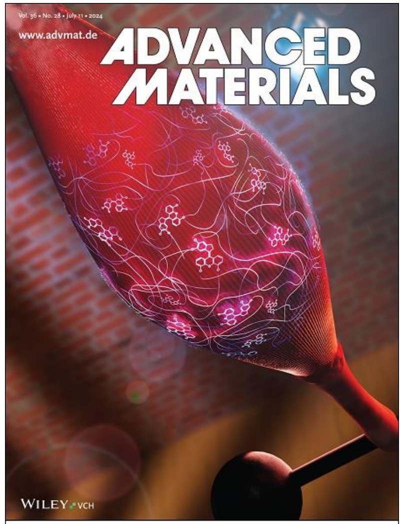
gel-**6**: n=108
gel-**7**: n=238

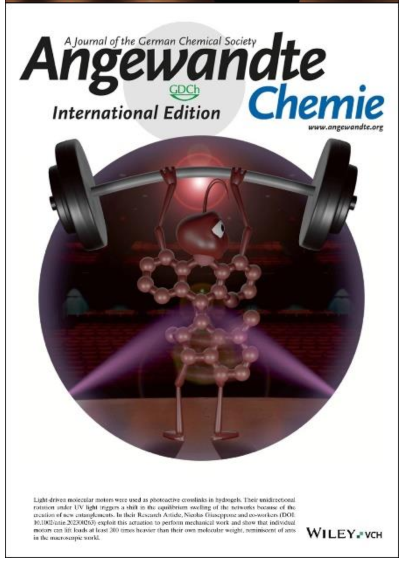
Yields 50-60%

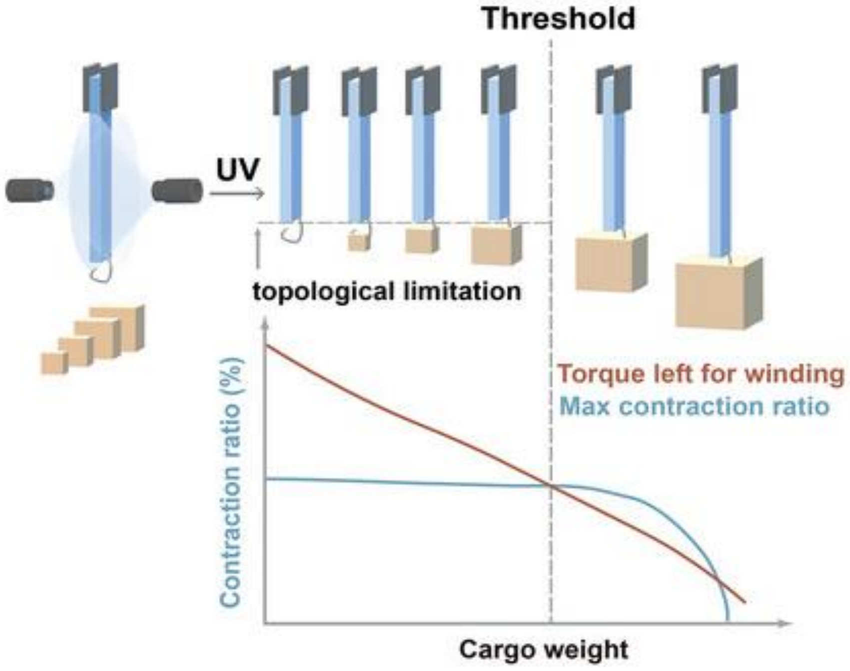



Li, Q., N. Giuseppone, *et al. Nature Nanotech*. **2015**, *10*, 161-165.

# Matériaux mécaniquement actifs



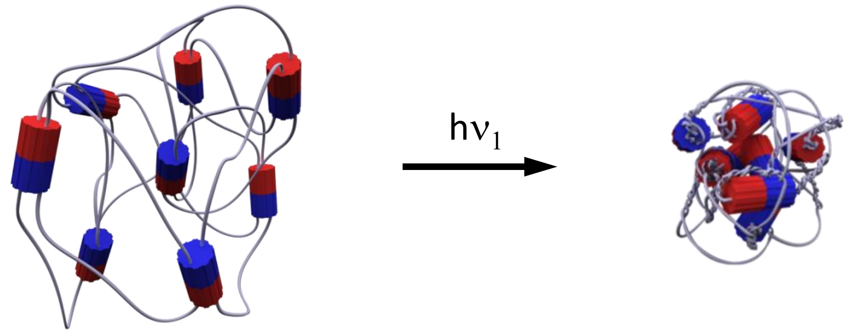

*Actionneurs*

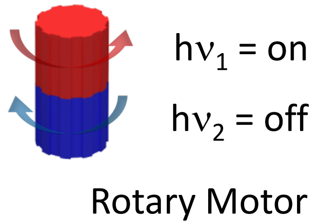
- *2800 x masse moteur!*
- *100 x masse matériau sec!*

