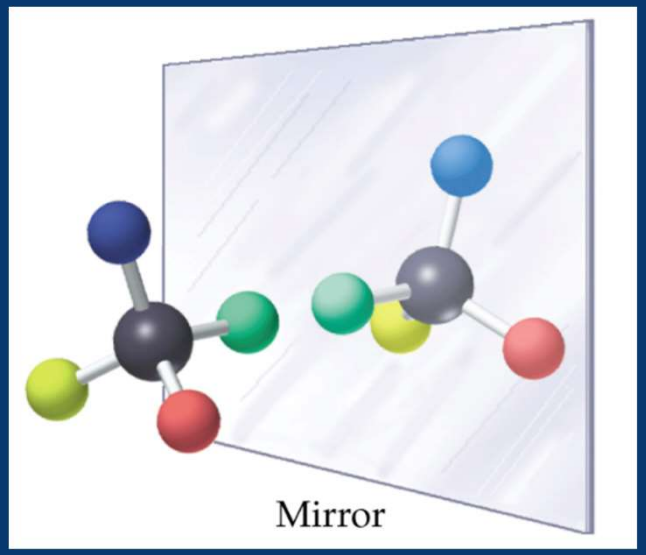


物理学院《近代物理进展》

让化学选择一面镜子

Chemistry is to Pick a Mirror

2026 年诺贝尔化学奖
与生命的“同手性”之谜

The 2026 Nobel Prize and the Mystery of Biological Homochirality

张国庆 PhD and Professor of Chemistry
合肥微尺度物质科学国家研究中心

7:00 PM, 2026/11/10@东区5301

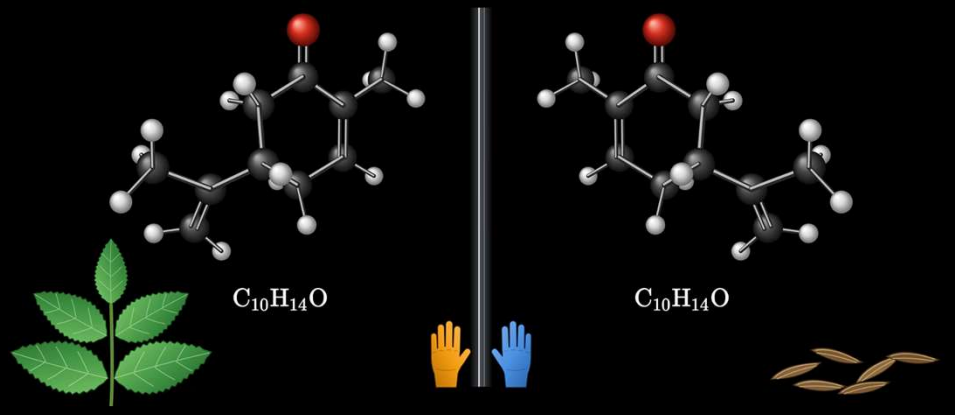
生命为什么选择一种镜像?

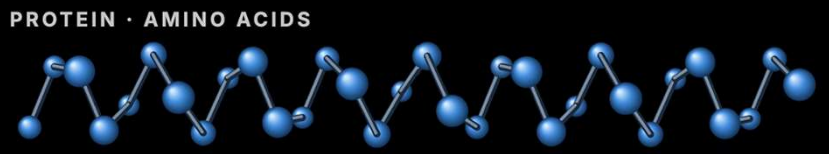
Why Does Life Choose Only One of the Two Mirror Images?

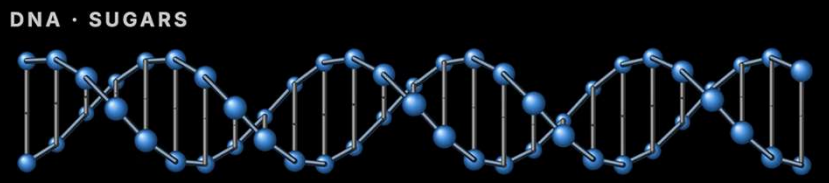
留兰香与葛缕子籽：
同一组成，镜像结构，
却呈现不同气味?

嗅觉受体蛋白也有手性，因此能区分香芹酮（carvone）的对映体

生命更普遍地选择单手性：
L-氨基酸构建蛋白质，D-糖构建核酸





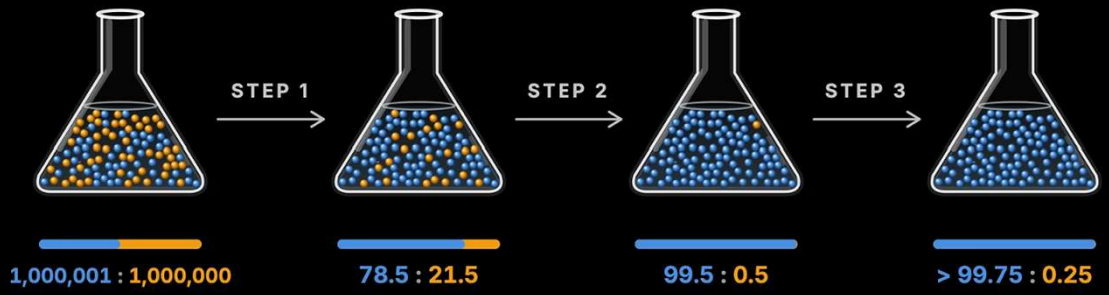


2026 年诺奖表彰的是“手性如何被放大”

The 2026 Nobel Prize: Amplifying Chirality

Henri B. Kagan & Kenso Soai

“for the discovery of non-linear effects and autocatalysis in asymmetric organic synthesis”



1953 — **Frank 模型**

复制手性 + 相互抑制

1986 — **非线性效应**

活性池可以比配体更纯

1995 — **不对称自催化**

产物催化自身并放大 ee

2003 — **极低涨落放大**

可达 >99.5% ee

2026 — **诺奖总结**

手性生成、传递与放大

报告提纲：从定义到可讨论的前沿

Learning Route: From Definitions to Research Frontiers

01	镜像分子之谜	会定义手性、ee 并理解镜像等价
02	从 Frank 到 Soai	Frank → Kagan → Soai
03	手性物理拓展	会区分光、自旋、声子与拓扑手性
04	前沿与讨论	能提出可检验的手性调控问题

01

近代物理进展 · 专题报告 / MODERN PHYSICS PROGRESS

手性是对称性(破缺)问题

CHIRALITY AS A SYMMETRY PROBLEM

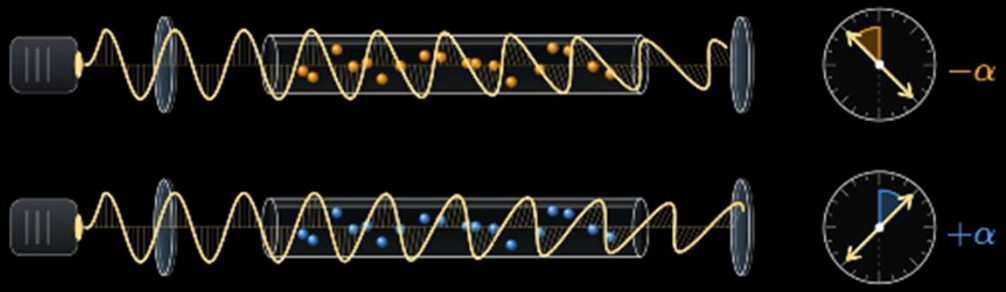
怎样把“左右不同”转化为可计算、可测量的物理量？

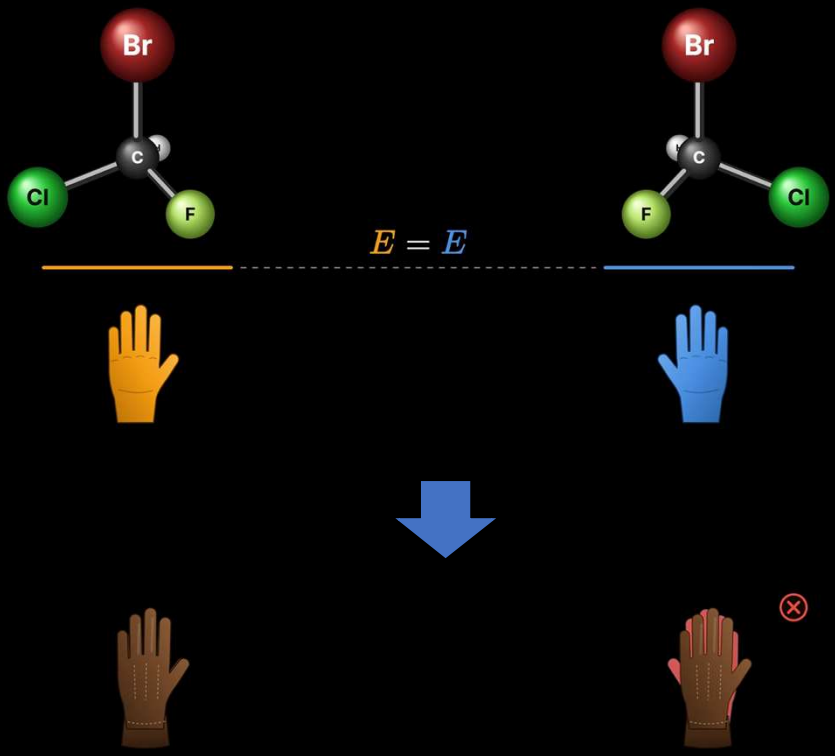
手性：镜像存在，但不能通过旋转与平移重合

Chirality and Enantiomers

镜像不可重合，
即为手性（chirality）

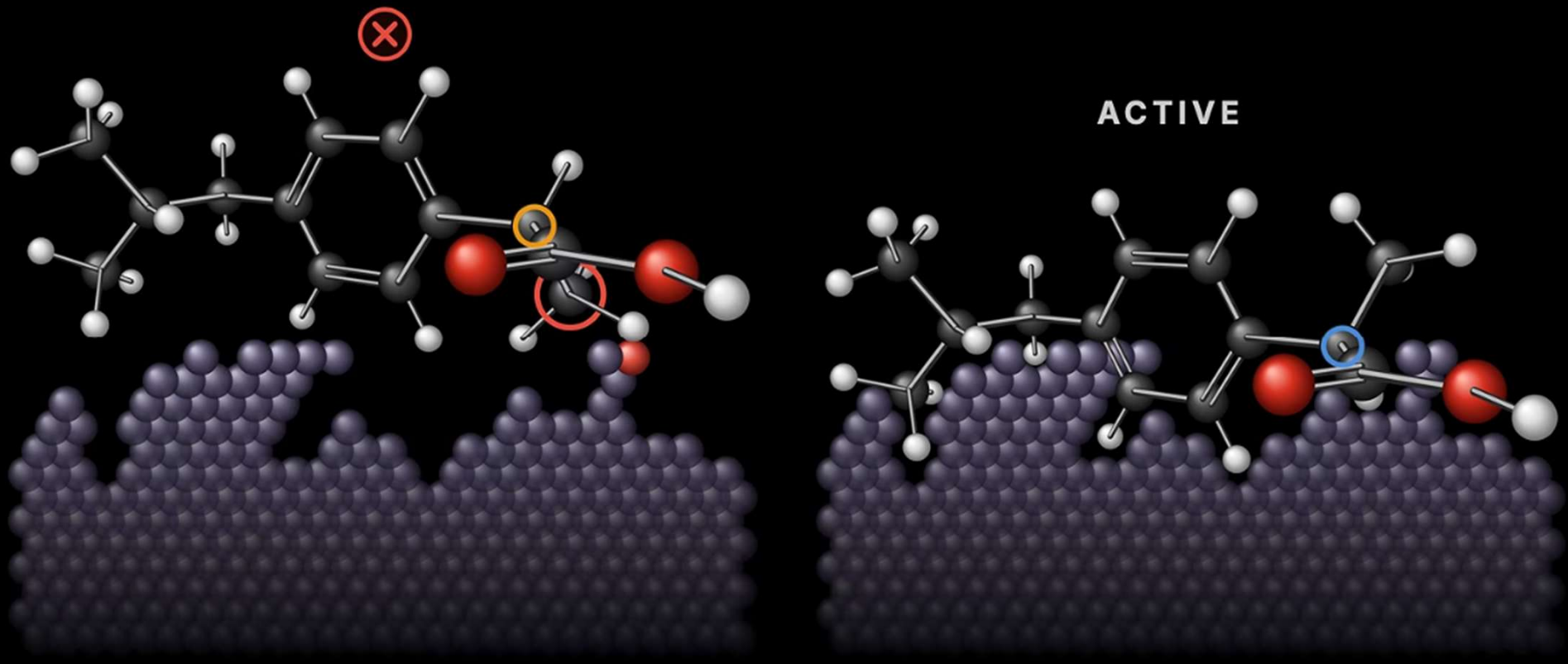
- **对映体（enantiomers）**：互为镜像的一对分子
- **非手性（achiral）**：镜像可通过真旋转与平移重合





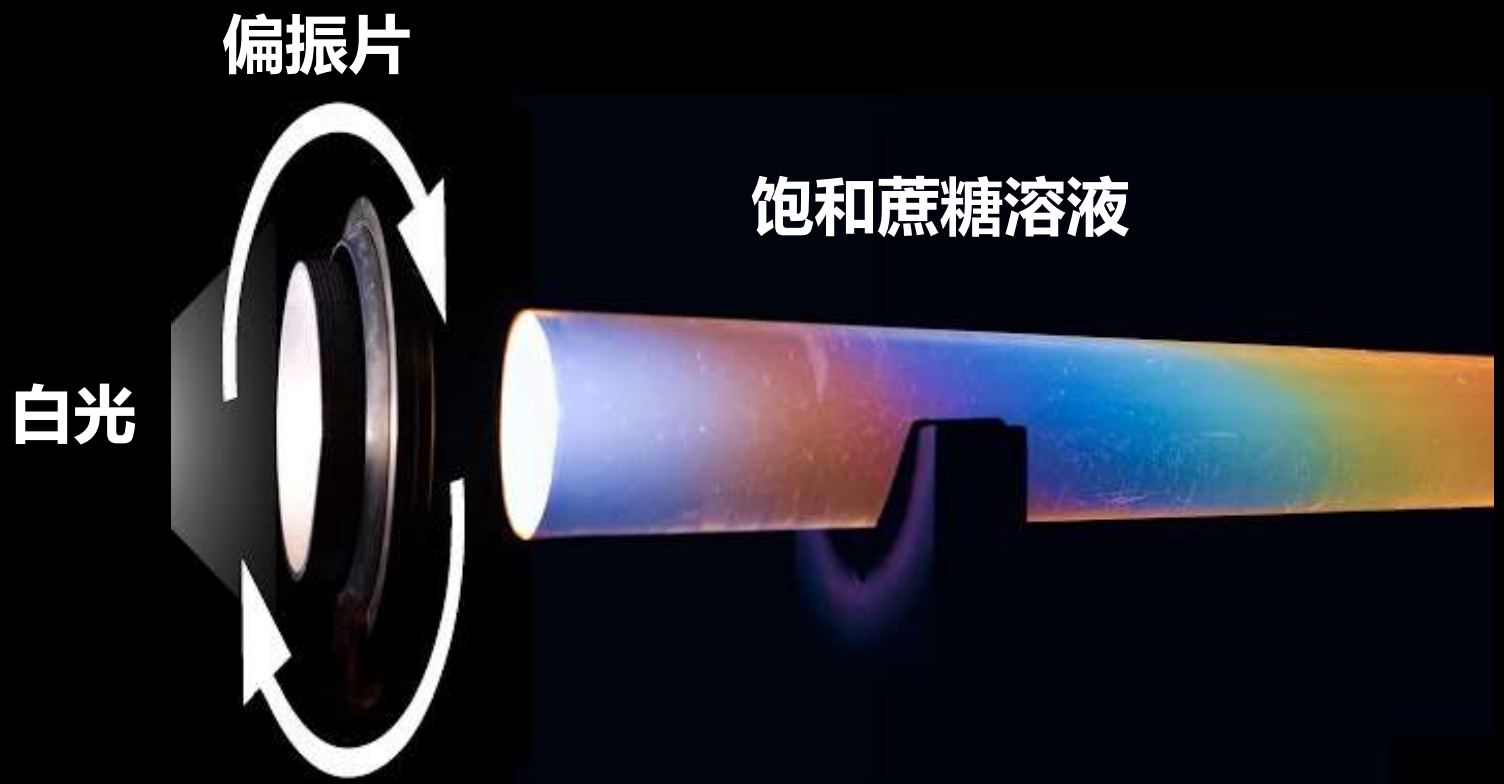
手性：镜像存在，但不能通过旋转与平移重合

Chirality and Enantiomers



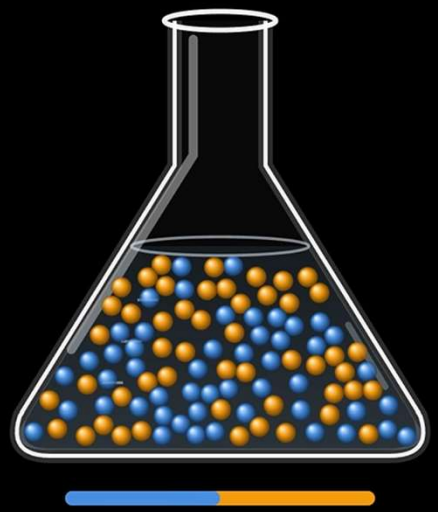
手性分子可以改变光的偏振方向

Chirality and Enantiomers



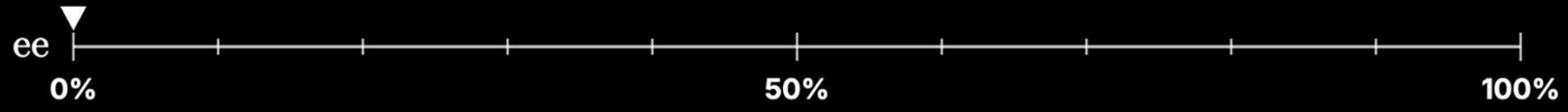
有机化学家如何定量表示手性产物?

How do organic chemists quantify enantiomers?



$$ee = \frac{\text{主手性产物} - \text{副手性产物}}{\text{总产物}}$$

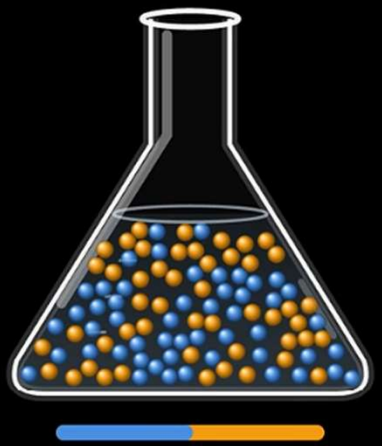
$$ee = \frac{50 - 50}{100} = 0\%$$



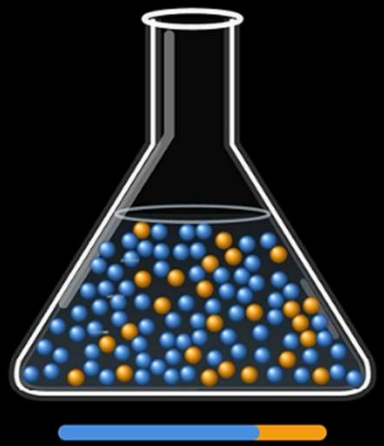
外消旋产物

有机化学家如何定量表示手性产物?

