CHEMISTRY OF MATERIALS

pubs.acs.org/cm

Editorial

Clément Sanchez and the Hybrid Materials Community: *L'Imagination au Pouvoir*

Cite This: *Chem. Mater.* 2023, 35, 7875−7877

Read Online

ACCESS | Metrics & More | Article Recommendations

"A researcher is an artist: he must be able to create, to explore, to have original ideas and to take risks!" His own phrase[1] can adequately summarize Clément Sanchez's brilliant and extensive career, driven by his passion for discovery, his imagination, and his ability to disentangle the complexities beneath chemical synthesis and processing through rational thinking and the use of high-end characterization tools.

Clément Sanchez had an atypical education within the French system. He started very young as a laboratory assistant at Rhodia while pursuing his University diploma, studying at nights and weekends while working during the day. At the age of 26, he was allowed to enter the prestigious École Nationale Supérieure de Chimie de Paris (at present, Chimie Paris Tech), and completed a chemistry degree as the first of his class in 1978. He was then scouted by a young and irreverent professor, Jacques Livage, who was his PhD mentor at the *Université Pierre et Marie Curie*, in Paris. After obtaining a CNRS researcher position, he completed his basic education with a postdoctoral fellowship in the Somorjai group at the University of California Berkeley, where he tackled a then emergent field—the photoelectrochemistry of highly dispersed oxides. Back to France, he became a CNRS researcher at Université Pierre et Marie Curie in Paris, then Director of Research and then Professor Lecturer at Ecole Polytechnique, for 12 years. Thereafter, he directed the Laboratoire de Chimie de la Matière Condensée de Paris for more than 8 years, becoming CNRS Researcher of exceptional class. Finally, in 2011, Clément Sanchez was appointed Professor at the Collège de France as a new Chair (Chemistry of Hybrid Materials). He became the 19th chemist to enter the elite of the Collège de France since its creation in 1530 (Figure 1).

> "He was always investing in the young people, polishing brilliant minds as maybe just a few ahead of him, a "Mensch" in jiddish."
> **Markus Antonietti**

This scientific journey allowed Clément to develop a unique profile, combining the solid state, mineral chemistry, and spectroscopy from his academic experience, with training in organic synthesis, molecular chemistry, and process engineering through his work in industry. Clément's unique balance of competences in the inorganic, organic, and physical chemistry worlds, added to his interest in both basic and applied subjects,

Figure 1. Photograph of Clément Sanchez during his inaugural lecture at Collge de France (credit to Patrick Imbert/Collège de France).

forged his way into the powerful and emerging field of soft-chemistry-derived materials.

His early work with Jacques Livage was decisive to the development of the field of *chimie douce* or soft chemistry, a steppingstone in modern materials chemistry.[2] Their first studies focused on understanding the complexities involved in sol−gel reactions leading to metal oxides (such as vanadium or titanium), a molecular pathway to nanostructured materials.[3] The mild temperature conditions are akin to those found in Nature and thus permit the integration of organic and inorganic nanobuilding blocks within hybrid materials with extended interfaces.[4,5] Indeed, the organic−inorganic interface (nature of the interactions, energy, and linkability) plays a preponderant role in modulating different functions: mechanical behavior (flexibility vs. stiffness), density, controlled permeability, color, transparency, hydrophobicity, etc. In the 1980s and 1990s, Clément played a key role in establishing the foundations of the extensive field of hybrid materials.[6] He mastered the molecular origins of hybrid organic−inorganic structures,[7] organized the first meetings related to hybrid materials, and introduced a general classification of such hybrid

Published: October 10, 2023

materials, depending on the nature of the interface between the organic and mineral components.[8]

> "Clément Sanchez has made most remarkable contributions to the Chemistry of Hybrid Materials as well as Sol-Gel Science and Technology. He is widely acknowledged as a pioneer of an innovative chimie douce approach to design and generate a wide range of multi-functional hybrid materials. He is an exceptionally creative scientist who has been leading the establishment of this new field, generating both academic and industrial impact of the highest order."
> **Jean-Marie Lehn**

At this point, new tools were needed to analyze the kinetics and reaction mechanisms that led to harnessing the huge variety of hybrid materials being discovered, and their yet unknown nanoscale components, which ultimately constitute the functional materials. In this framework, Sanchez made again seminal contributions, employing advanced spectroscopies[9] such as ESR, EXAFS-XANES, and multinuclear NMR and MAS NMR, for in-depth characterization of the local coordination of the constituents of sol−gel systems, as well as SAXS to understand their size, spatial distribution, and fractal dimension.