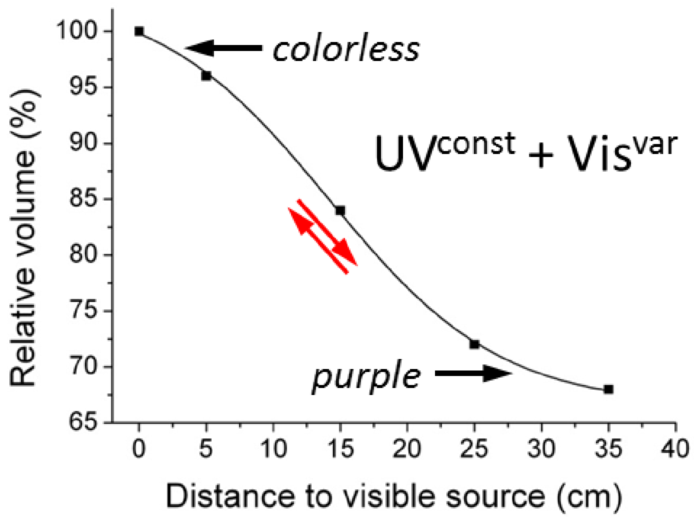

A. Perrot, N. Giuseppone, *et al.*, *Angew. Chem. Int. Ed.* **2023**, 202300263.

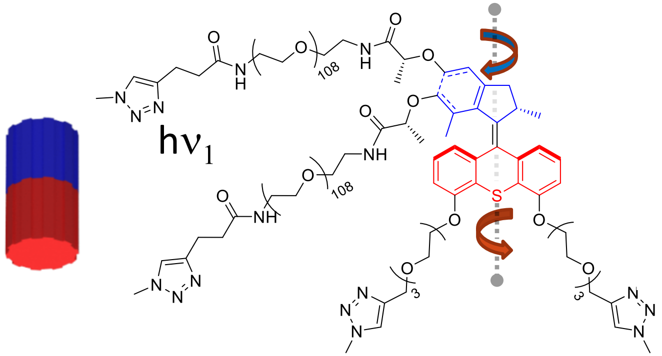
X. Yao, N. Giuseppone, *et al.*, *Advanced Materials.* **2024**, 2403314.

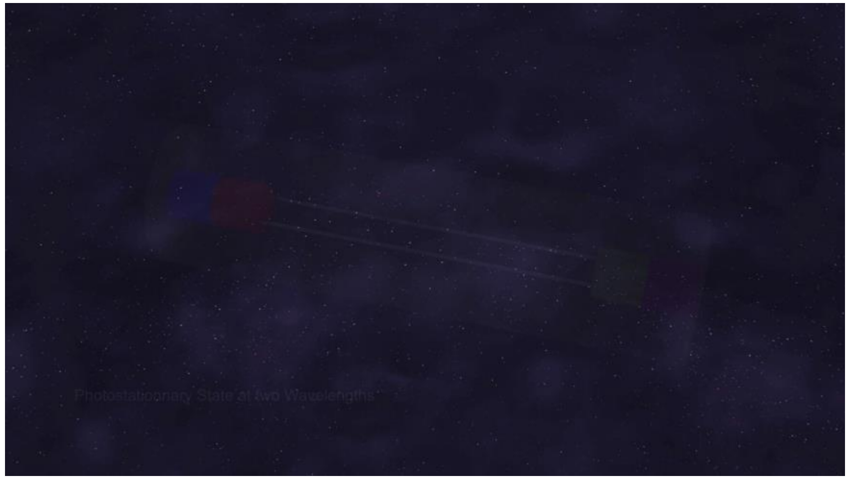
# Couplages de moteurs et réversibilité des systèmes