How do organic chemists quantify enantiomers?

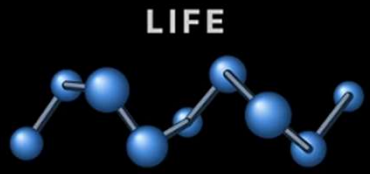


51 : 49



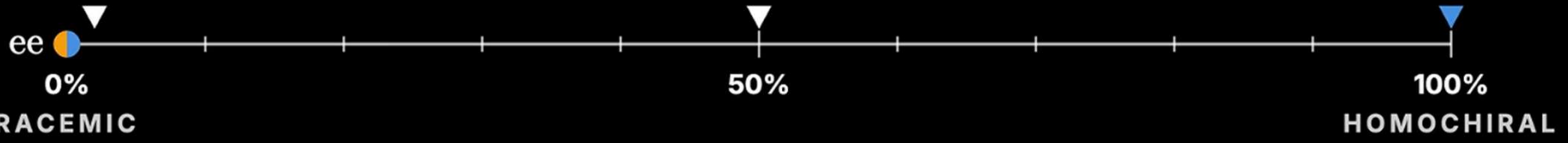
75 : 25

100%的ee值



$$ee = \frac{51 - 49}{100} = 2\%$$

$$ee = \frac{75 - 25}{100} = 50\%$$



对映体过量 ee 把“手性偏向”写成序参量

Enantiomeric Excess as an Order Parameter

$$ee = \frac{[R]-[S]}{[R]+[S]} \times 100\% \equiv \eta$$

带符号的 ee（signed enantiomeric excess）记作 η：

η → −η 对应镜像变换。

外消旋体 **η = 0**

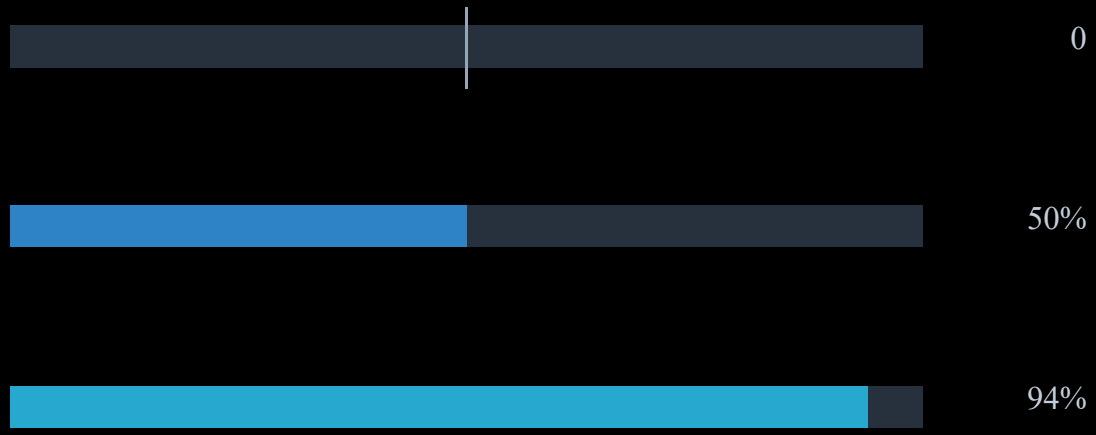
R 与 S 等量，宏观无手性偏向

非外消旋混合物 **0 < |η| < 1**

75:25 → 50% ee；51:49 → 2% ee

同手性极限 **|η| → 1**

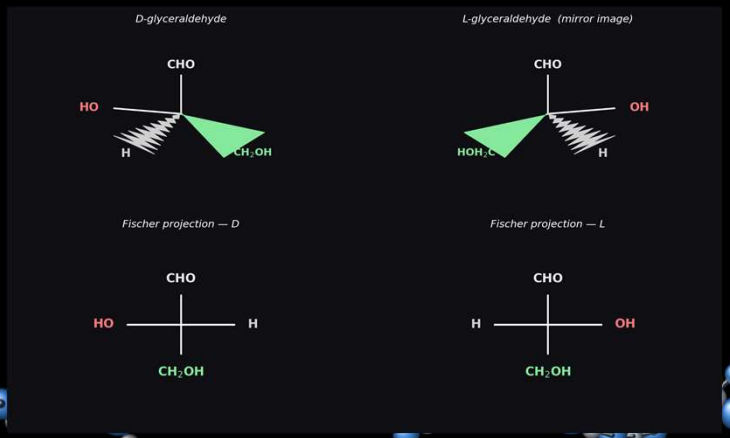
体系几乎只保留一种对映体

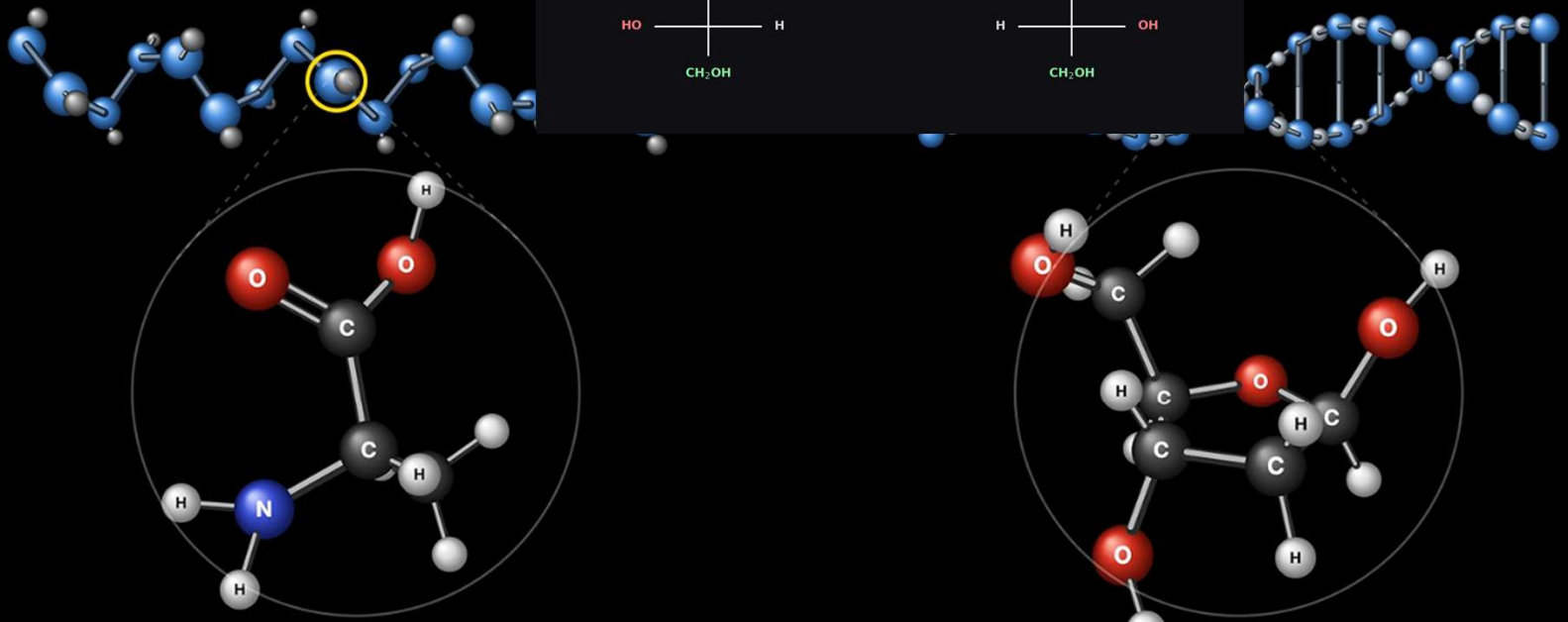


|η| 描述偏向大小；正负号记录“哪一只手”。

手性的符号表示 L/D

Symbols of chiral molecules

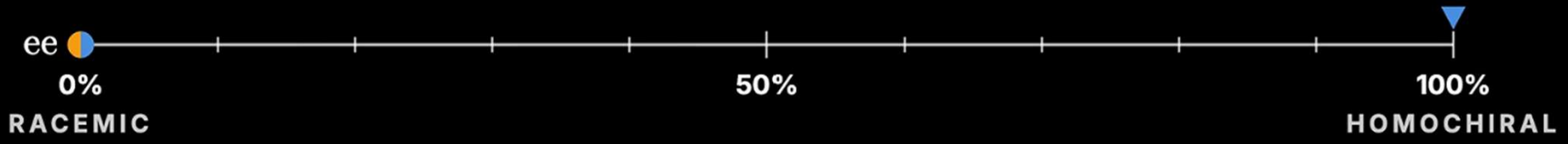




L amino acid

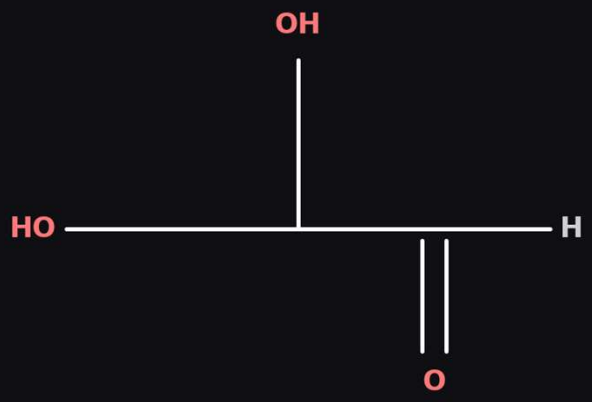
What is L and what is D?

D sugar

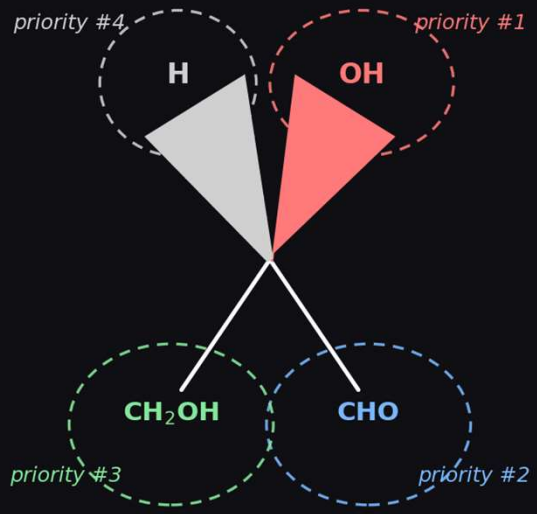


手性的符号表示 R/S

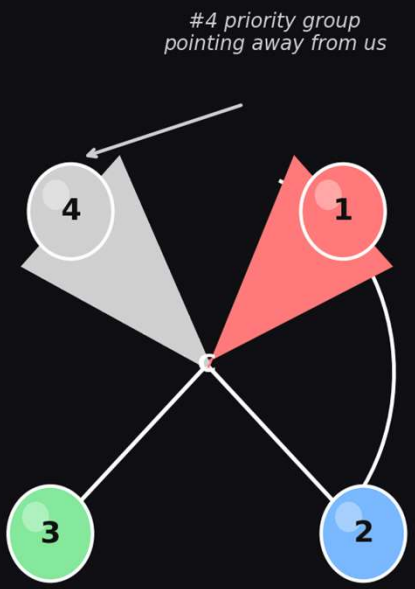
How do organic chemists quantify enantiomers?



glyceraldehyde



(R)-glyceraldehyde



clockwise = R

测量分子手性的常见谱学方法

Chiroptical Measurements

旋光色散 / ORD

平面偏振光的偏振面旋转

两对映体旋光方向相反

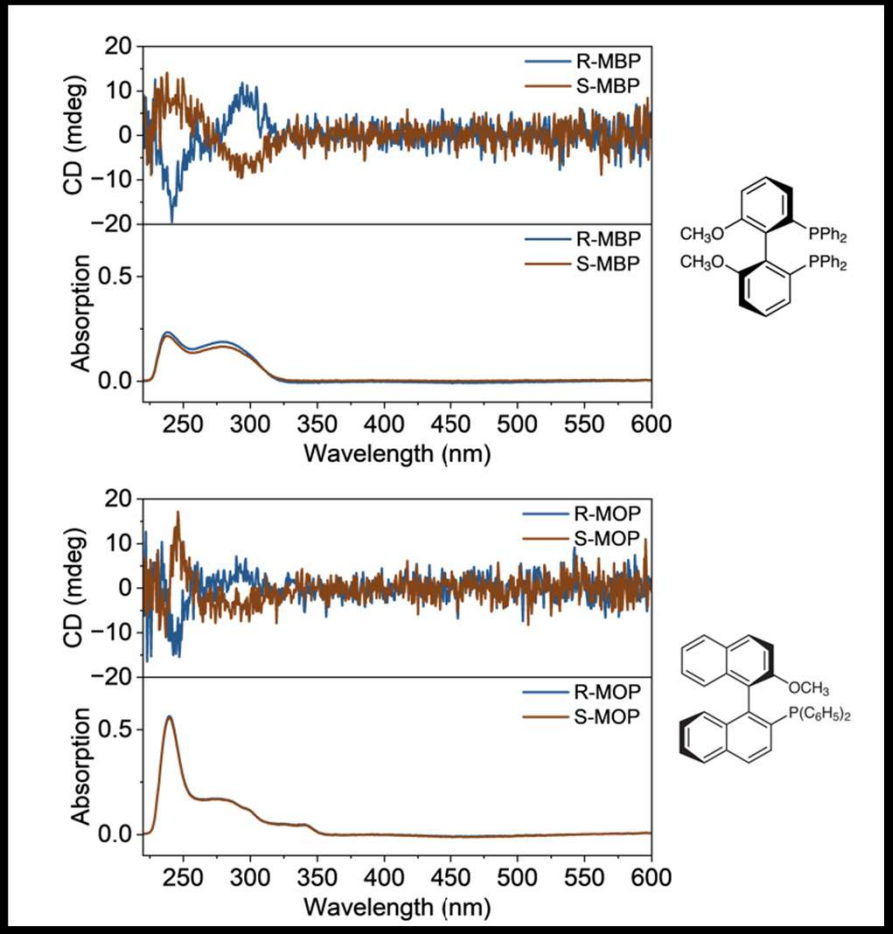
圆二色 / CD

对左、右圆偏振光吸收不同：

$\Delta A = A_L - A_R$

VCD / ROA

振动圆二色与拉曼光学活性：把振动谱与手性结合，提供结构信息。



02

近代物理进展 · 专题报告 / MODERN PHYSICS PROGRESS

Frank 配方：从理论到实验

FROM FRANK'S RECIPE TO A REAL REACTION

自催化、对映选择性和相互抑制，如何依次在 Kagan 与 Soai 的实验中获得对应？

Frank：先写下同手性形成的三个必要条件

The Frank Model

1	**自催化**	产物促进自身生成	**体系获得正反馈**
2	**对映选择性**	R 更利于生成 R，S 更利于生成 S	**手性信息被传递**
3	**相互抑制**	一种对映体抑制另一种的生成	**微小差异不被平均掉**

正反馈 + 竞争

自然界中生命为何只选择其中一个手性？弗兰克假说。

Why has life in nature only chosen one of the two chiral molecules?

ON SPONTANEOUS ASYMMETRIC SYNTHESIS

by

F. C. FRANK

The H. H. Wills Physical Laboratory, University of Bristol (England)

I am informed by my colleague Professor W. MOORE that there is still widely believed to be a problem of explaining the original "asymmetric synthesis" giving rise to the general optical activity of the chemical substances of living m
supposed that this was no problem on the basis of a supposition th
duction of life is a rare event. We may take as the defining property
the ability to reproduce its own kind. Omitting such simple entitie
are included by such a definition, and confining attention to chemical molecules, the complexity of any having this essential property of life is likely to be great enough to make it highly improbable that it has a centre of symmetry. It is likely, in fact, to contain α-amino acids which are necessarily asymmetric. Then, if the production of living molecules is an infrequent process, compared with the rate of multiplication of living molecules, the whole earth is likely to be extensively populated with the progeny of the first before another appears. In fact they may have so modified the environment by then that no other has a chance of generation. There are, of course, variants of this hypothesis: *e.g.* that a second living molecule is produced before the progeny of the first has colonised the whole earth, and competes successfully with it for nutrient material, "starving", or even "poisoning" the other out of existence. This leads to the same result, and depends essentially on the same initial hypothesis, that spontaneous germination of life is a rare event.

On the other hand, Dr. J. C. FISHER of the G.E.C. Laboratories in Schenectady, in a conversation during the summer of 1951, argued that this initial hypothesis was neither theoretically well-founded nor necessary to explain the facts of observation, such as the optical asymmetry of living matter. I gather from Professor MOORE that there are a m
correctness of
A simple
which is a cat
its optical ant
respectively, a

$$\frac{dn_1}{dt} = (k_1 - k_2 n_2) n_1 \quad (1)$$

$$\frac{dn_2}{dt} = (k_1 - k_2 n_1) n_2 \quad (2)$$

where k_1 and k_2 are positive.

Subtracting we have

$$d(n_1 - n_2)/dt = k_1(n_1 - n_2) \quad (3)$$

and hence

$$(n_1 - n_2) = (n_{01} - n_{02})\, e^{k_1 t} \quad (4)$$

where n_{01}, n_{02} are initial values: *i.e.* the excess of one over the other increases exponentially; whereas the total, $(n_1 + n_2)$, governed by the differential equation

$$d(n_1 + n_2)/dt = k_1(n_1 + n_2) - 2 k_2 n_1 n_2 \quad 5)$$

has a slower relative rate of increase.

Eliminating dt from (1) and (2) we have

$$\frac{dn_1}{dn_2} = \frac{(k_1 - k_2 n_2) n_1}{(k_1 - k_2 n_1) n_2} \quad (6)$$

$$n_1/n_2 = (n_{01}/n_{02}) \exp.\ [k_2 (n_{01} - n_{02})(e^{k_1 t} - 1)] \quad (8)$$

i.e. this ratio increases at a more than exponential rate if $n_{01} - n_{02}$ is positive, and decreases correspondingly if this initial difference is negative.

