Rendiconti Lincei. Scienze Fisiche e Naturali (2023) 34:317–320
https://doi.org/10.1007/s12210-023-01164-2

RESEARCH PAPER

Quasicrystals: fragments of history and future outlooks

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Received: 25 April 2023 / Accepted: 26 April 2023 / Published online: 5 May 2023

Abstract
With this article, we briefly retrace the history of quasicrystals and introduce the Topical collection on "*Quasicrystals: State of the art and outlooks*", consisting of a number of review articles published in the frame of a conference held at the Accademia dei Lincei in November 2022.

Keywords Quasicrystals · Discovery · Applications · New materials

The approximately forty years that have characterized the history of quasicrystals have truly been a mixture of emotions: from the excitement of discovery by chance, to the most unbridled skepticism of the scientific community, to the crowning with the Nobel Prize in 2011 for their discovery to Dan Shechtman (Fig. 1).

Quasicrystals represent a magnificent example of what both Paul J. Steinhardt (Steinhardt 2019) and one of the authors of this contribution (Bindi 2021) define as the *second kind of impossible*. Why second type? Because it is easy to understand what is impossible for everyone: everything that violates the fundamental laws of the universe. This represents the *first kind of impossible*. But there is another kind of impossible. What the whole community considers impossible but which then through intuitions, experiments, stubbornness and incredible love and passion for science turns to be possible. This was true for Dan Shechtman, who fought hard to prove his discovery right in the 1980s, and it was true for Paul J. Steinhardt and Luca Bindi to get acceptance of the discovery of quasicrystals in nature.

For hundreds of years, pure compounds either synthesized in the laboratory or found in nature were thought to form crystals. Crystals are solids with long-range periodic translational order and rotational symmetry restricted to one of the 32 point symmetries. Some 2D rotational symmetries—i.e., five-, seven-, eleven- and higher fold symmetries—and 3D icosahedral symmetry, conflict with periodicity and are strictly prohibited for crystals. Therefore, the publication in 1984 by Dan Shechtman, Ilan Blech, Denis Gratias and John Cahn (Shechtman et al. 1984) of an Al-Mn alloy diffracting like a crystal, but showing forbidden icosahedral symmetry, was met with skepticism. The reason? Dan Shechtman's discovery smashed a belief accepted for centuries. However, as well documented by Senechal (2022), a diffraction pattern having analogies with that shown by Shechtman et al. (1984) was reported by the British crystallographer Alan Mackay in 1981, at the *International Union of Crystallography* meeting in Ottawa, Canada. The idea of quasiperiodic crystals was actually older than the McKay studies, but it was a pretty general idea not related to higher symmetry groups (de Wolff et al. 1981; Ruelle 1982). The Mackay's pattern exhibited sharp spots, which implied it as coming from an ordered structure (Fig. 2a).

Yet, a new type of order coming from an aperiodic object (Mackay 1982). Mackay developed his ideas starting from the two-dimensional Penrose tiling (Penrose 1974). Penrose, Nobel prize in Physics in 2020, had identified a pair of tile shapes that can only fit together non-periodically, forming

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This paper belongs to the topical collection "Quasicrystals: State of the art and outlooks" originated from an international conference organized by the Accademia dei Lincei, held in Rome on November 18, 2022 in the frame of the 2022 International Year of Mineralogy.

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Fig. 1 Dan Shechtman (right) and one of the authors (GP) during an event organized by the Israelian Embassy in Rome, the Wolf Foundation, and the Accademia dei Lincei on June 7th, 2021, in the occasion of the 2021 Wolf Prize ceremony