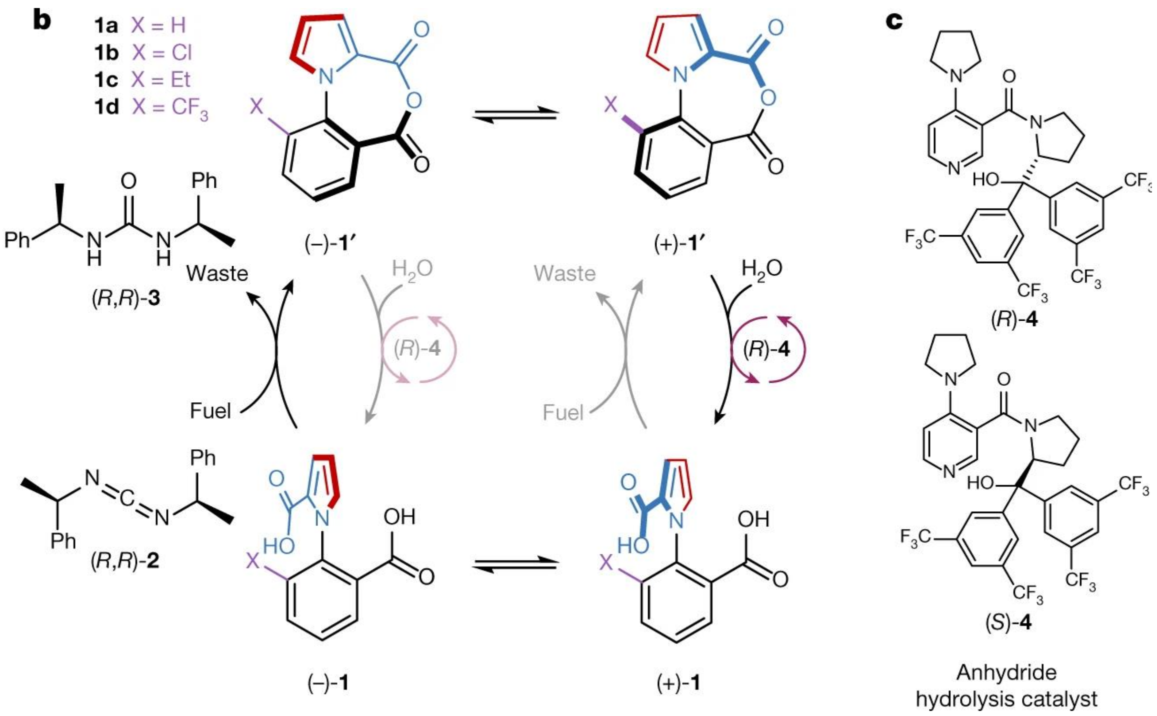



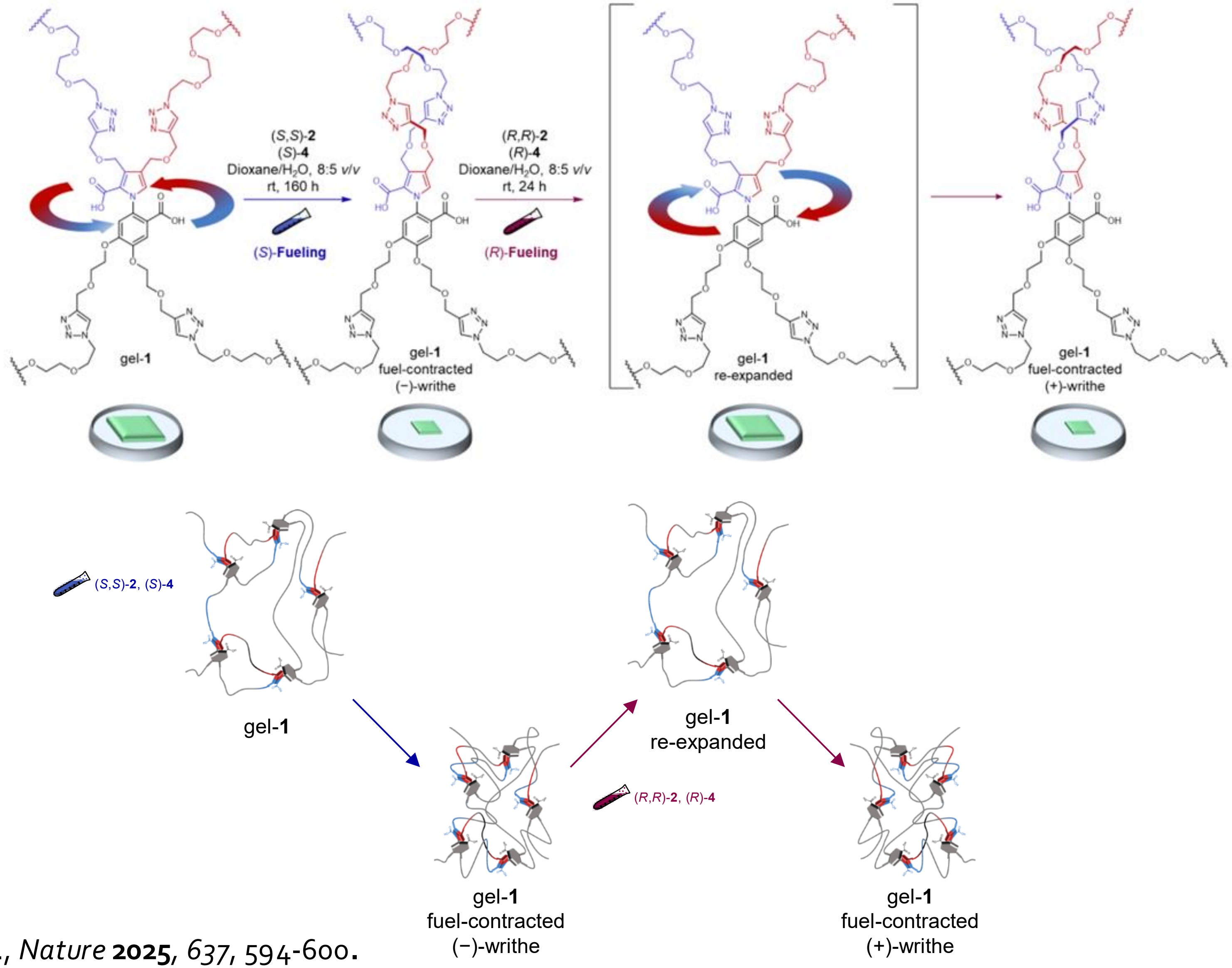
Foy, J. T., *et al. Nature Nanotech*. **2017**, *12*, 540-545.