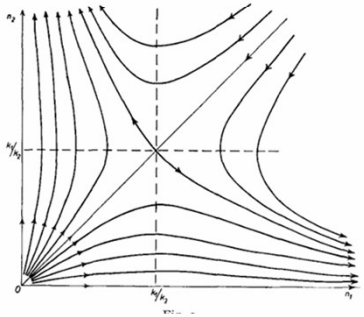
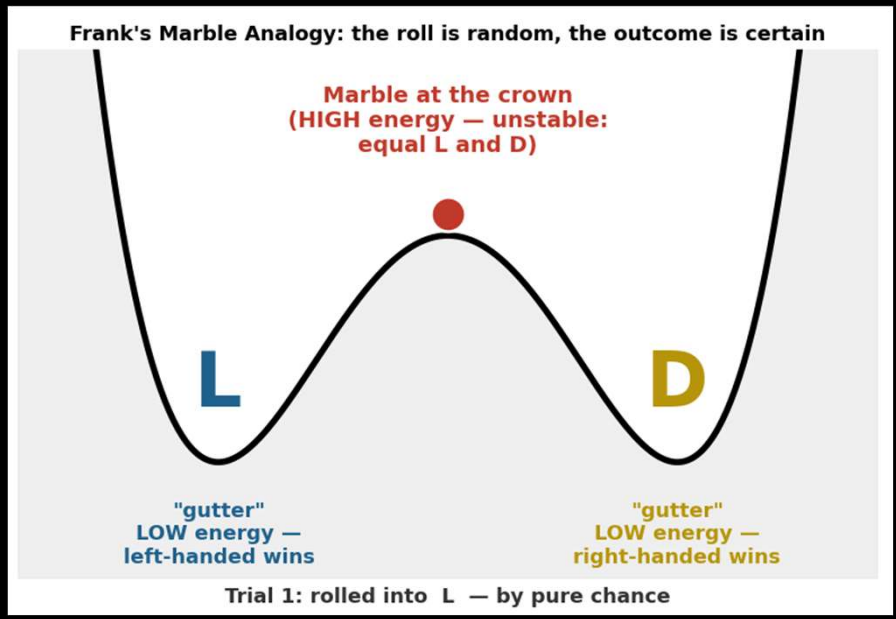


Fig. 1 sh
constructed b
correct slope.
from the line

$$t_1 \sim \frac{1}{k_1} \ln \frac{k_1/k_2}{n_{01} + n_{02}}$$

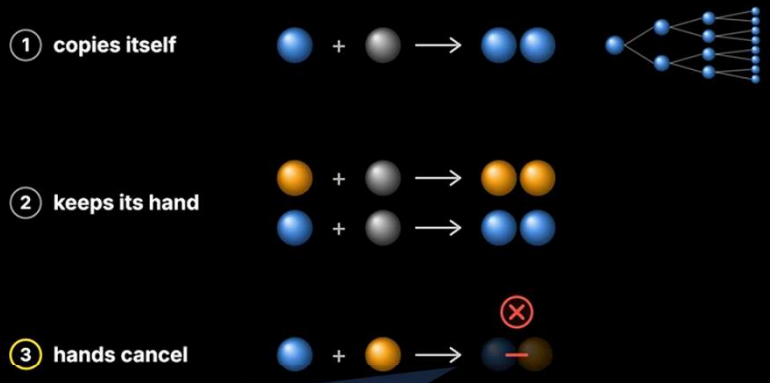
is of equations (1), (2), h everywhere have the arithm of the distance ds to one of the asymptotes $n_2 = 0$ or $n_1 = 0$. The curves shown include those in which $(n_1 + n_2)$ first diminishes with time, but curves starting with small values can never enter this region.

Frank's answer: You don't need any special outside cause. It arises automatically from the way living things reproduce.

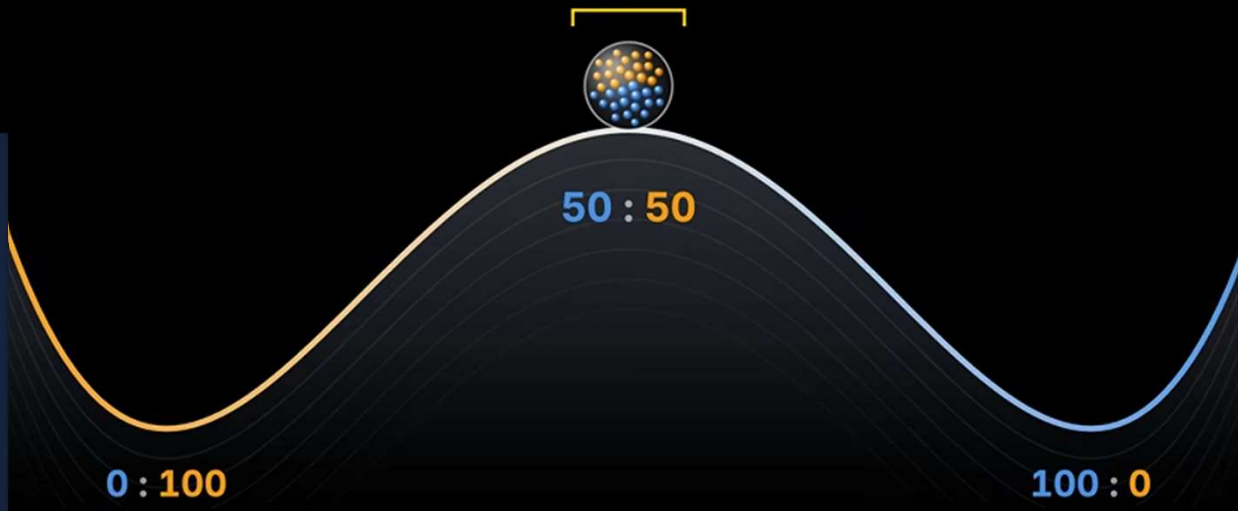


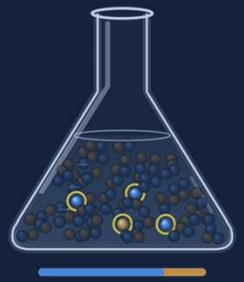
三个假设条件

Three assumptions







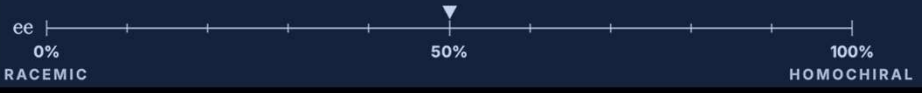


$$\text{ee} = \frac{51-49}{100} = 2\%$$

$$\text{ee} = \frac{(51-48)-(49-48)}{100-96}$$

$$= \frac{3-1}{4} = 50\%$$





自发对称破缺

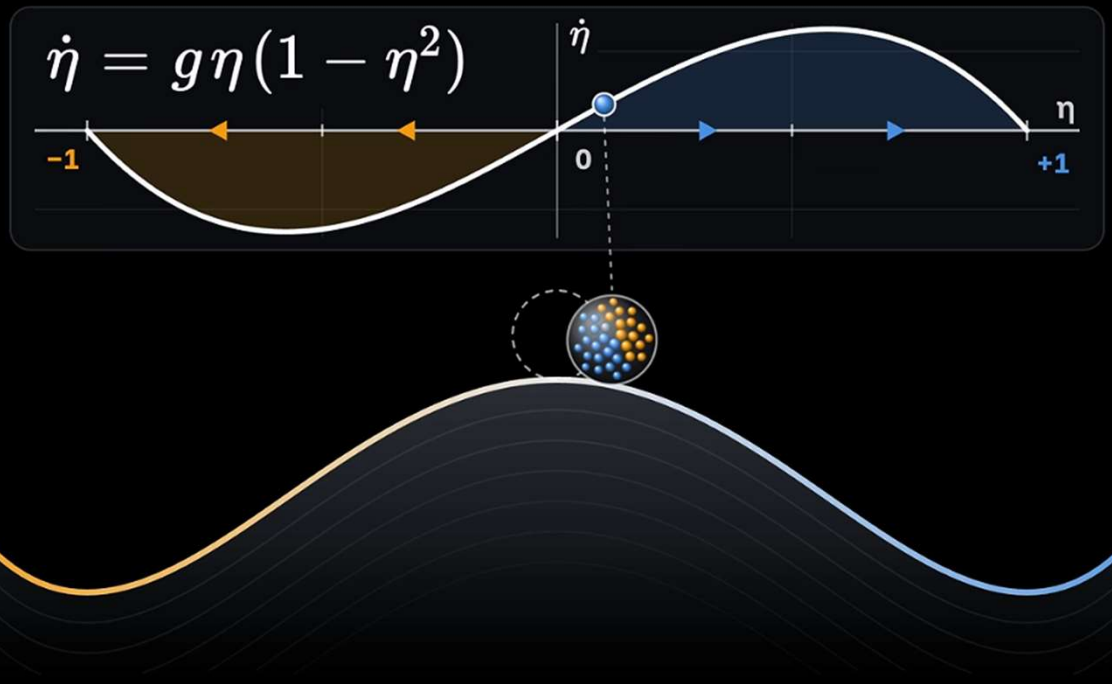
Spontaneous symmetry breaking

$$\dot{R} = kSR - mRL$$

$$\dot{L} = kSL - mRL$$

复制　　抑制

$$\eta = \frac{R - L}{R + L}$$



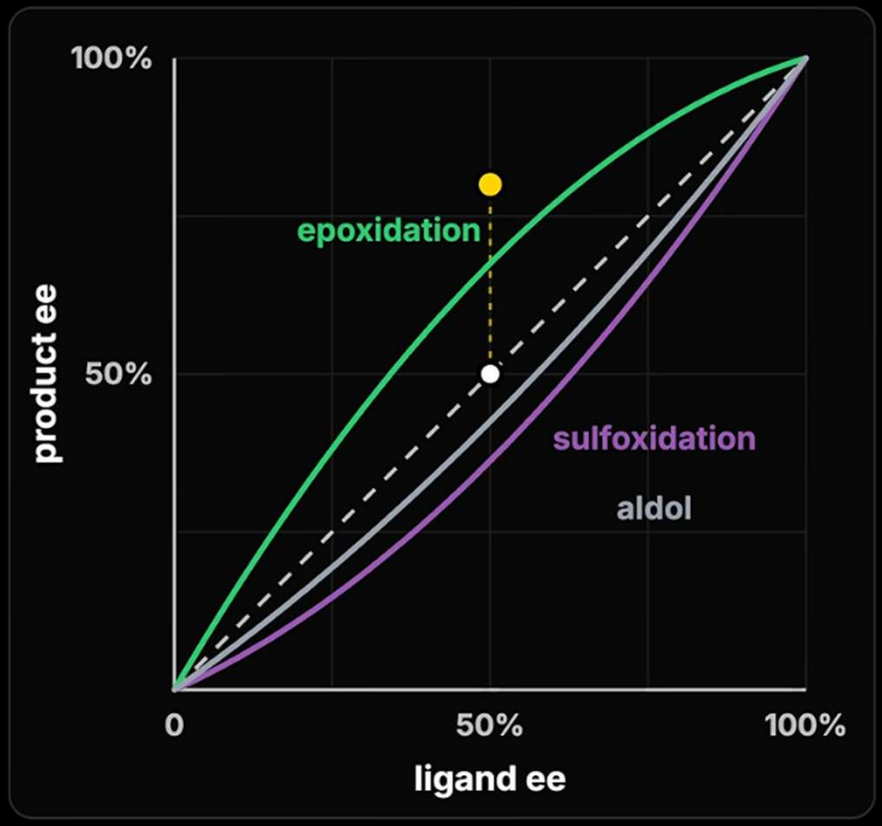
Kagan：非线性效应让多数手性“扣留”少数手性

Kagan’s Nonlinear Effects

线性预期： $ee_{prod} = ee_{max}\, ee_{ligand}$

- **正非线性效应（+NLE）**：曲线在线性上方，产物手性纯度被放大
- **负非线性效应（−NLE）**：曲线在线性下方，产物选择性被削弱。
- 偏离直线说明：活性物种、聚集体或竞争路径不能忽略。

关键：反应网络可重新分配并放大手性信息。



1986年的重要发现

A major breakthrough in 1986

F. C. FRANK 1953

a laboratory demonstration may not be impossible.

catalysts favor one hand ✓

majority disables minority 1986

copies its own hand ?



Henri B. Kagan

FRANCE

1953 1986 1995

Nonlinear Effects in Asymmetric Synthesis. Examples in Asymmetric Oxidations and Aldolization Reactions

C. Puchot,[†] O. Samuel,[‡] E. Duñach,[‡] S. Zhao,[‡] C. Agami,[†] and H. B. Kagan*[‡]

Contribution from UA CNRS N°255, Laboratoire de Synthèse Asymétrique, Université Paris-Sud, 91405 Orsay, France, and UA CNRS N°408, Laboratoire de Chimie Organique, Université Paris VI, 75005 Paris, France. *Received August 1, 1985*

Abstract: It has been shown in three experiments that there is a strong departure from the linear relationship usually assumed between the enantiomeric excess of a chiral auxiliary and the extent of the asymmetric synthesis. This gives useful information on the reaction mechanisms. Asymmetric oxidation of methyl *p*-tolyl sulfide or asymmetric epoxidation of geraniol in the presence of various chiral titanium complexes, as well as the proline-catalyzed Hajos–Parrish reaction, is investigated in detail.

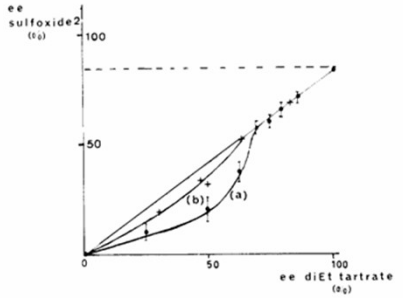
Horeau and Guettê[1] discussed the importance of diastereomeric interactions of a mixture of enantiomers in the liquid phase. These interactions are responsible for some *unusual physical properties* of mixtures of enantiomers such as the nonequivalence of the enantiomeric excess and the optical purity[2] or the different NMR spectra for a racemic mixture or a pure enantiomer.[3-6] The

[†] Université Paris VI.
[‡] Université Paris-Sud.

(1) Horeau, A.; Guettê, J. P. *Tetrahedron* **1974**, *30*, 1923–1931.
(2) Horeau, A. *Tetrahedron Lett.* **1969**, 3121–3124.

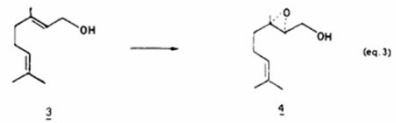
0002-7863/86/1508-2353$01.50/0 © 1986 American Chemical Society

Scheme II. Nonlinear Effect in the Asymmetric Oxidation of Sulfide **1** (Equation 2) and Enantiomeric Excess of (*R*)-**2** as a Function of the Enantiomeric Excess of (+)-DET[a]



[a] (a) Stoichiometric conditions: Ti(O-*i*-Pr)$_4$/DET/H$_2$O/*t*-BuOOH/**1**, 1:2:1:0.5 or 1:1:1:1.1. (b) Catalytic conditions: Ti(O-*i*-Pr)$_4$/DET/H$_2$O/*t*-BuOOH/**1**, 0.5:1:0.5:1:1.

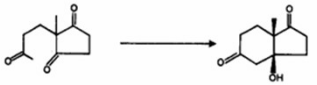
was also investigated in the specific case of (*E*)-geraniol (**3**) (eq 3).



(eq. 3)

3 **4**

Finally, we studied a catalytic system dealing with an asymmetric Robinson annulation. The Hajos–Parrish reaction is a useful asymmetric synthesis which allows, for example, to transform the triketone **5** into *cis*-ketol **6** (ee 92%) in DMF under the influence of a catalytic amount of pure (*S*)-proline[24,25] (eq 4). Two of us are currently investigating extensively the mechanism of this reaction.[26,27]

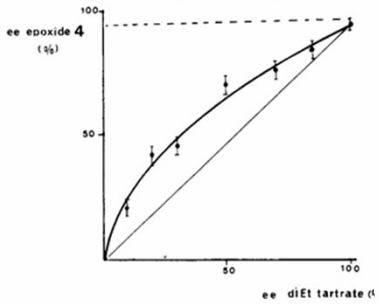


(eq. 4)

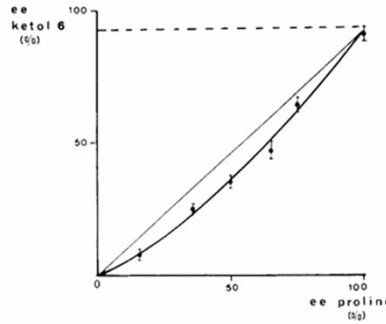
Results

A. The asymmetric oxidation of sulfide **1** (eq 2) was studied in the presence of the complex Ti(O-*i*-Pr)$_4$/DET/H$_2$O (1:2:1), by using (+)-diethyl tartrate of different enantiomeric purities. In order to favor the formation of all the possible diastereomeric complexes, we first used stoichiometric conditions (1 equiv of complex with respect to sulfide) but carried out the reaction by addition of only 0.5 mol equiv of *t*-BuOOH. Under these circumstances, the yield of sulfoxide is quantitative with respect to the oxidant in all the experiments. Sulfide **1** and sulfoxide **2** are easily separated and recovered by flash chromatography, and the enantiomeric excess of **2** is measured. The results obtained are plotted in Scheme II. A strong departure from linearity is clearly observed (curve a). Unexpectedly, the linearity is recovered in the oxidations by using diethyl tartrate of optical purity higher

Scheme III. Nonlinear Effect in the Epoxidation of Geraniol **3** (Equation 3) and Enantiomeric Excess of (−)-**4** as a Function of th ee of (+)-DET with Ti(O-*i*-Pr)$_4$/DET/*t*-BuOOH/**3**, 1:1:2:1



Scheme IV. Nonlinear Effect in the Hajos–Parrish Reaction (Equation 4) and Enantiomeric Excess of Ketol **6** as a Function of the ee of (*S*)-Proline under Catalytic Conditions (See Experimental Section)



than 70%. Experiments using 1 mol equiv of *t*-BuOOH were performed, in order to operate in the standard conditions for this asymmetric oxidation. The same strong departure from linearity was again observed, and curve a (Scheme II) could be reproduced.

Recently, we found that the reaction **1** → (*R*)-**2** can be catalytic with a turnover of 2. We repeated the oxidation procedure by using diethyl tartrate of different enantiomeric purities, in the following conditions: (Ti complex)/(sulfide)/(*t*-BuOOH) = 0.5:1:1. The curve b of Scheme II was obtained.