This critical knowledge permitted him and his team to tackle the designed synthesis of complex architectures inspired by nature, using chemical strategies that combined sol−gel, self-assembly, and soft matter processing. In the early 2000s, Clément was in the front wave of a novel school of creative thinking, which exploited biomimetic approaches. Having mastered the molecular origins of hybrid organic−inorganic structures created through *chimie douce*, the line of thought went further. New ideas aimed at coupling a variety of inorganic nanobuilding blocks with organic or biological components, and to spatially harness their interactions to achieve multiscale organized architectures.[10] Notably, he was a pioneer in the synthesis of porous materials with controlled composition and morphology. Among his countless milestones in the field, we should mention the first examples of mesoporous TiO_2 crystalline films,[11] Ti-based metal−organic frameworks,[12] or mesoporous aluminosilicate catalysts.[13] This new area required a completely new study of fundamental processes, all the way from molecular precursors through self-assembly processes at mesoscopic scales, to the final oxide or hybrid material.[14] Importantly, Sanchez was always aware of the relevance of kinetic control in the formation of these structures. Consequently, he paid particular attention to coupling the basic bottom-up approaches via *chimie douce* (i.e., implementing room temperature polycondensation reactions in green solvents, self-assembly, ...) with chemical processing and materials shaping approaches (i.e., wet film deposition, aerosol, electrospinning, etc.). In this way, sophisticated nanoarchitectures can be controlled and processed from the molecular scale to the functional material.

> "Many researchers, including ourselves, followed Clément's original contributions to the field of organic−inorganic hybrid materials, an area he put on the science map and which literally exploded in recent years."
> **Krzysztof Matyjaszewski**

Interestingly, he created a bridge between high-end basic science and industrial development, translating many of his fundamental concepts into technologies, through numerous industrial partnerships and more than 75 patents. His research enabled functional materials whose use will be key to addressing our needs in the fields of energy, environment, and medicine.[15,16]

In the past decade, Clément's interests focused on novel chemistry and processing pathways, namely, in the coupling of mineral reactive extrusion to attain new phases, the in-depth *in situ* and operando study of the formation processes of nanosystems such as perovskites, metal oxides, or biominerals, through liquid HRTEM, NMR, and SAXS, as well as the development of new electroactive systems via electrochemically assisted carbon-based hybrid materials. In addition, he continues building new bridges with other fields, for example, by revisiting the chemical origins of "old" hybrid materials used in art.[17]

In his nearly 45 years of career, Clément Sanchez has had deep impact and exerted a huge influence on the Materials Chemistry community, through the development of a new axis of original research in hybrid materials, combining creativity and chemical intuition with the application of transversal state-of-the-art characterization techniques and *in situ* analysis, to ultimately gain insight in the delicate steps that lead to bioinspired nanomaterials. He has built solid bridges between local molecular structure and multiscale properties in complex hybrid nanoarchitectures. Additionally, he pushed these innovative approaches and basic knowledge to make a real impact in several industrial domains, as diverse as petrol, coatings, or cosmetics. Last, but not least, he has been at the root of a truly multidisciplinary "school of thinking" and unified the broad hybrid materials scientific community, which meets every two years at the "Multifunctional, Hybrid and Nanomaterials", conference, a reference event organized by Clément since its first edition in 2009.

His main interest and driving force along this long scientific journey has always focused on playing with chemistry and understanding the modes of construction of complex systems. He has been and still is, with no doubt, a great source of inspiration and a generous mentor for many generations dedicated to exploring new pathways toward materials design.

Clément Sanchez is, in summary, a true force of nature with a unique and deep look at scientific-technological problems, as well as the ability to solve complex problems through his creativity and his vast knowledge of chemistry, physics and materials science. Our community should be thankful that he

https://doi.org/10.1021/acs.chemmater.3c02224
Chem. Mater. 2023, 35, 7875−7877

did not follow his youth football talent as a professional player, and chose instead to enlighten the paths of our discipline.

This virtual issue reflects the broad impact of Clément's work on the Chemistry of Materials community. The reader will find here a wealth of new synthetic pathways for nanostructured materials and their formation mechanisms. Hybrid and nanocomposite materials with novel properties such as self-repair, chirality, luminescence, controlled transport, or responsiveness, are described and discussed. Novel multiscale architectures are presented, which include porous frameworks obtained through interfacial and topological control. Applications of these materials are expected in the fields of environment, energy, and health. But the most interesting underlaying concept is that globally, these complex spatial architectures present emergent properties due to the coupling of their electronic properties, their surfaces, or the interaction between building blocks. This is central in the future of designed materials chemistry, a path that Clément helped us visualize and enter into, using all the sophisticated tools that soft chemistry methods borrow from Nature.

Galo J. A. A. Soler-Illia orcid.org/0000-0001-9984-3806
Marco Faustini orcid.org/0000-0002-6254-5116
Luis M. Liz-Marzán orcid.org/0000-0002-6647-1353

AUTHOR INFORMATION

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.chemmater.3c02224

Notes

Views expressed in this editorial are those of the authors and not necessarily the views of the ACS.