# Moteur moléculaire rotatif à énergie chimique



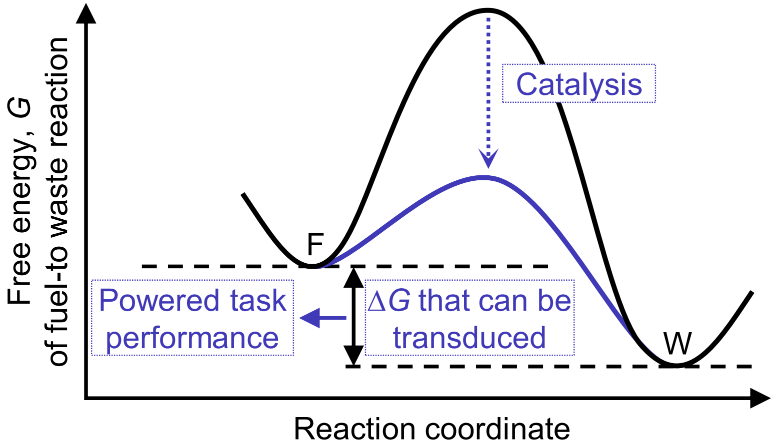

D. Leigh et al. *Nature* **2022**, *604,* 80-85.

# Utilisation d'un carburant chimique dans un matériau

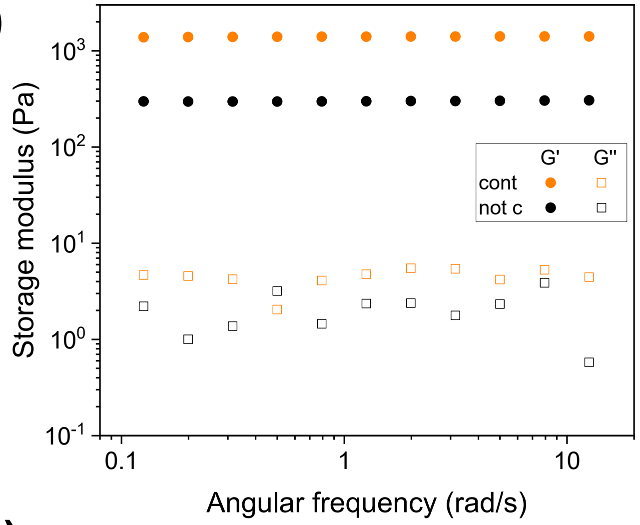



Giuseppone* and Leigh* *et al.*, *Nature* **2025**, *637*, 594-600.

# Utilisation d'un carburant chimique dans un matériau

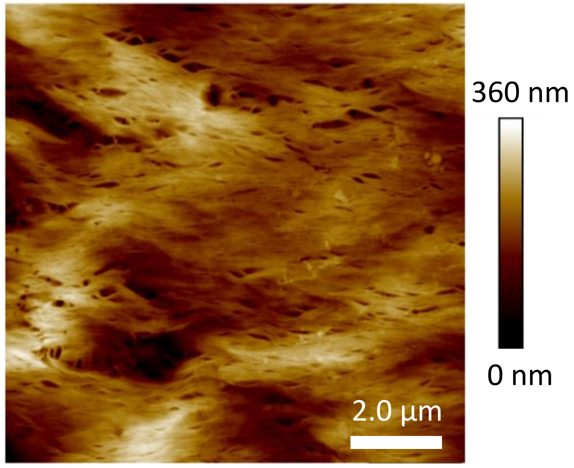



a)




b)