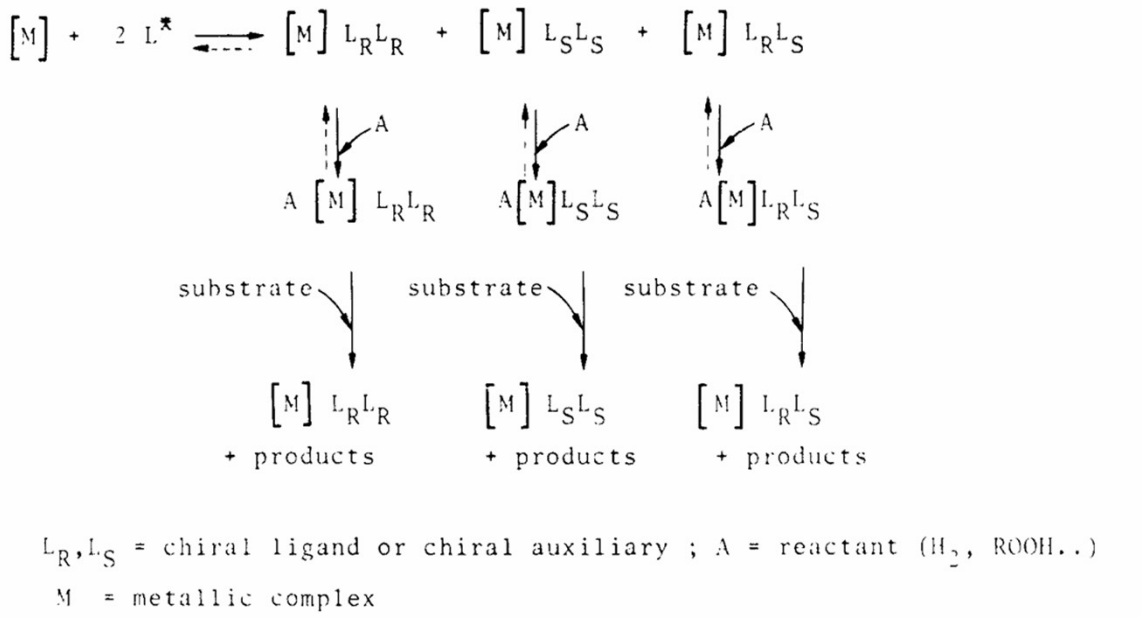
B. The epoxidation of geraniol **3** by 1 equiv of the Sharpless reagent[23] Ti(O-*i*-Pr)$_4$/(+)-DET/*t*-BuOOH (1:1:2) (eq 3) was consequently investigated under the described[23] conditions but with diethyl tartrate of various optical purities. Epoxygeraniol (**4**) was recovered with an excellent yield and with enantiomeric excesses which are not at all linearly correlated with the enantiomeric purity of the diethyl tartrate (Scheme III).

C. A kinetic study[27] has recently shown that the enantioselective Robinson annulation (Hajos–Parrish reaction)[24–26] catalyzed by (*S*)-proline (eq 4) involves two amino acid molecules in the transition state of the enantiodifferentiating step.

Here again, experiments show that there is a nonlinear relationship between the (*S*)-proline enantiomeric purity and the enantioselectivity of the annulation product **6** (Scheme IV): in all cases, the observed enantiomeric excess is smaller than the values calculated by assuming a linear dependency between the

(24) Hajos, Z. G.; Parrish, D. *J. Org. Chem.* **1974**, *39*, 1615–1621.
(25) Cohen, N. *Acc. Chem. Res.* **1976**, *9*, 412–417.
(26) Agami, C.; Sevestre, H. *J. Chem. Soc., Chem. Commun.* **1984**, 1385–1386.
(27) Agami, C.; Levisalles, J.; Puchot, C. *J. Chem. Soc., Chem. Commun.* **1985**, 441–442.

Scheme V



L$_R$,L$_S$ = chiral ligand or chiral auxiliary ; A = reactant (H$_2$, ROOH..)
M = metallic complex

The Nobel background document calls 1986 the year that "transformed the field," and Kagan himself recounts that the whole project began serendipitously in 1983, when his group stumbled on a Ti(OiPr)$_4$/DET/H$_2$O recipe that gave 80–90% ee in sulfide oxidations and they set out to understand why.

ML^*_2 模型：随机配对如何纯化活性催化剂

The ML^*_2 Model and Catalyst Aggregates

两个配体随机配对；以 75:25 为例：RR = 56.25%，SS = 6.25%，RS = 37.5%。

ML_RL_R
同手性 / homochiral

ML_SL_S
同手性 / homochiral

ML_RL_S
异手性 / heterochiral · meso

优先生成 R
速率 k_RR

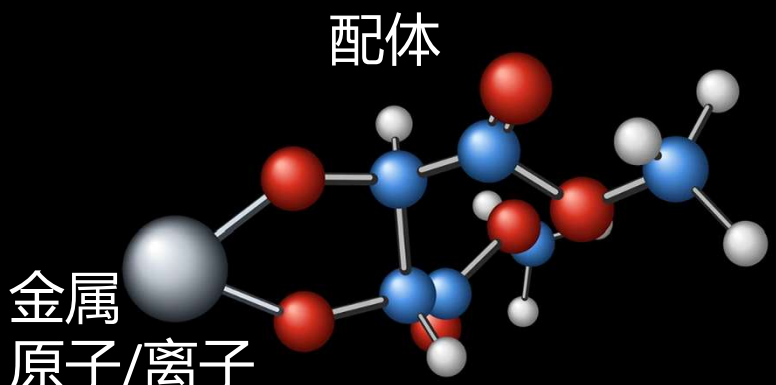
优先生成 S
速率 k_SS

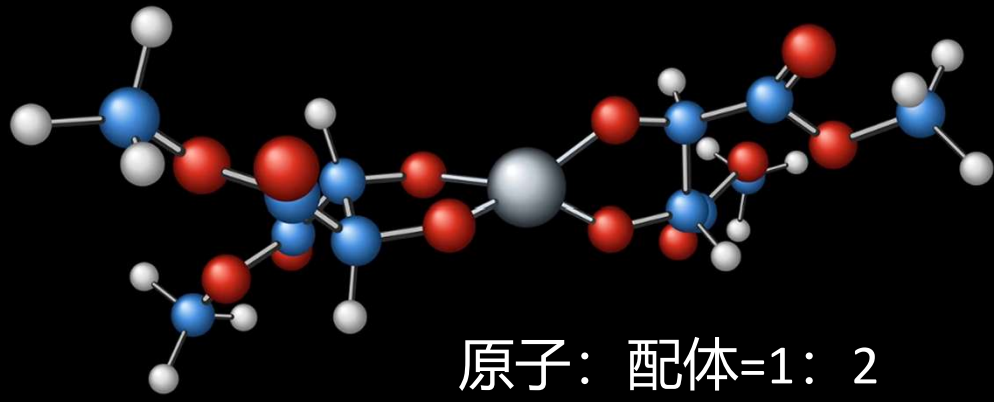
可能低活性 / 无活性
或形成“储库”

去掉低活性 RS：RR:SS = 90:10，活性池 ee = 80%（原配体仅 50%）。

手性催化剂一般都是金属有机络合物

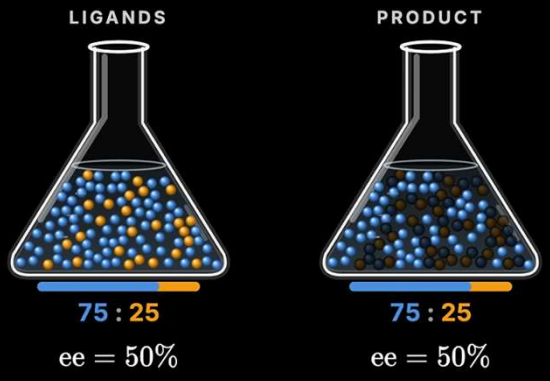
Chiral catalysts are usually organometallic complexes

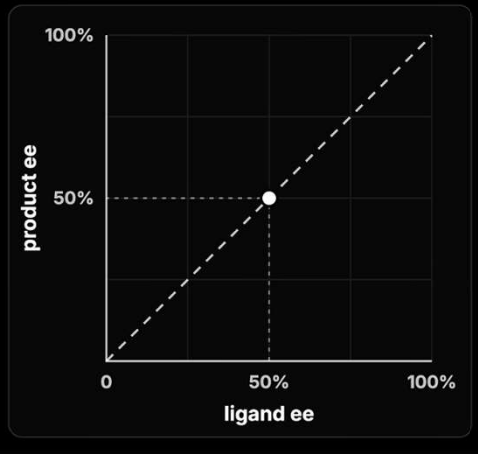


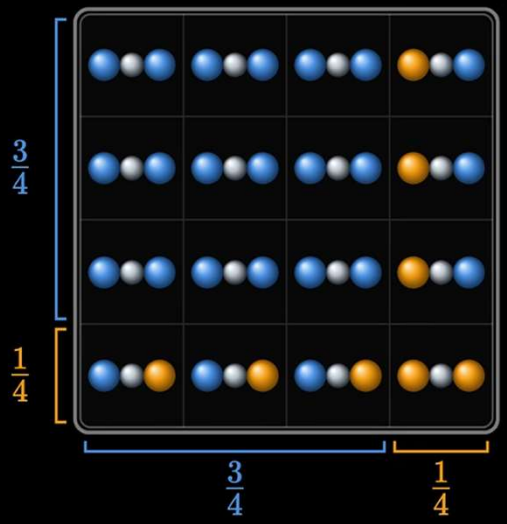


原子：配体=1：2

原子：配体=1：1







$\frac{3}{4} \times \frac{3}{4} = 56.25\%$

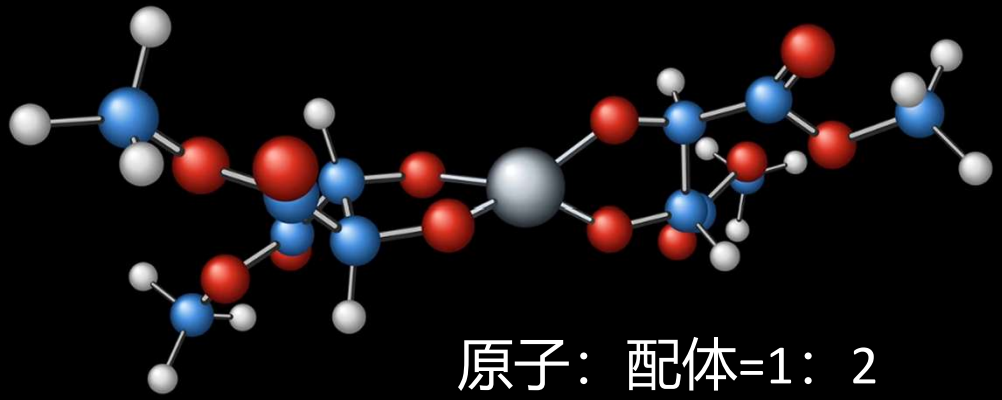
$\frac{1}{4} \times \frac{1}{4} = 6.25\%$

$2 \times \frac{3}{4} \times \frac{1}{4} = 37.5\%$

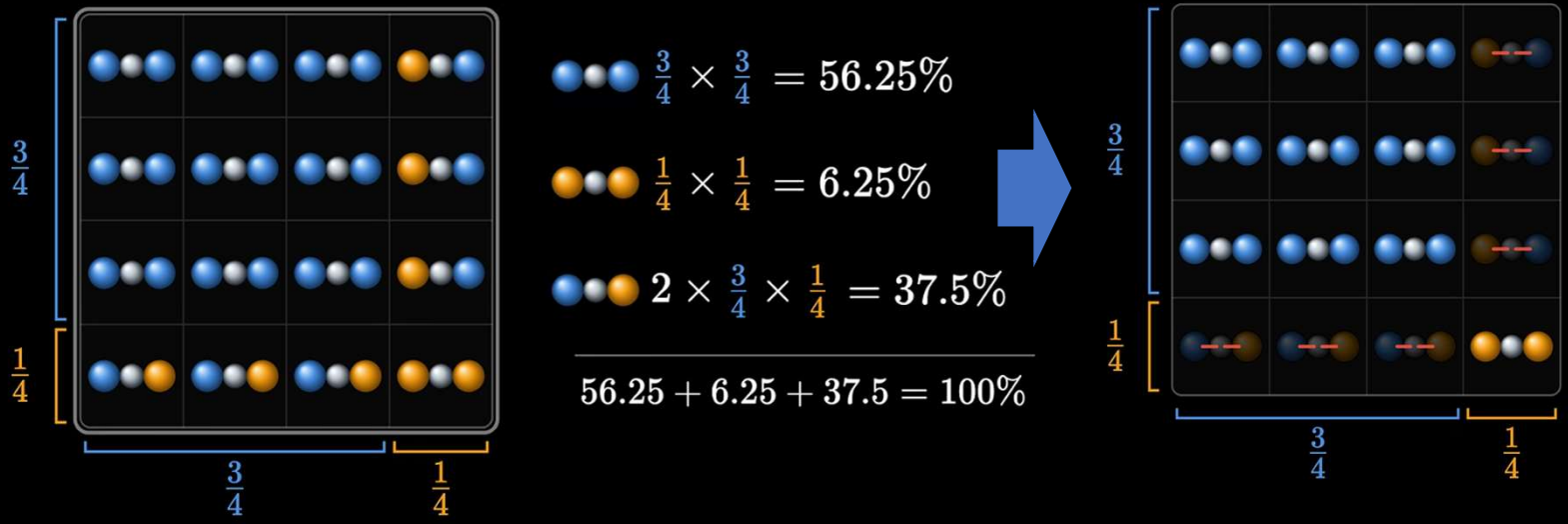
$56.25 + 6.25 + 37.5 = 100\%$

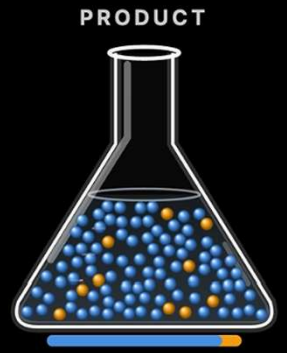
手性催化剂一般都是金属有机络合物

Chiral catalysts are usually organometallic complexes



原子：配体=1：2





$56.25 : 6.25 = 90 : 10$

$$ee = \frac{90 - 10}{100} = 80\%$$

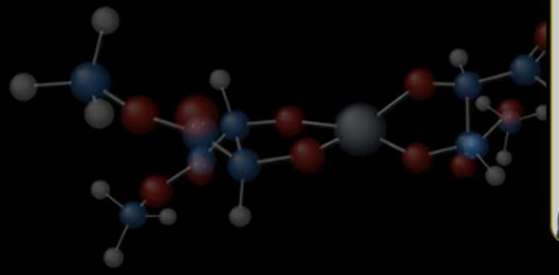
手性可以自我放大吗?

Can chirality be amplified?

catalysts favor one hand ✓

majority disables minority ✓ 1986

copies its own hand ?



catalyst



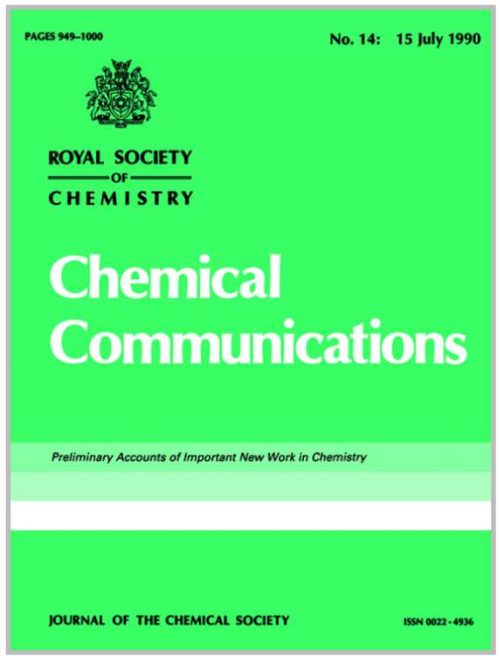
Kenso Soai

JAPAN

?



Volume 26, Issue 14
1990



Previous Next

Paper | 01 January 1990

Asymmetric self-catalytic reaction. Self-production of chiral 1-(3-pyridyl)alkanols as chiral self-catalysts in the enantioselective addition of dialkylzinc reagents to pyridine-3-carbaldehyde FREE

Cross-journal themed collections: 2026 Chemistry Nobel Prize themed collection

Kenso Soai; Seiji Niwa; Hiroshi Hori

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+ Author and article information

J. Chem. Soc., Chem. Commun. (1990) 26 (14): 982–983.

The 1990 paper is the discovery of *self-reproduction of chirality*, and the 1995 paper is the demonstration of *amplification of chirality*.

This was the **first example of an asymmetric autocatalytic reaction**, *i.e.*, a chemical system where the chiral product makes more of itself.

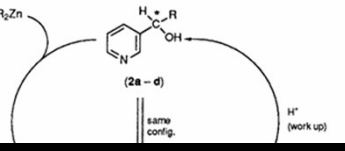
This was the first demonstration of a chemical reaction that both reproduces and **exponentially amplifies** its own handedness from nearly nothing.

Asymmetric Self-catalytic Reaction. Self-production of Chiral 1-(3-Pyridyl)alkanols as Chiral Self-catalysts in the Enantioselective Addition of Dialkylzinc Reagents to Pyridine-3-carbaldehyde

Kenso Soai,* Seiji Niwa, and Hiroshi Hori
Department of Applied Chemistry, Faculty of

Optically active 1-(3-pyridyl)alkanols, chiral s
enantioselective addition of dialkylzinc reage

Increasing interest has been centred on catal
carbon bond forming reactions.[1] However in ne
reported, the structures of the chiral catalysts and
are *different*. If the structures of the product a
catalysts were the *same* (chiral self-catalyst),



acts as a chiral self-catalyst to produce itself with retention of configuration [(−)-(**2c**), 0.102 g, 67% yield, 35% e.e.].§ In a similar manner, (−)-1-(3-pyridyl)propan-1-ol (**2b**) (20 mol%, 56% e.e.) produced itself [(−)-(**2b**) (66%, 14% e.e.)] in the enantioselective addition of Et_2Zn to (**1**). Asymmetric self-catalytic reaction was also observed in methylation [(*S*)-(−)-(**2a**) of 42% e.e. afforded (*S*)-(−)-(**2a**) of 7% e.e.] and in butylation [(−)-(**2d**) of 47% e.e. afforded (−)-(**2d**) of 6% e.e.].

MeOH) (86% enantiomeric excess, e.e.)† as a chiral catalyst, (−)-(**2c**) (0.132 g, 47% e.e., determined by HPLC using a chiral column) was obtained.‡ This result shows that (−)-(**2c**)

† Prepared from the reaction of pyridine-3-carbaldehyde and diisopropylzinc using (1*S*,2*R*)-(−)-*N*,*N*-dibutylnorephedrine[5,6] as a chiral catalyst.