REFERENCES

(1) https://www.inc.cnrs.fr/fr/cnrsinfo/clement-sanchez-createur-dune-ecole-de-pensee-en-science-des-materiaux.
(2) Livage, J.; Sanchez, C. Sol-gel chemistry. *J. Non-Cryst. Solids* **1992**, *145*, 11−19.
(3) Livage, J.; Henry, M.; Sanchez, C. Sol-gel chemistry of transition metal oxides. *Prog. Solid State Chem.* **1988**, *18*, 259−341.
(4) Sanchez, C.; Soler-Illia, G. J. de A. A.; Ribot, F.; Lalot, T.; Mayer, C. R.; Cabuil, V. Designed Hybrid Organic−Inorganic Nanocomposites from Functional Nanobuilding Blocks. *Chem. Mater.* **2001**, *13*, 3061−3083.
(5) Sanchez, C.; Arribart, H.; Giraud Guille, M. M. Biomimetism and Bioinspiration as Tools for the Design of Innovative Materials and Systems. *Nat. Mater.* **2005**, *4*, 277−288.
(6) Faustini, M.; Nicole, L.; Ruiz-Hitzky, E.; Sanchez, C. History of Organic−Inorganic Hybrid Materials: Prehistory, Art, Science, and Advanced Applications. *Adv. Funct. Mater.* **2018**, *28*, No. 1704158.
(7) Sanchez, C.; Livage, J.; Henry, M.; Babonneau, F. Chemical Modification of Alkoxide Precursors. *J. Non-Cryst. Solids* **1988**, *100*, 65−76.
(8) Sanchez, C.; Ribot, F. Design of Hybrid Organic-Inorganic Materials Synthesized via Sol-Gel Chemistry. *New J. Chem.* **1994**, *18*, 1007−1047.
(9) Sanchez, C.; Livage, J.; Tougne, P.; Legrand, A. P. ESR Analysis of Brownian Motion in V_2O_5 Xerogels after Adsorption of Water. *Magnetic Resonance in Colloid and Interface Science: Proceedings of NATO Advanced Study Institute and Second International Symposium*; Menton, France, June 25−July 7, 1979; Springer: 1980; pp 559−564.
(10) Soler-Illia, G. J. d. A. A.; Sanchez, C.; Lebeau, B.; Patarin, J. Chemical Strategies to Design Textured Materials: From Microporous and Mesoporous Oxides to Nanonetworks and Hierarchical Structures. *Chem. Rev.* **2002**, *102*, 4093−4138.
(11) Crepaldi, E. L.; Soler-Illia, G. J. d. A. A.; Grosso, D.; Cagnol, F.; Ribot, F.; Sanchez, C. Controlled Formation of Highly Organized Mesoporous Titania Thin Films: From Mesostructured Hybrids to Mesoporous Nanoanatase TiO_2. *J. Am. Chem. Soc.* **2003**, *125*, 9770−9786.
(12) Dan-Hardi, M.; Serre, C.; Frot, T.; Rozes, L.; Maurin, G.; Sanchez, C.; Férey, G. A New Photoactive Crystalline Highly Porous Titanium(IV) Dicarboxylate. *J. Am. Chem. Soc.* **2009**, *131*, 10857−10859.
(13) Pega, S.; Boissière, C.; Grosso, D.; Azaïs, T.; Chaumonnot, A.; Sanchez, C. Direct Aerosol Synthesis of Large-Pore Amorphous Mesostructured Aluminosilicates with Superior Acid-Catalytic Properties. *Angew. Chem., Int. Ed.* **2009**, *48*, 2784−2787.
(14) Sanchez, C.; Boissière, C.; Grosso, D.; Laberty, C.; Nicole, L. Design, Synthesis, and Properties of Inorganic and Hybrid Thin Films Having Periodically Organized Nanoporosity. *Chem. Mater.* **2008**, *20*, 682−737.
(15) Sanchez, C.; Julian, B.; Belleville, P.; Popall, M. Applications of Hybrid Organic-Inorganic Nanocomposites. *J. Mater. Chem.* **2005**, *15*, 3559−3592.
(16) Sanchez, C.; Belleville, P.; Popall, M.; Nicole, L. Applications of Advanced Hybrid Organic-Inorganic Nanomaterials: From Laboratory to Market. *Chem. Soc. Rev.* **2011**, *40*, 696−753.
(17) Pasco, H.; de Viguerie, L.; Faustini, M.; Coelho-Diogo, C.; Ersen, O.; Gervais, C.; Gobeaux, F.; Ihiawakrim, D.; Jaber, M.; Walter, P.; Sanchez, C. Shedding Light on Functional Hybrid Nanocomposites 19th Century Paint Medium. *Adv. Funct. Mater.* **2022**, *32*, No. 2106346.

https://doi.org/10.1021/acs.chemmater.3c02224
Chem. Mater. 2023, 35, 7875−7877