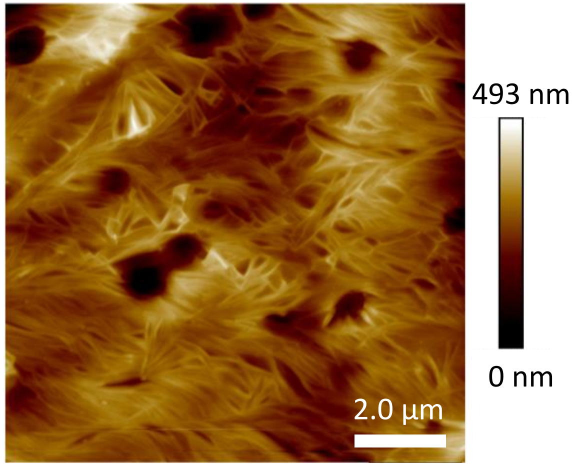
Unfuelled Gel-**1**




Height Sensor

c)

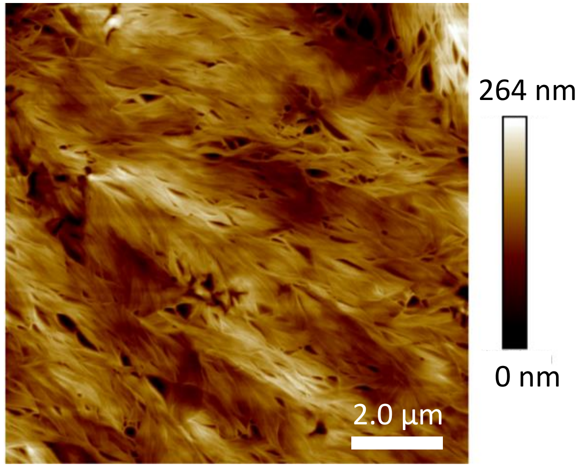
Fuel-contracted Gel-**1**




Height Sensor

d)

DMAP fully re-expanded Gel-**1**




Height Sensor

~ 5 efficient entanglements / motor

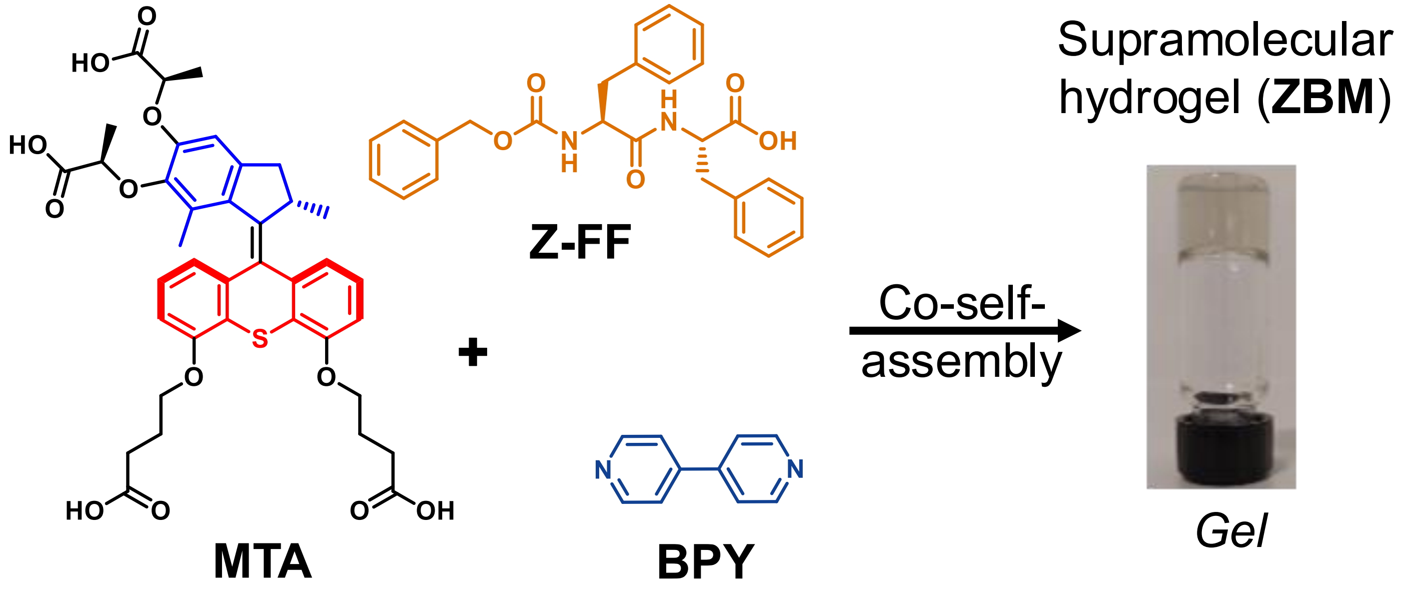
20% (+) bias in the rotation

Chemical energy transduction ~ 55%

$$G(\phi) \cong kT\,\frac{\phi}{Nb^3}\left(\frac{\lambda R_0}{R_{ref}}\right)^2 \cong kT\,\frac{\phi}{Nb^3}\left(\frac{\phi_0}{\phi}\right)^{2/3}\left(\frac{\phi}{\phi_0}\right)^{(2\upsilon-1)/(3\upsilon-1)}$$

Giuseppone* and Leigh* *et al.*, *Nature* **2025**, *637*, 594-600.