‡ Pr^i_2Zn (2 ml of 1 M hexane solution) was added to a toluene solution (2 ml) of (−)-(**2c**) (0.2 mmol) at room temperature. After 20 min, (**1**) (1.0 mmol) was added, then the mixture was stirred at room temperature for 2 h. The mixture was cooled to 0 °C, and quenched by the addition of HCl (1 M; 5 ml). The mixture was adjusted to pH 8—9 by the addition of satd. aq. $NaHCO_3$, and the precipitate was filtered off. The filtrate was extracted with AcOEt (4 × 20 ml), dried (Na_2SO_4), and evaporated under reduced pressure. The residue was purified by TLC (silica gel, eluant AcOEt–MeOH, 20:1), followed by bulb-to-bulb distillation (140 °C at 2 mmHg). HPLC analysis was performed with Daicel Chiralcel OD, eluant 10% propan-2-ol in hexane, flow rate 0.2 ml/min, UV detector (254 nm), retention time 62.7 min for major isomer (−)-(**2c**), 70.3 min for minor isomer (+)-(**2c**).

1987, **109**, 7111; E. J. Corey, P.-W. Yuen, F. J. Hannon, and D. A. Wierda, *J. Org. Chem.*, 1990, **55**, 784; R. Noyori, S. Suga, K. Kawai, S. Okada, M. Kitamura, N. Oguni, M. Hayashi, T. Kaneko, and Y. Matsuda, *J. Organomet. Chem.*, 1990, **382**, 19; E. J. Corey and F. J. Hannon, *Tetrahedron Lett.*, 1987, **28**, 5237.

8 The metal alkoxide of an aminoalcohol catalyses the addition of Et_2Zn to benzaldehyde: see T. Mukaiyama, K. Soai, T. Sato, H. Shimizu, and K. Suzuki, *J. Am. Chem. Soc.*, 1979, **101**, 1455. For the non-self-catalytic asymmetric induction, see refs. 6 and 7; P. A. Chaloner and S. A. R. Perera, *Tetrahedron Lett.*, 1987, **28**, 6163; K. Soai and M. Watanabe, *J. Chem. Soc., Chem. Commun.*, 1990, 43; K. Soai, M. Watanabe, and M. Koyano, *ibid.*, 1989, 534, and references cited therein.

§ The same (−)-(**2c**) (86% e.e.; 20 mol%) catalyses the enantioselective addition of Et_2Zn to benzaldehyde in hexane at room temperature to afford (*S*)-(−)-1-phenylpropanol of 16% e.e. in 87% yield.

Science University of Tokyo, Kagurazaka, Shinjuku-ku, Tokyo 162, Japan

THE homochirality of natural amino acids and sugars remains a puzzle for theories of the chemical origin of life[1–18]. In 1953 Frank[7] proposed a reaction scheme by which a combination of autocatalysis and inhibition in a system of replicating chiral molecules can allow small random fluctuations in an initially racemic mixture to tip the balance to yield almost exclusively one enantiomer. Here we show experimentally that autocatalysis in a chemical reaction can indeed enhance a small initial enantiomeric excess of a chiral molecule. When a 5-pyrimidyl alkanol with a small (2%) enantiomeric excess is treated with diisopropylzinc and pyrimidine-5-car-

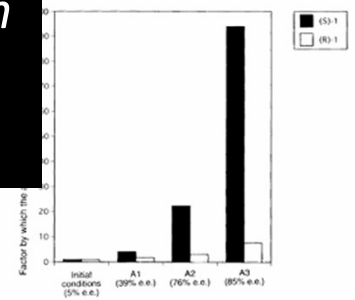


FIG. 1. Asymmetric autocatalysis of chiral pyrimidyl alkanol (**1**). Runs A1–3 correspond to Table 1. The enantiomeric excess of (*S*)-**1** increases from 5 to 89% e.e. without the use of additional chiral auxiliaries. During the reactions (runs A1–3), the (*S*)-**1** increases by a factor of 94 times, while (*R*)-**1** increases by a factor of only eight times.

isomer = 69.5:30.5) (Fig. 1). This shows that (*S*)-**1** with 55% e.e. (note; >5% e.e.) was newly formed in 42% yield as a result of the asymmetric autocatalytic reaction of catalyst (*S*)-**1** (Table 1, run A1; Fig. 1). The reaction was performed successively, with the products of one round serving as the reactants for the next, resulting in an overwhelming imbalance between the two stereo isomers (Table 1).

In a similar manner, starting from the chiral catalyst (*S*)-**1** with even lower enantiomeric excess (2% e.e., *S*-isomer: *R*-isomer = 51:49) (20 mol%), asymmetric autocatalytic reaction of **1** and the amplification of the e.e. of **1** are also observed (series B in Table 1, runs 1–5). The e.e. of (*S*)-**1** has increased successively from 2% to 10%, 57%, 81% and 88% (runs 1–5). The amount of (*S*)-**1** of the initial catalyst (2% e.e., run B1) has increased by the factor of 942 times (run B5). When (*S*)-**1** with 88% e.e. was pyzlinc to aldehyde **3** to yield **2** with increased e.e. Subsequent

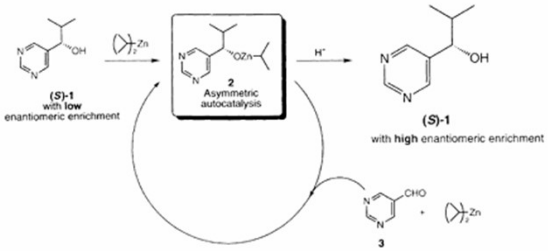
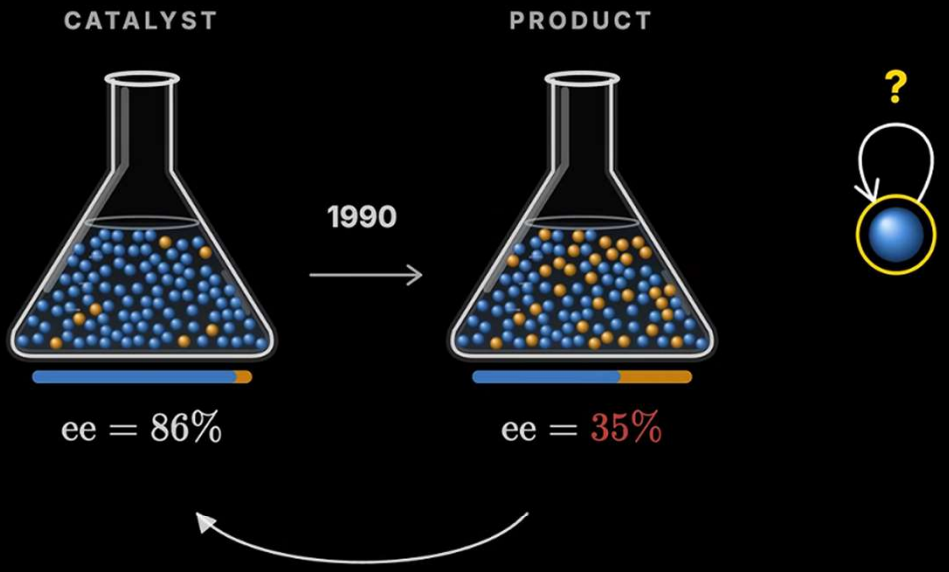
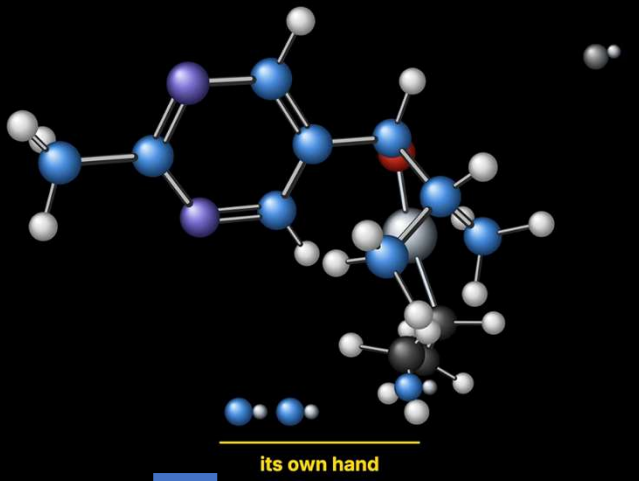


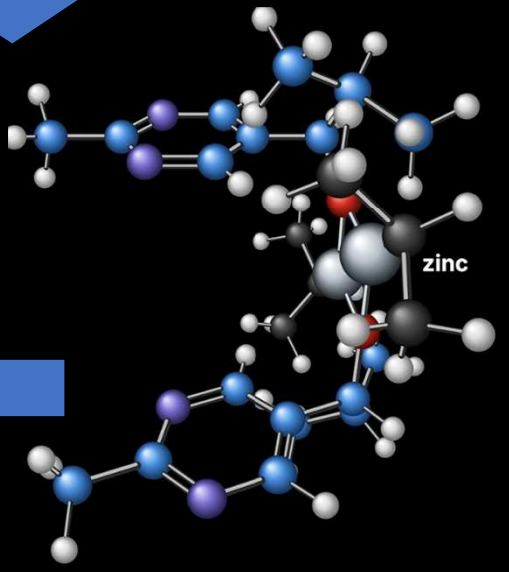
FIG. 2 Proposed reaction scheme of asymmetric autocatalysis of (S)-**1**.

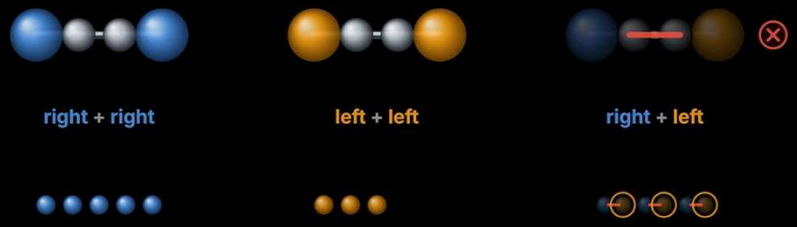
Soai的1990年和1995年的工作

Soai's studies in 1990 and 1995



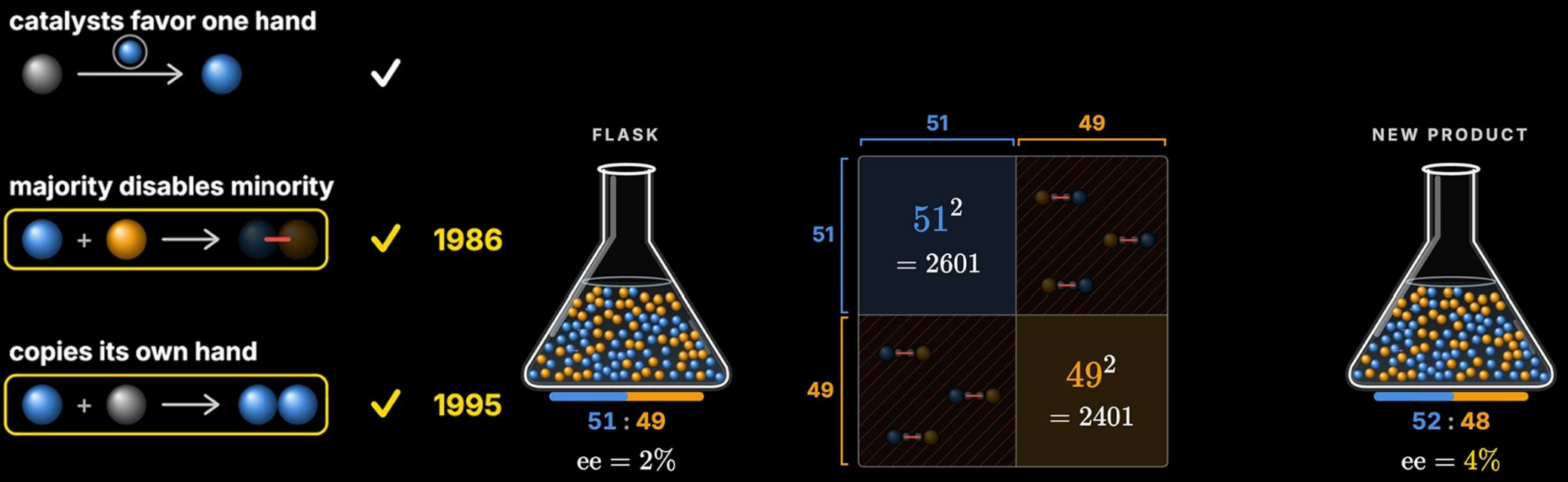






Soai的1990年和1995年的工作

Soai's studies in 1990 and 1995



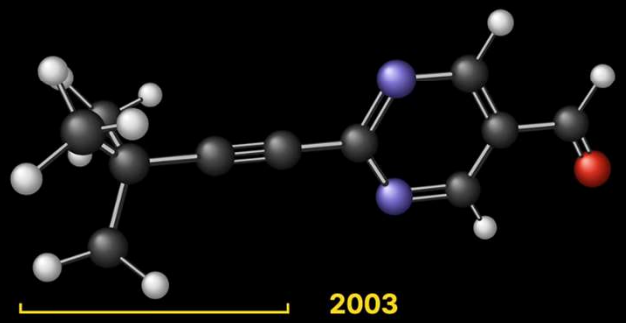
Soai2003年的工作

Soai's studies in 2003

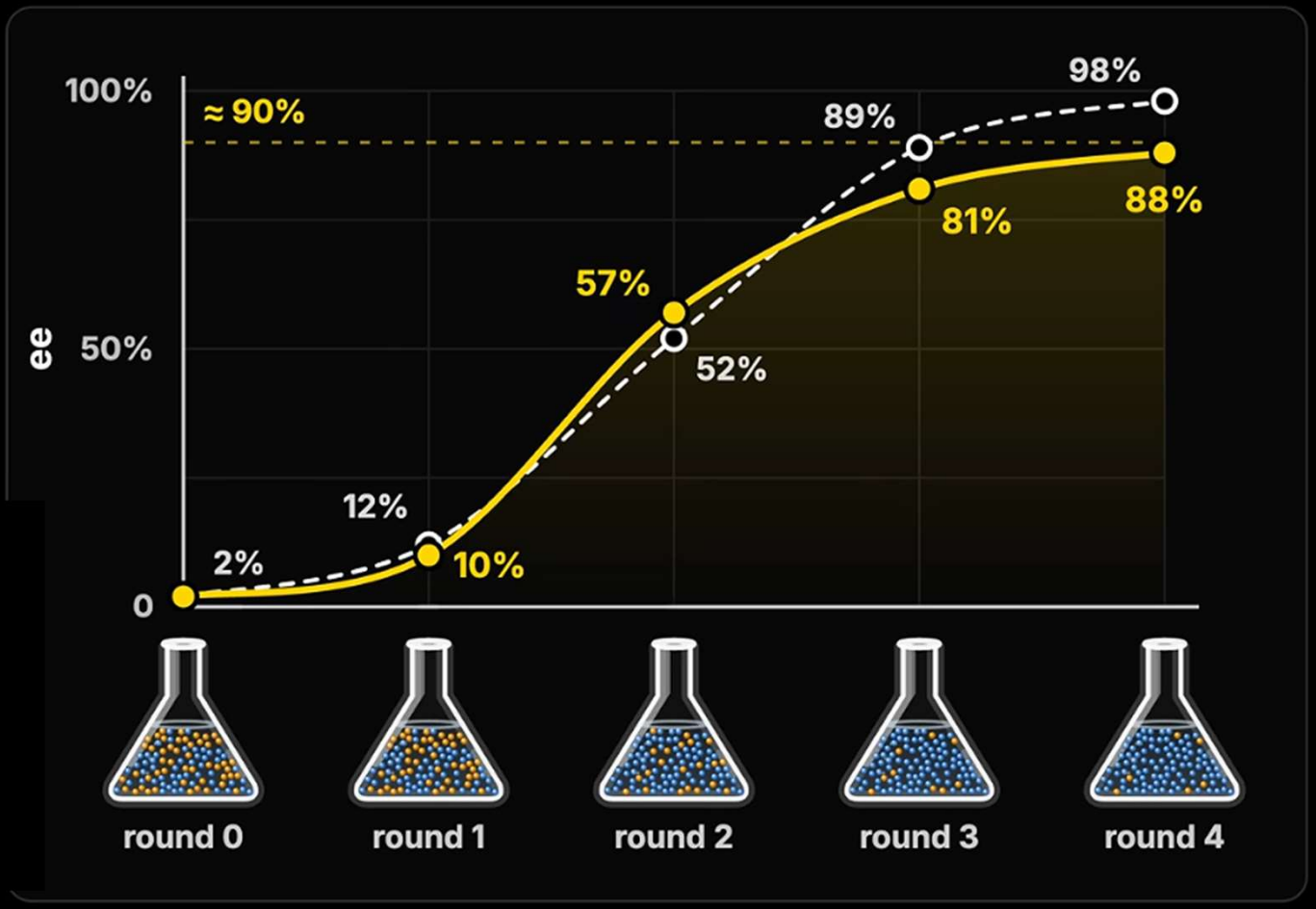
嘧啶-5-甲醛

+ 5-嘧啶基烷醇

(R 或 S)