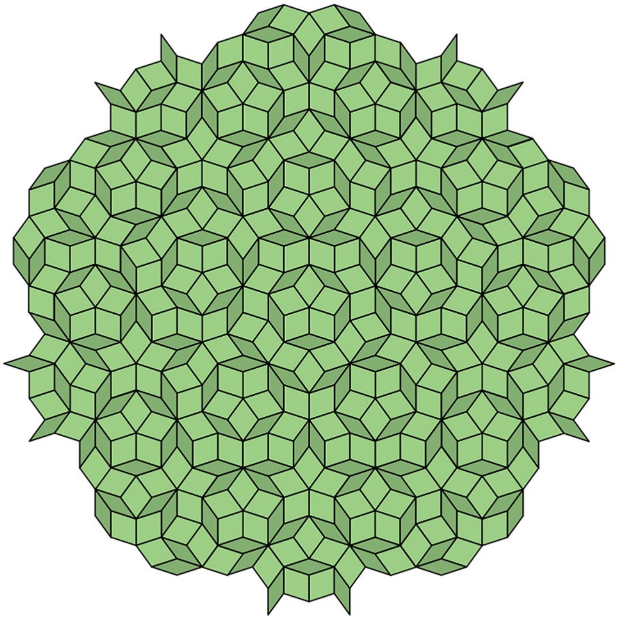

Fig. 2 Fragment of a two-dimensional Penrose tiling composed of two types of tiles (dark and light green) arranged with crystallographically forbidden five-fold symmetry

a self-similar pattern full of five-fold symmetric clusters of tiles (Fig. 3).

The same year of the Mackay's paper there was the Shechtman's discovery (Fig. 2b), but it took him two years to get it published because of the community disbelief. Almost in the same months of 1984 Dov Levine and Paul J. Steinhardt (Levine and Steinhardt 1984) hypothesized the existence of a novel type of material with theoretically impossible characteristics (Fig. 2c), and which they dubbed *quasicrystals*, short for "quasiperiodic crystals". Few years later, Tsai et al. (1987) discovered a new quasicrystal alloy ($Al_{63}Cu_{24}Fe_{13}$), which should perhaps be viewed as the first *bona fide* synthetic quasicrystal (Fig. 2d). Finally, twenty-five years later the Shechtman's discovery, Bindi et al. (2009) discovered this peculiar form of matter in nature. They called it *icosahedrite*, which represents the first natural quasicrystal (Steinhardt 2013; Bindi and Stanley 2020).

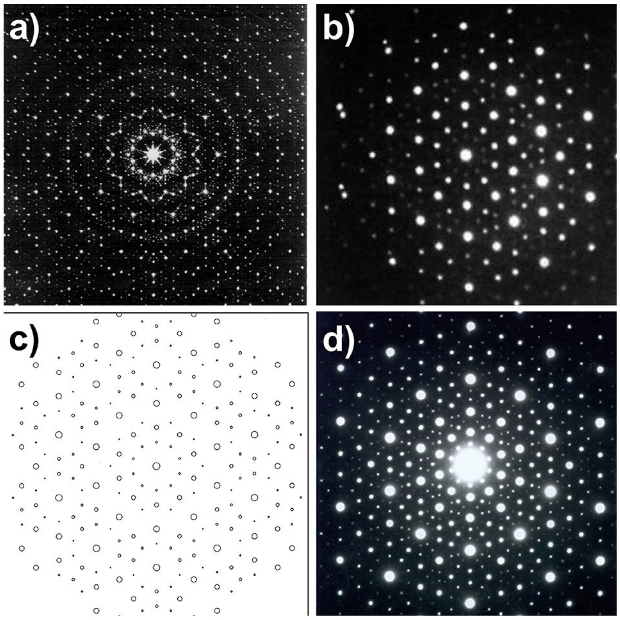

Fig. 3 Progress in the knowledge of diffraction patterns in icosahedral quasicrystals. **a** First theoretical pattern proposed by Mackay (1982); **b** experimental electron diffraction pattern reported by Shechtman et al. (1984) for a synthetic Al-Mn alloy; **c** theoretical pattern hypothesized by Levine and Steinhardt (1984); **d** experimental electron diffraction pattern reported by Tsai et al. (1987) for a synthetic Al-Cu-Fe alloy

A temporal succession of the main players in the history of quasicrystals is given in Fig. 4.