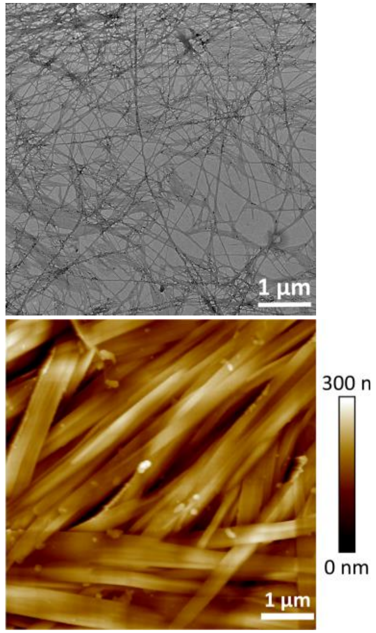
# Moteurs auto-assemblés: hydrogels β-amyloïdes

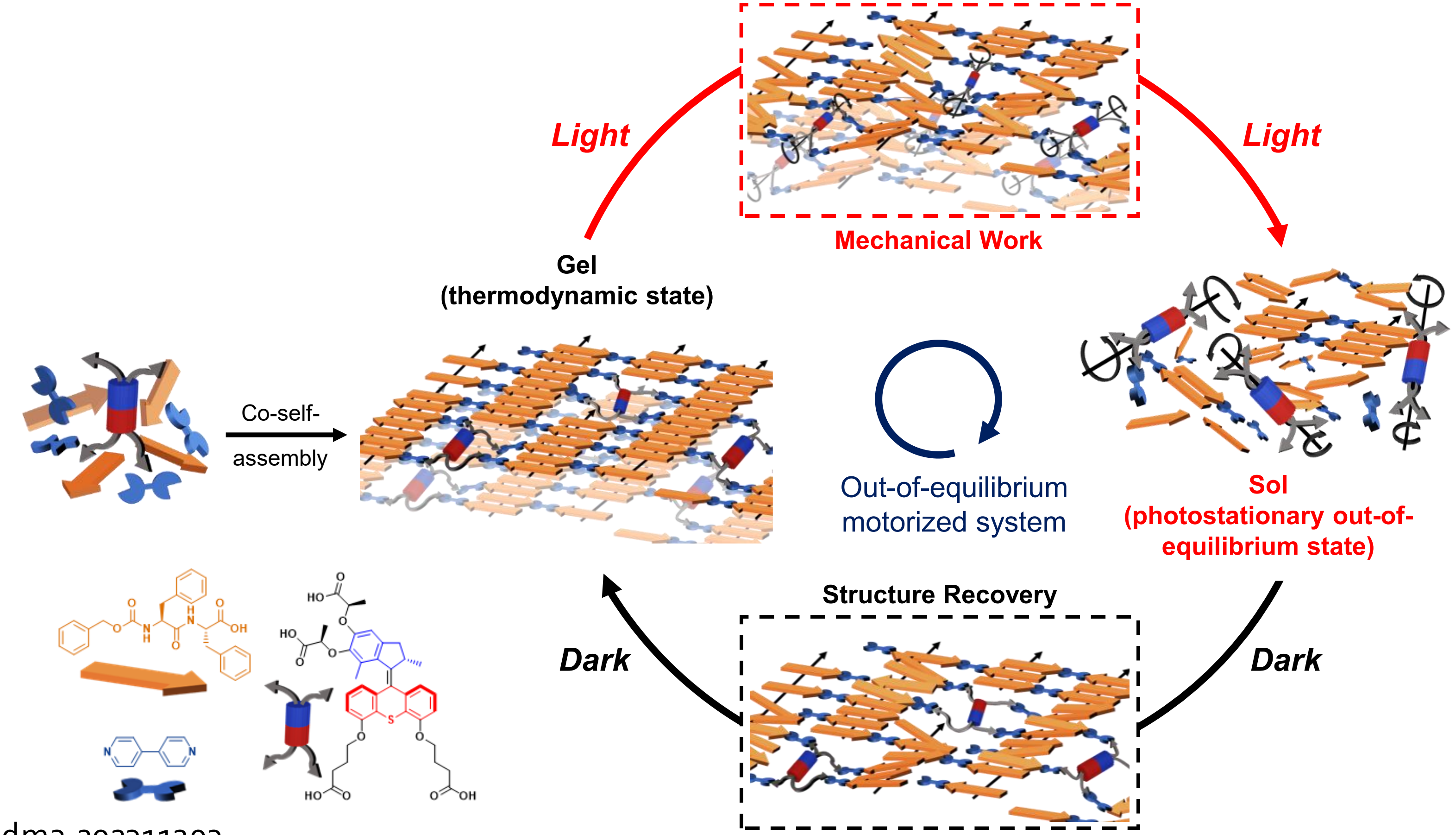



Dania Daou, *et al. Advanced Materials*, **2024**, 10.1002/adma.202311293.

# Moteurs auto-assemblés: hydrogels β-amyloïdes