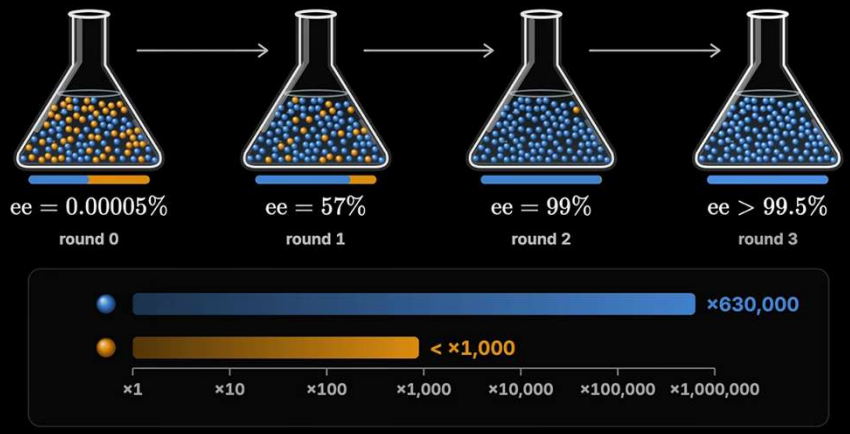
经典连续运行 / Consecutive cycles：5% ee 起始

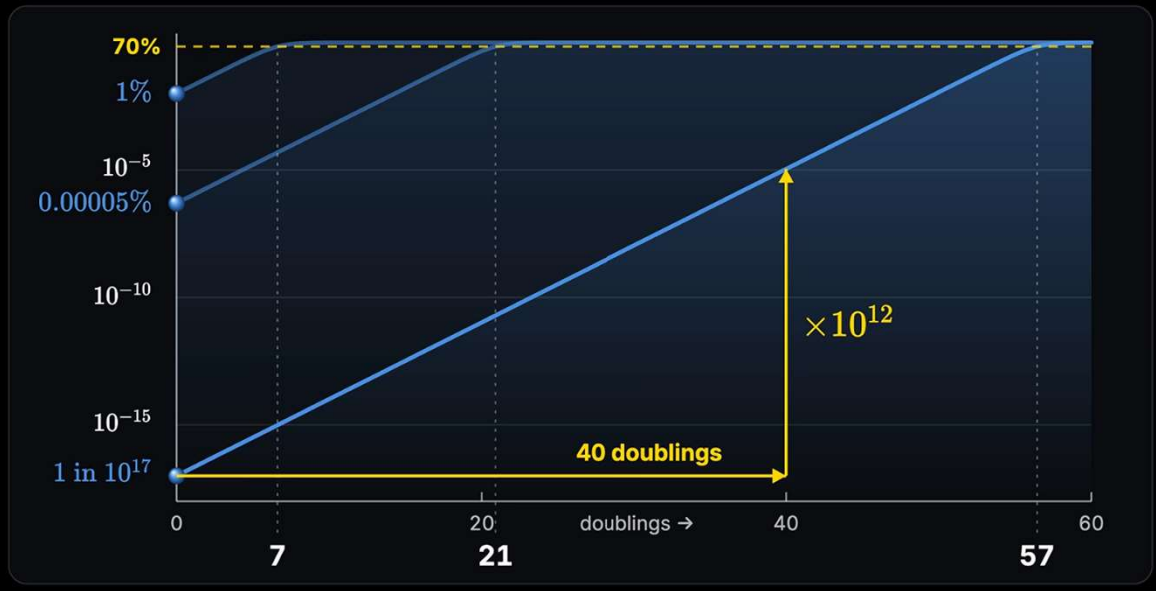


2003年之后的工作

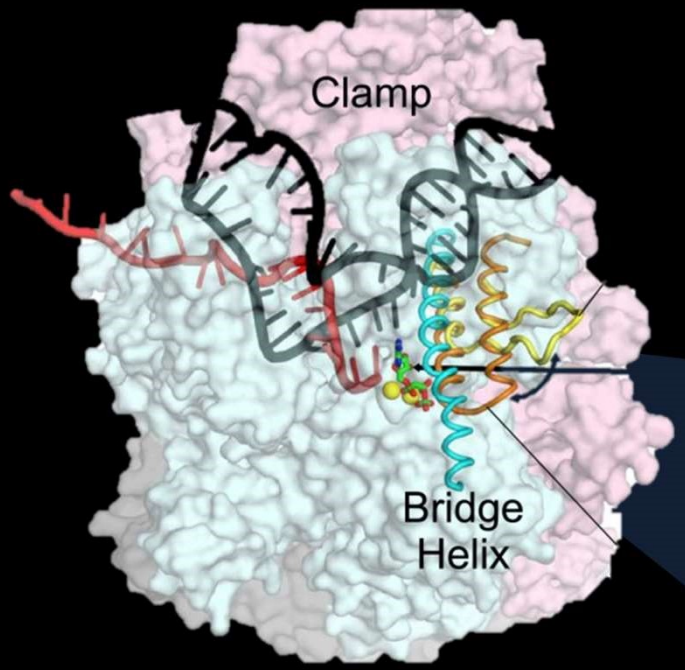
Soai's studies in 2003

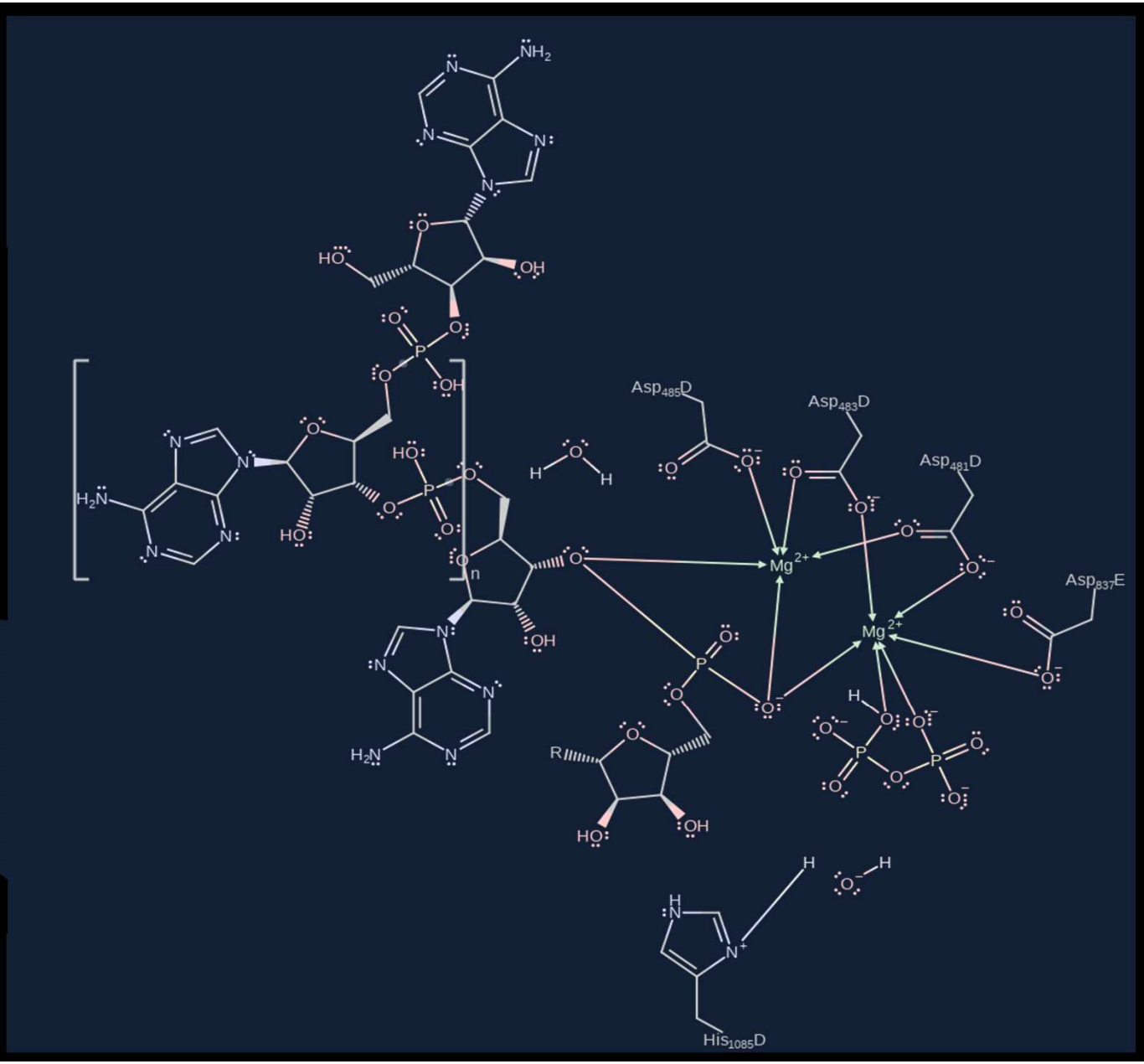
教学模型： $\dot{\eta} = a\eta(1-\eta^2) + h + \xi(t)$

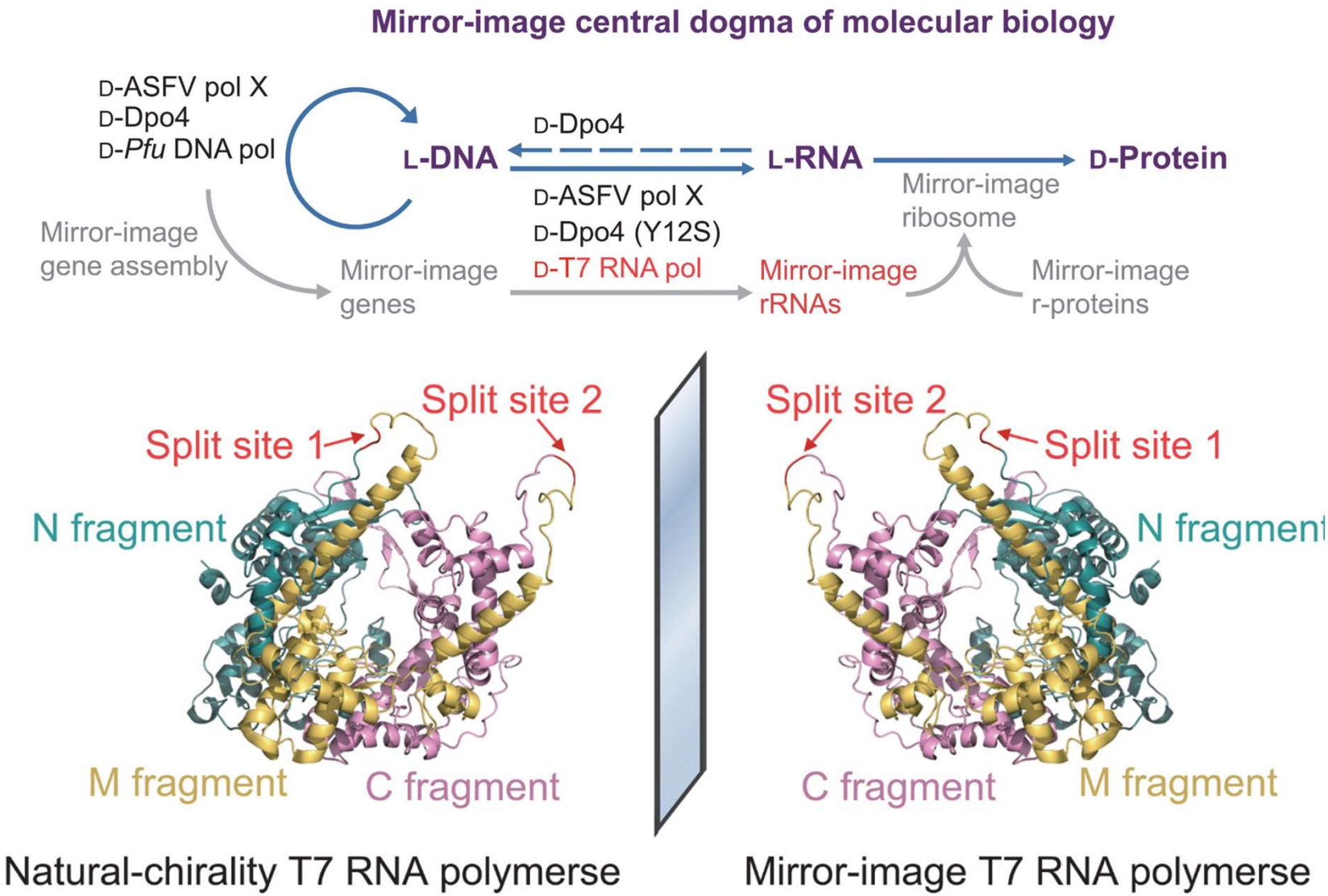




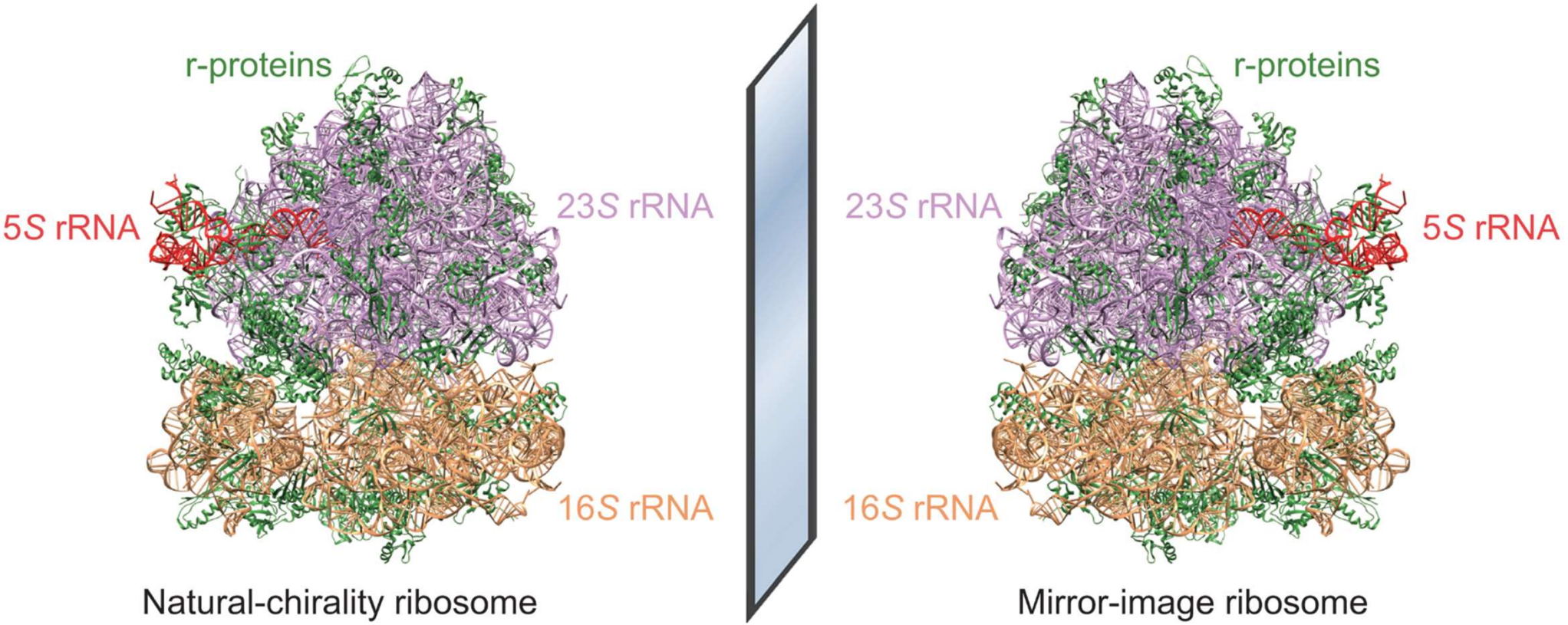
RNA聚合酶的活性中心







Xu et al., *Science* 378, 405–412 (**2022**)



Xu et al., *Science* 378, 405–412 (**2022**)

前生物化学：机制已证明，起源仍是开放问题

Prebiotic Chemistry and Open Questions

实验与模型已经说明

- 产物 ee 可以超过初始配体 ee
- 自催化与相互抑制可形成强烈正反馈
- 随机涨落能被放大为宏观手性选择
- 手性生成、传递与放大可由同一反应网络连接

仍未被这项成果回答

- 早期地球采用了哪条化学路径?
- 为何是今天特定的 L / D 组合?
- 如何在水相中实现 Soai 反应?
- 如何连接单一反应与生命网络?

Soai 反应使用干燥有机溶剂与对空气 / 水敏感的有机锌试剂：它证明机制可行，并非早期地球情景的复原。

03

近代物理进展 · 专题报告 / MODERN PHYSICS PROGRESS

手性物理：从分子到量子体系

CHIRALITY FROM MOLECULES TO QUANTUM SYSTEMS

同一种“镜像破缺”，如何在光、电子、晶格与拓扑态中留下不同指纹?

初始手性偏向可来自外部选择，也可只来自涨落

Sources of Initial Chiral Bias

随机涨落
Fluctuations

有限分子数使瞬时 R / S 不完全相等

圆偏振光
CPL

光的螺旋性对两种对映体产生不同作用

手性晶体 / 表面
Chiral surfaces

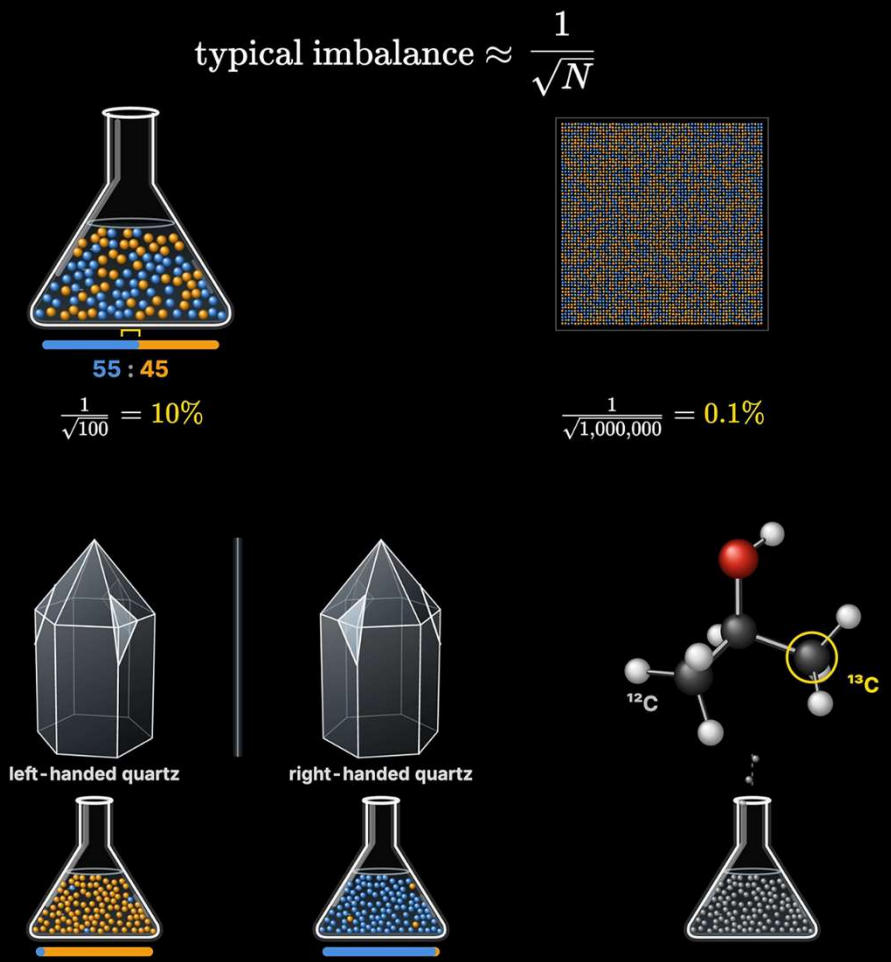
提供固定手性的吸附、成核或催化环境

同位素手性
Isotopic chirality

同位素取代也可形成微弱手性信息

宇称破缺
Parity violation

弱相互作用使镜像分子的能量并非严格相同

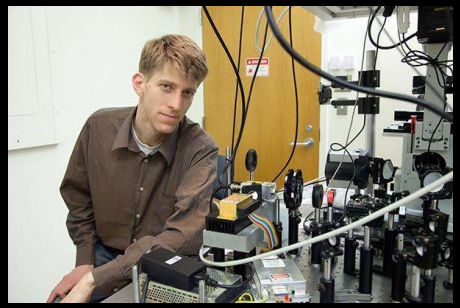


手性光：不仅看偏振，还要看局域电磁场结构

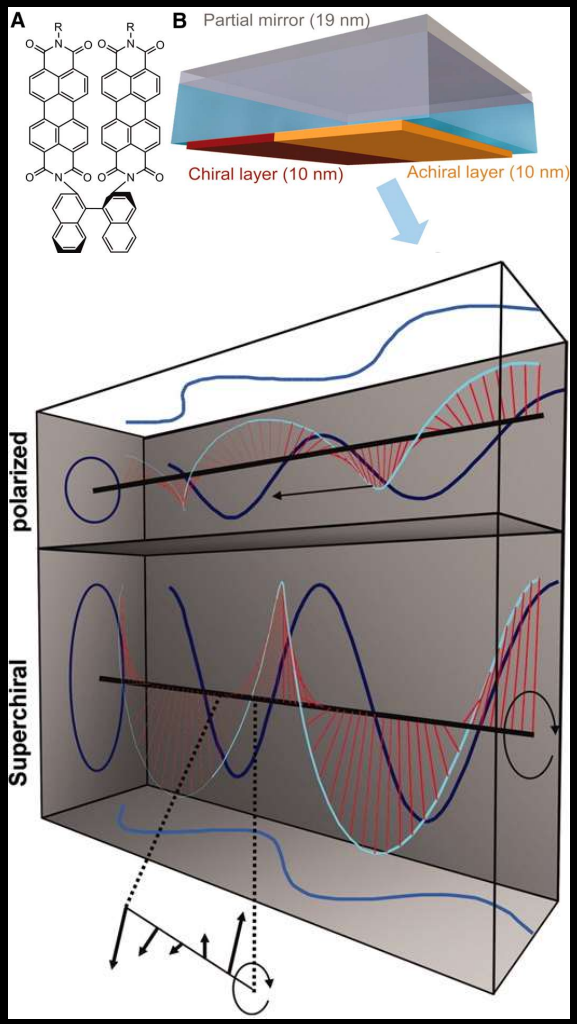
Optical Chirality and Superchiral Fields

$$C = \frac{\epsilon_0}{2} E \cdot (\nabla \times E) + \frac{1}{2\mu_0} B \cdot (\nabla \times B)$$