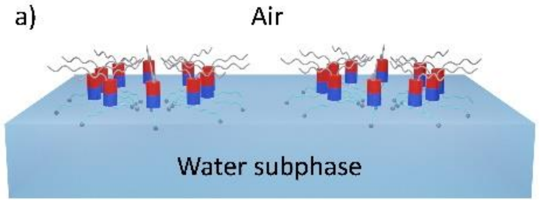
(a)

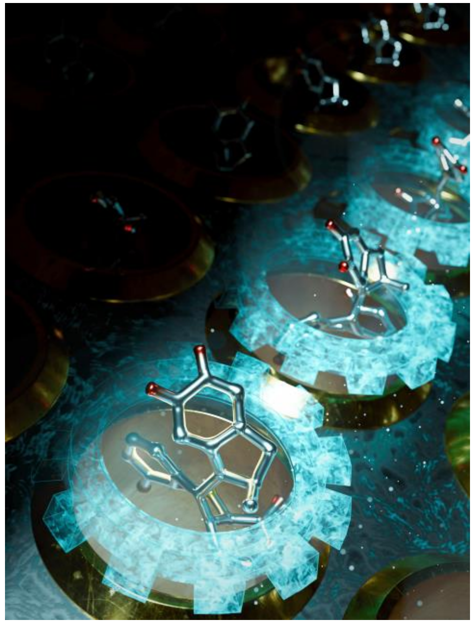


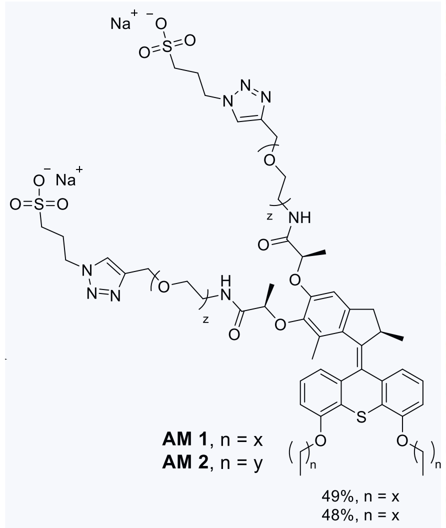



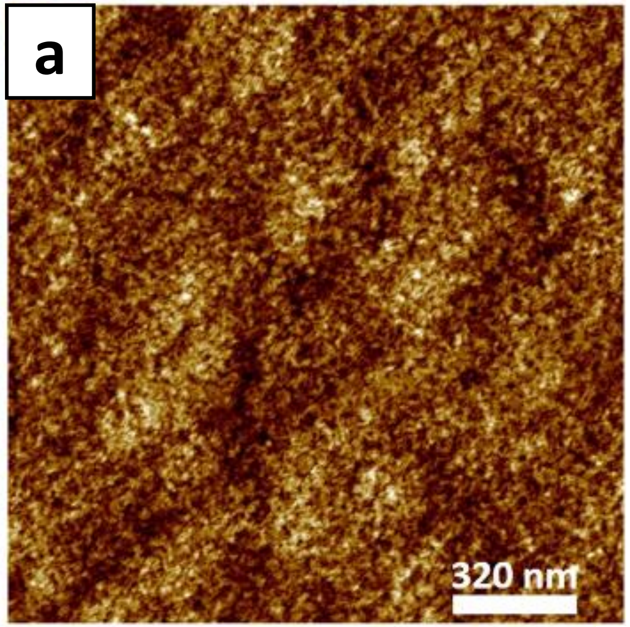

Dania Daou, *et al. Advanced Materials*, **2024**, 10.1002/adma.202311293.

# Moteurs amphiphiles et organisation par le mouvement



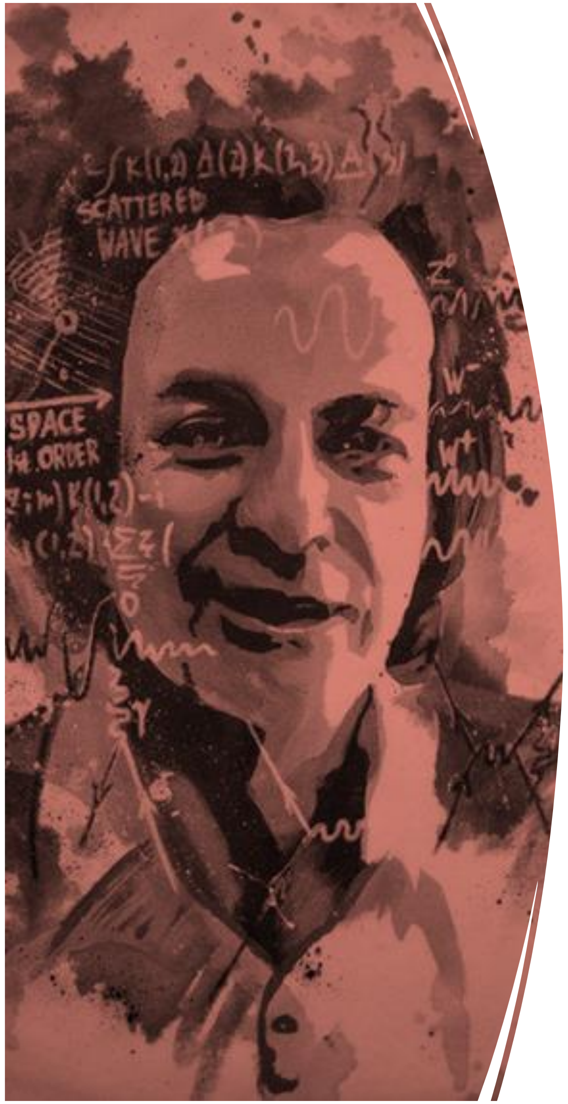






Philippe Schiel, N. Giuseppone, *et al.*, *Nature Nanotech.* **2025**, *20*, 1052-1061.

# Machines moléculaires : concepts et réalisation




Les moteurs moléculaires sont à la base de fonctionnement du vivant. On en connait donc le potentiel.

Leur mode de fonctionnement est tout à fait particulier. On commence aujourd’hui à le mimer avec de petites molécules de synthèse.

Les premiers travaux liant ces moteurs moléculaires à des systèmes fonctionnels apparaissent depuis peu dans la littérature scientifique. On commence à accéder à des systèmes et matériaux actifs.

Des potentialités infinies (« there’s plenty of room at the bottom ») sont espérées dans des domaines aussi variés que la robotique, la médecine et les nanotechnologies.

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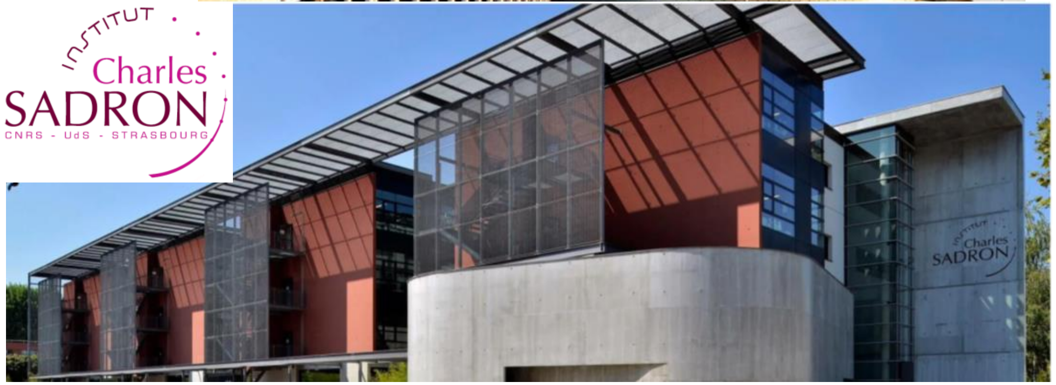

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Pr. Mounir Maaloum (AFM)
Dr. Michel Rawiso (SAXS, WAXS)
Dr. Olivier Schiffman (Mathematics)

Fondation Jean-Marie Lehn

***ERC AdG (SPRING), ERC StG (SelfChem),***
*FET OPEN (Magnify),*
***Marie Curie DNs*** *(**MonaLisa**, ArtMoMa, READ, and DYNANO),*
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*IRTG SoMaS, Institut Universitaire de France, LabEx CSC, icFRC,*
*Chinese Scholarship Council, IUF, Université de Strasbourg*

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