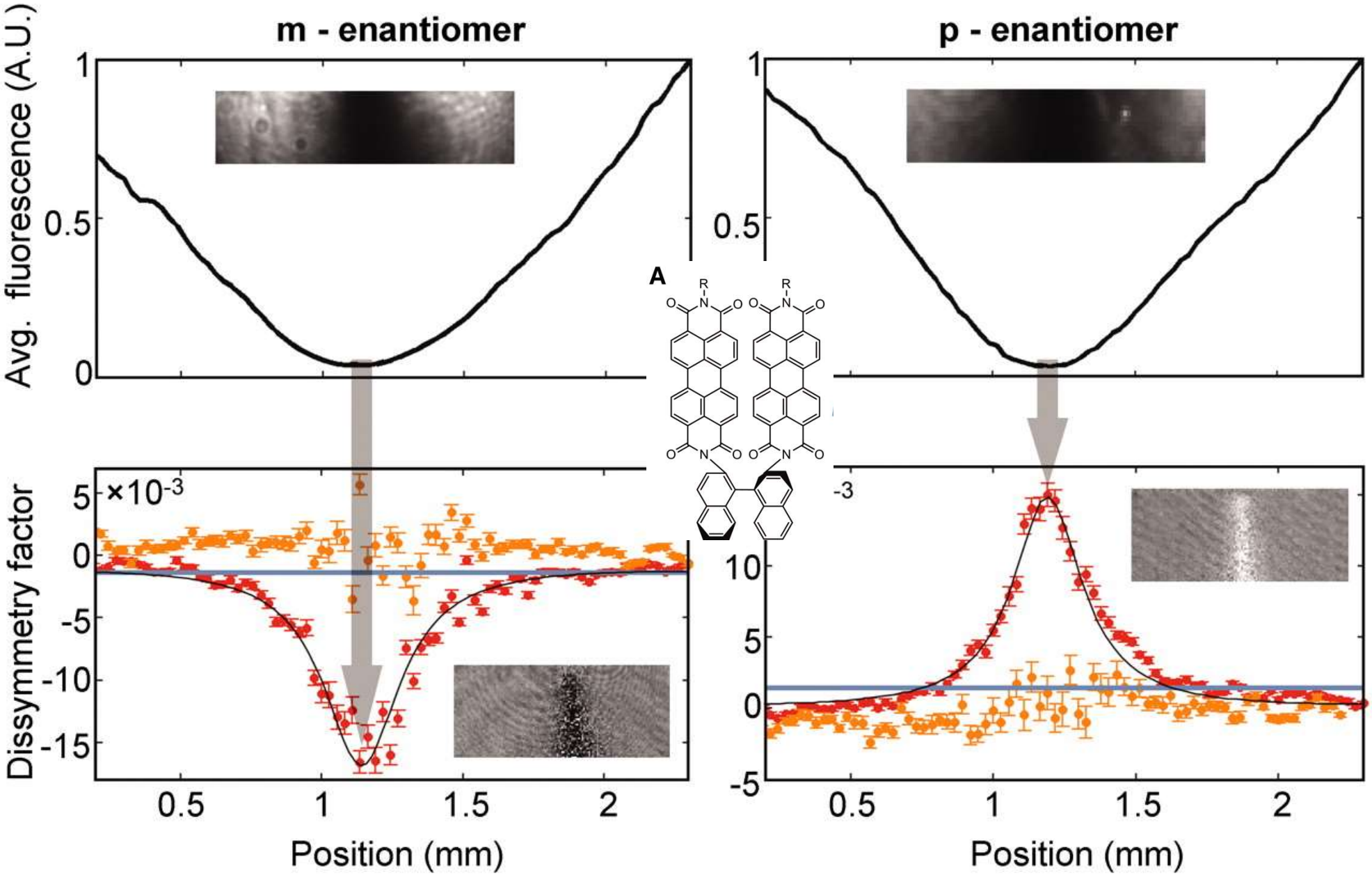
Tang–Cohen 光学手性密度（optical chirality density）C：
描述局域电磁场与手性小分子激发速率差异的关系
（*Science,* **2011**, 332, 333）



- 圆偏振与传播方向共同定义光的螺旋性
- 近场可增强手性区分，形成“超手性光”
- 分子手性不保证任意圆偏振光都有同样响应

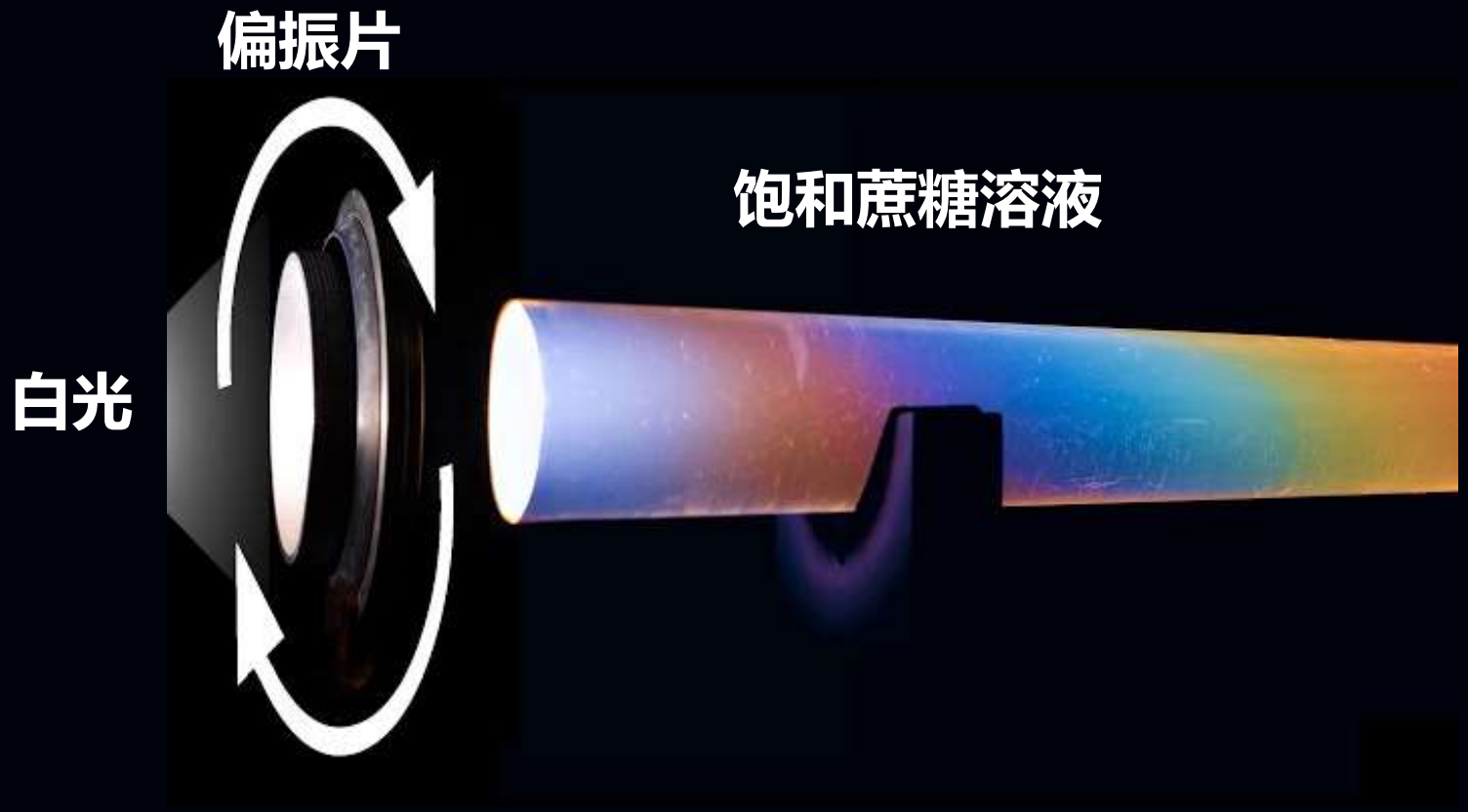


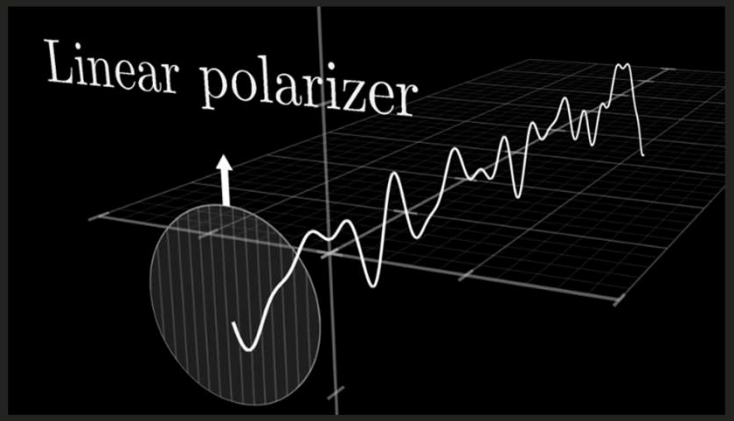
Frank 曾提到"环境的不对称性（例如圆偏振光）"可能是初始手性失衡的来源，而这篇论文回答的是：**能不能造出比普通圆偏振光（CPL）手性"更强"的光，让光与手性分子的区分能力成倍放大？**

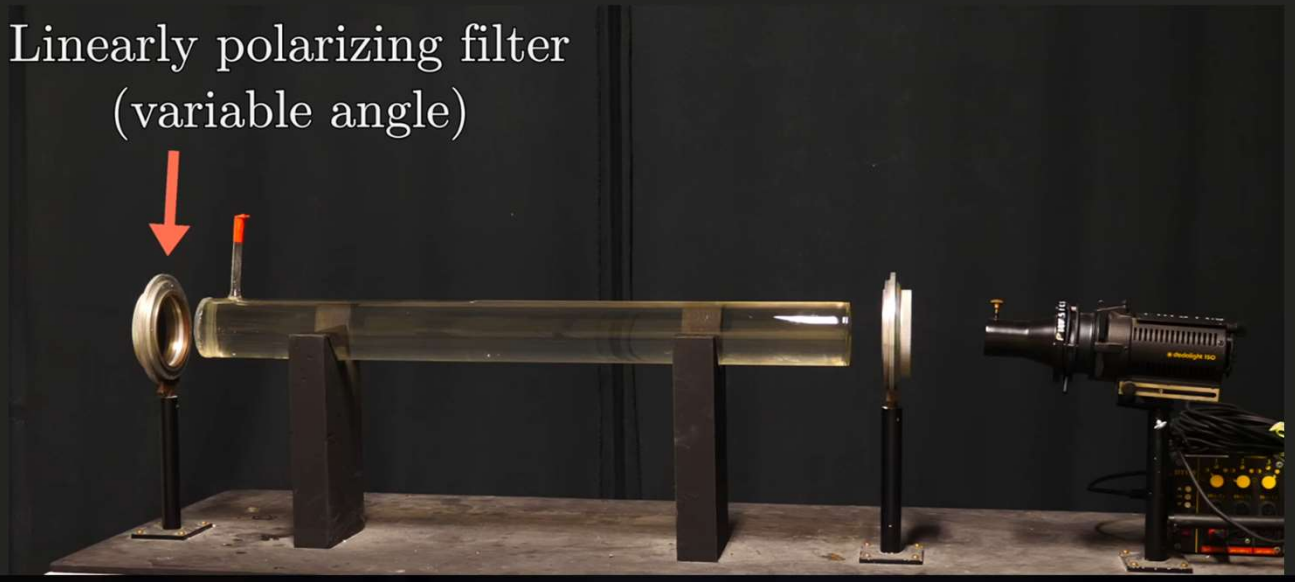

m - enantiomer
p - enantiomer
Avg. fluorescence (A.U.)
Dissymmetry factor
×10-3
Position (mm)
Position (mm)
A
R
N
O

手性分子可以改变光的偏振方向

Chirality and Enantiomers



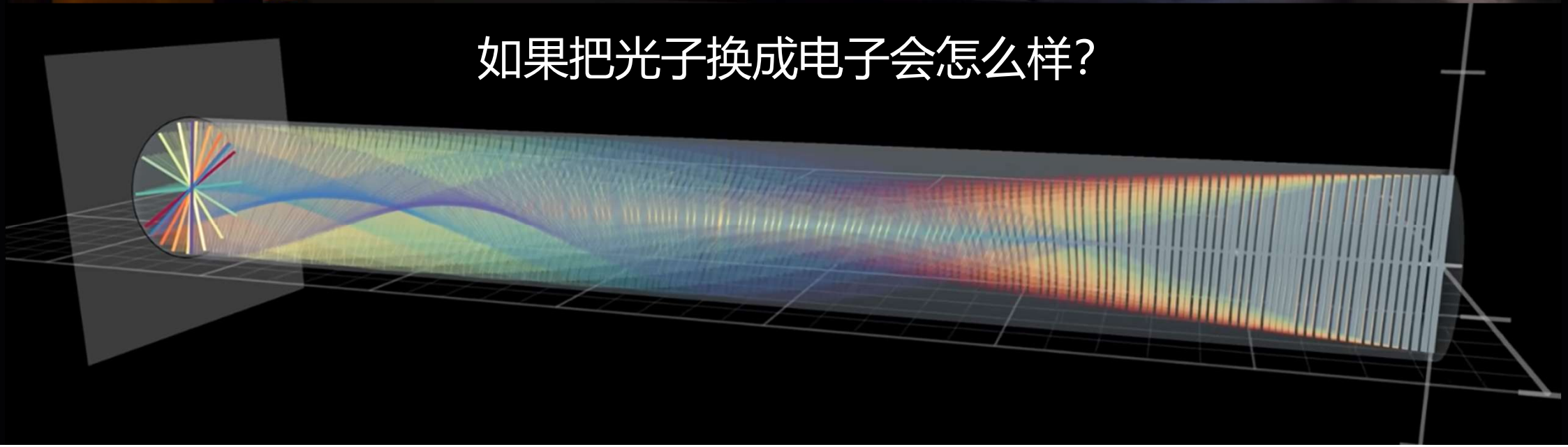

Linear polarizer


Linearly polarizing filter
(variable angle)





如果把光子换成电子会怎么样？



CISS：手性介质可以把电荷输运与电子自旋耦合

Chirality-Induced Spin Selectivity

手性诱导自旋选择（CISS）

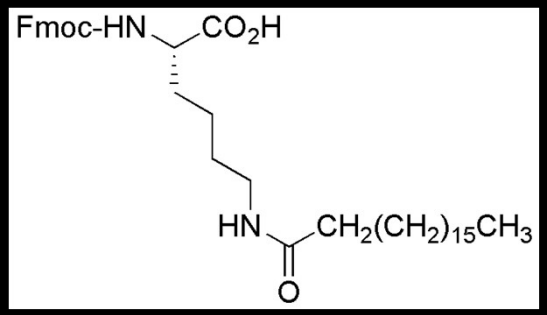
Chirality-Induced Spin Selectivity

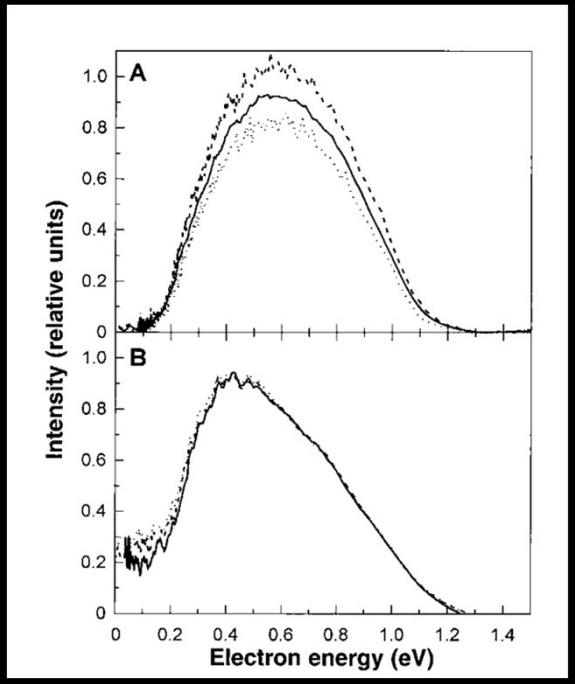
Chiral Induced Spin Selectivity | Chemical Reviews

作者：BP Bloom · 2024 · 被引用次数：815 — CISS refers to the connection between chiral symmetry and electron spin in molecules and materials and it can manifest for electron transmission ...

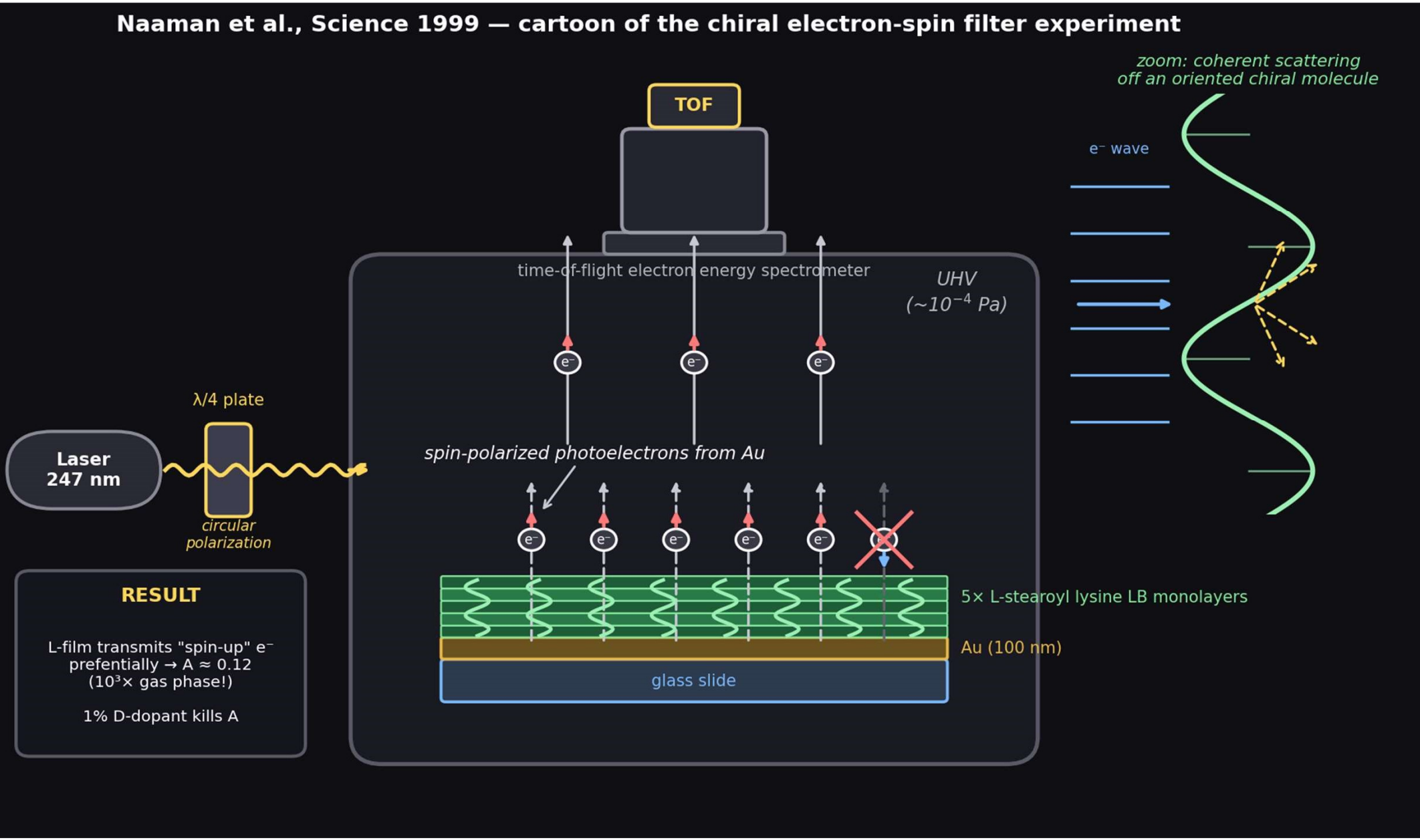
电极 → **手性分子 / 材料** → **电极**

某一自旋方向更易通过；
反转手性或流向会改变选择





- 结构手性联系轨道运动、自旋轨道耦合与耗散
- 应用：自旋电子学、手性分离、自旋依赖电催化
- 微观机理仍在发展（彭新华老师牵头的科学院先导B）


Naaman et al., Science 1999 — cartoon of the chiral electron-spin filter experiment
zoom: coherent scattering
off an oriented chiral molecule
e⁻ wave
TOF
time-of-flight electron energy spectrometer
UHV
(~10⁻⁴ Pa)
λ/4 plate
Laser
247 nm
circular
polarization
spin-polarized photoelectrons from Au
5× L-stearoyl lysine LB monolayers
Au (100 nm)
glass slide
RESULT
L-film transmits "spin-up" e⁻
prefentially → A ≈ 0.12
(10³× gas phase!)
1% D-dopant kills A

声子与 Weyl 费米子的“手性”并不等同于分子手性

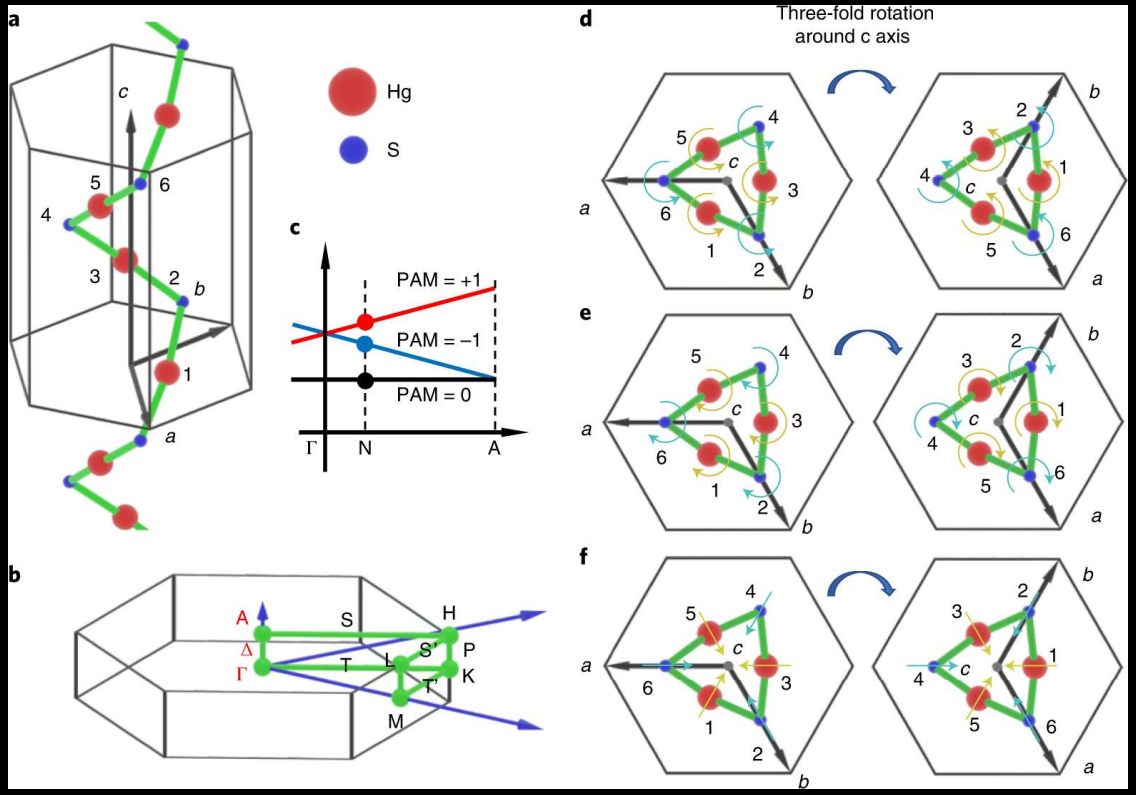
Chiral Phonons and Weyl Fermions

手性声子 / Chiral phonons

- 旋转原子位移形成圆偏振晶格振动，携带声子角动量
- 可与自旋、轨道和圆偏振光交换角动量
- 手性声模不要求晶体结构本身有手性

Weyl 手性：动量空间的拓扑荷

- 由 Weyl 节点周围的 Berry 通量定义
- 结构手性可辅助实现 Weyl 态，但两者不等同



Ishito et al., *Nat. Phys.* **2023**, 19, 35,

04

近代物理进展 · 专题报告 / MODERN PHYSICS PROGRESS

从诺奖回到研究前沿

FROM THE NOBEL PRIZE TO RESEARCH FRONTIERS

哪些实验能够同时追踪手性结构、动力学与功能响应？

手性研究的主线：结构跨尺度传递，响应逐级放大

Chirality Across Scales

01	02	03	04	05
分子	**聚集体**	**晶体表面**	**量子态**	**生命体系**
Molecule	Aggregate	Crystals	Quantum state	Living system
构型 / 构象	**二聚体 / 高阶组装**	**螺旋 / 螺旋轴**	**自旋 / 声子 / 能带**	**聚合物 / 细胞网络**
CD、NMR	原位光谱、质谱	衍射、显微	输运、ARPES	成像、组学

可检验的问题：某一尺度的手性变化，是否必然在下一尺度产生可测响应？

传递效率由对称性、耦合强度、时间尺度与耗散共同决定

前沿一：从终点 ee 走向时间分辨的手性动力学

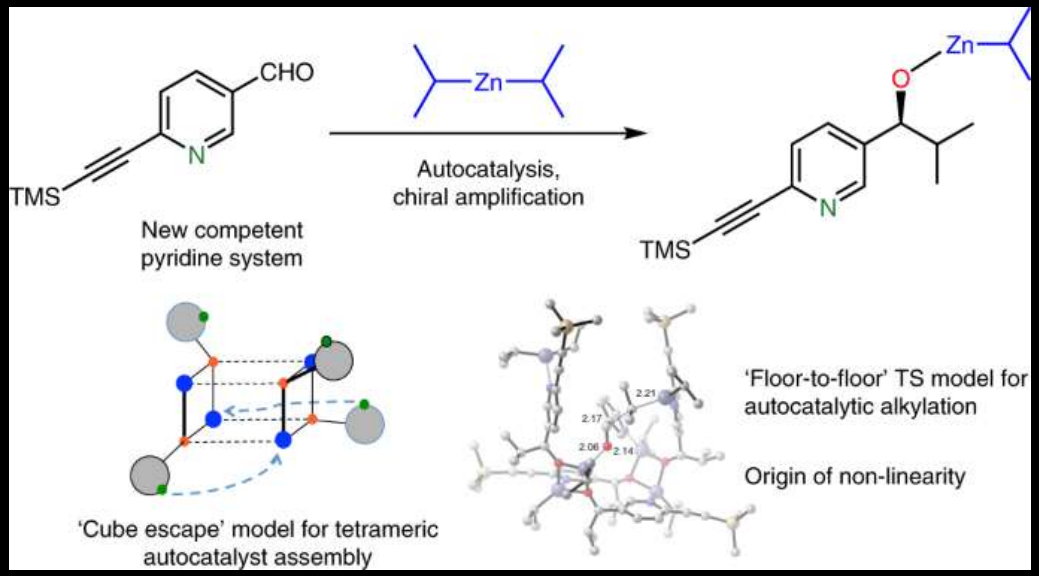
Time-Resolved Chiral Dynamics

只有终点纯度，往往无法区分
“生成更快”与“少数被扣留”。

01 **同时测** 产物 ee、催化剂聚集态、反应速率

02 **随时间测** 成核、增长、反馈启动与平台期

03 **跨空间测** 溶液、界面、晶格中的手性传递



目标：把手性放大曲线转化为可判别的动力学模型。

Athavale et al., Nat. Chem. 12, 412–423 (2020)

前沿二：把随机对称性破缺变成可编程的手性选择

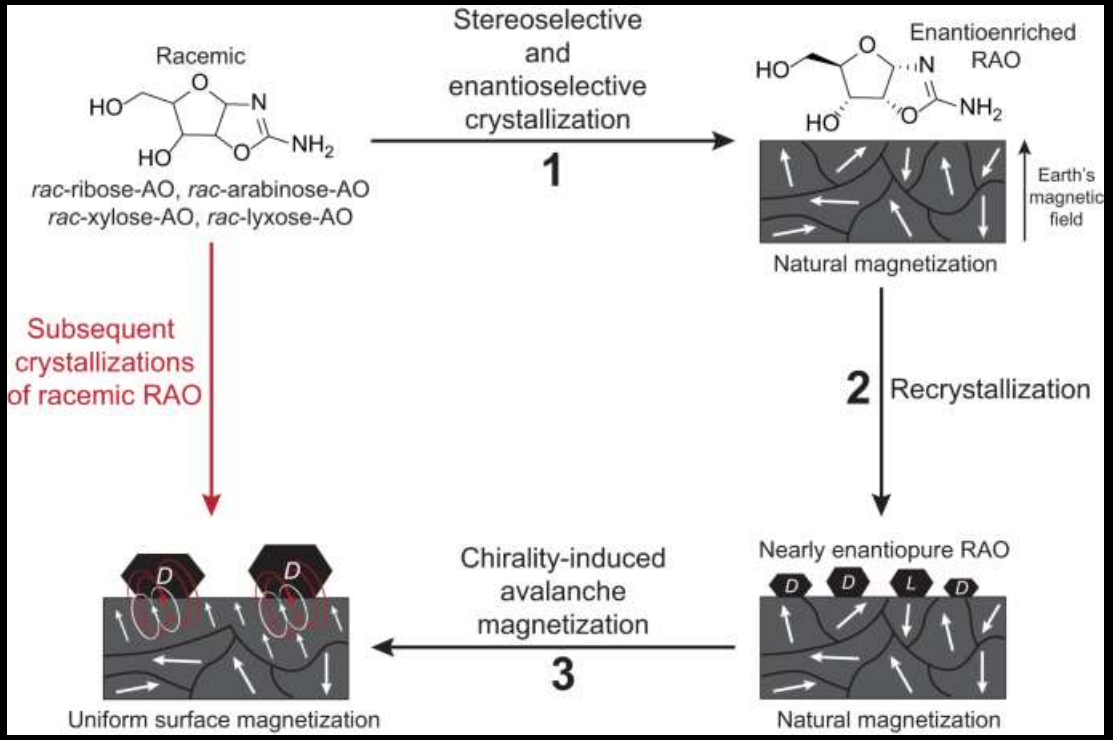
Programmable Chiral Selection

光 圆偏振、超手性近场、超快脉冲

界面 手性表面、晶体面、二维材料

输运 自旋极化电子、流场与剪切

网络 自催化、交叉抑制、持续物质流



评价标准：方向可控、重复性高、放大效率可量化，并能排除微量手性杂质。

Nature Communications, **14**, 6351 (2023)

讨论：怎样设计一个能说服物理同行的手性实验？

Discussion: Designing a Decisive Experiment

01 **若平均 ee 严格为零，体系还能发生手性选择吗？**

提示：区分单次实验与多次实验的系综平均；考虑有限尺寸涨落。

02 **观察到 +NLE，能否直接断言存在某一种二聚体机理？**

提示：列出可替代机理，并设计速率、聚集态和温度依赖测量。

03 **怎样证明“外场选择了手性”，而不是痕量手性杂质？**

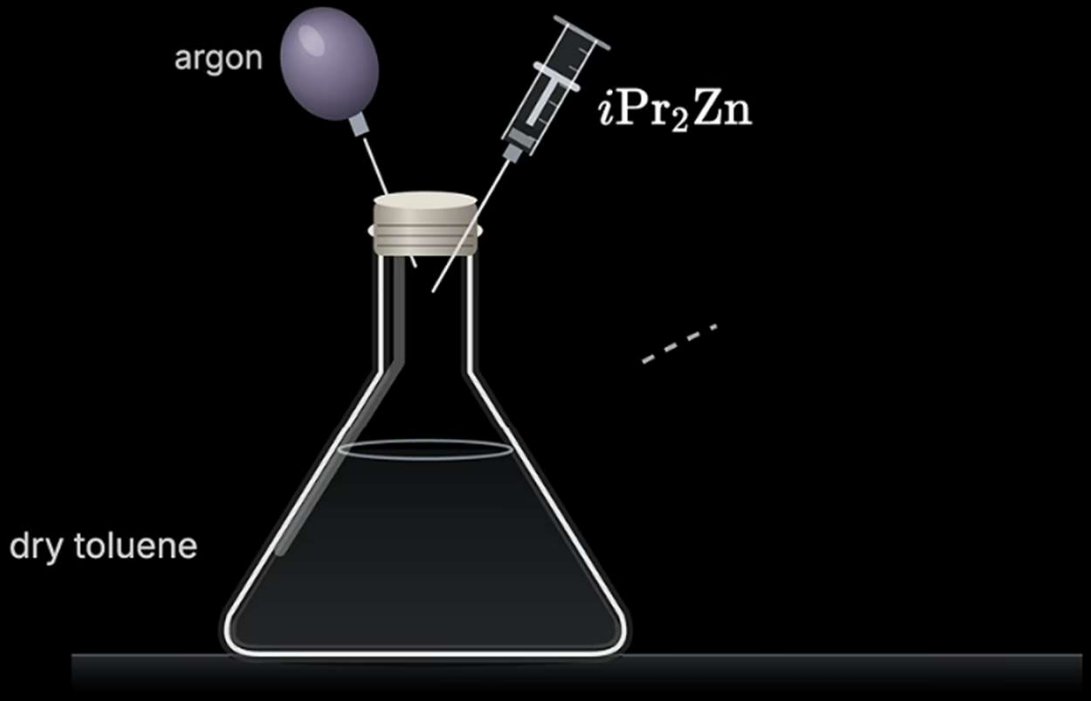
提示：镜像反号、空白对照、重复统计、杂质下限与外场强度依赖。

小组输出：一句可检验假设 + 一个观测量 + 一个最关键的排除性对照。

"It is important to stress that the Frank model is ***not an answer*** *to the origin of biological homochirality. It provides one possible solution, of which there are several, to an event that occurred about 3.5-4 billion years ago and to which we will probably never have a definitive answer.*

Instead, the experimental validation provided by ***Kagan*** *and* ***Soai*** *to the Frank model has deepened our fundamental understanding of how chirality is generated, transmitted and amplified in asymmetric catalysis and thus of intrinsic molecular properties that are central to organic chemistry and related disciplines. "–* ***The Nobel Prize Committee***

Beyond the Nobel Prize





谢谢

Thank You

如果一个体系可以选择“左”或“右”，
我们能否进一步控制它何时选择、选择多快？

对称性 · 涨落 · 反馈 · 测量

Symmetry · Fluctuations · Feedback · Measurement

References

1. Nobel Committee. Scientific Background to the Nobel Prize in Chemistry 2026.

2. Puchot et al. JACS 108, 2353–2357 (1986). DOI: 10.1021/ja00269a036.

3. Soai et al. Nature 378, 767–768 (1995). DOI: 10.1038/378767a0.

4. Tang & Cohen. PRL 104, 163901 (2010). DOI: 10.1103/PhysRevLett.104.163901.

5. Naaman et al. Nat. Rev. Chem. 3, 250–260 (2019).

6. Ishito et al. Nat. Phys. 19, 35–39 (2023).

7. Armitage et al. Rev. Mod. Phys. 90, 015001 (2018).