Quasicrystalline materials are nowadays quite common (Steurer and Deloudi 2008) and have numerous applications. A common application is the use of low-friction Al-Cu-Fe–Cr quasicrystals as a coating for frying pans. The quasicrystalline coating makes pans quite non-stick and easy to clean and makes the surface much harder than stainless steel. Quasicrystalline materials have been also employed to improve heat insulation, LEDs, diesel engines, and new materials that convert heat to electricity. The low heat conductivity of some quasicrystals makes them good for heat insulating coatings. Other uses include selective broad-wavelength reflectors, solar absorbers for power conversion, and bone repair and prostheses applications where biocompatibility, low friction and corrosion resistance are essential.

The topical issue on quasicrystals of the *Rendiconti Lincei* stems from an interdisciplinary conference resulting from mineralogical-crystallographic research, held at the Accademia dei Lincei in Rome on November 18, 2022,

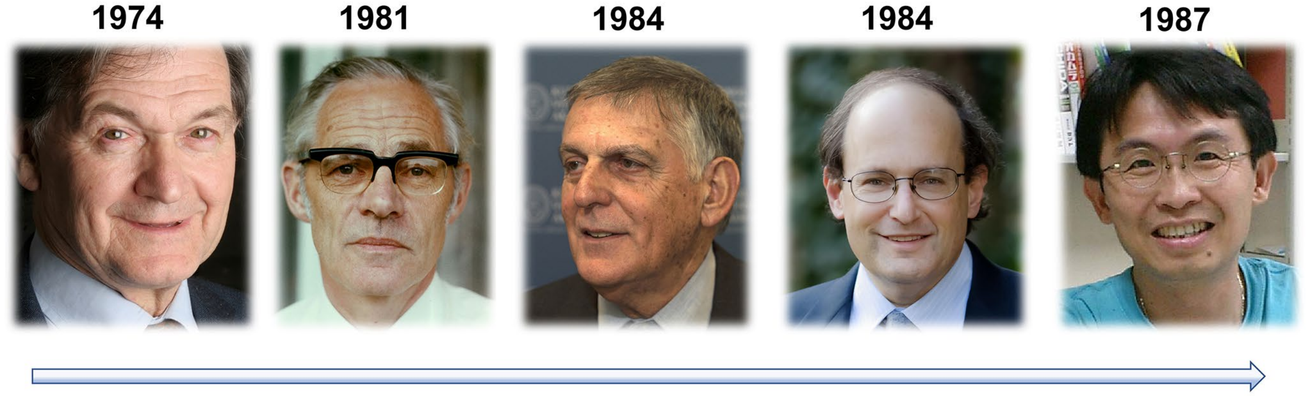

Fig. 4 Temporal succession (light blue arrow at the bottom indicating time) of the main protagonists of the history of quasicrystals. From left to right: Roger Penrose, Alan Mackay, Dan Shechtman, Paul J. Steinhardt, An-Pang Tsai

which was organized in the frame of the *2022 International Year of Mineralogy* with the aim at providing a discussion on the mathematics, geometry, structure, natural occurrence, applications and physical behavior of quasicrystals. The conference, with internationally renowned speakers, was attended by almost 80 participants, who contributed to making of this event an occasion to discuss the controversial issues and outlooks of quasicrystals while the ever-growing list of experiments continues to daily present new and challenging questions.

Sander Van Smaalen brought the audience in a crystallographic excursion in the superspace. Through many examples, he introduced in an elementary way the concept of aperiodic crystals, which includes incommensurately modulated structures, incommensurate composite crystals and quasicrystals.

Paul J. Steinhardt, starting from the definition of quasicrystal, went beyond this concept and showed that there is a multi-dimensional realm of heretofore unexplored structures to be investigated. This new world is characterized by "correlated disorder", a notion that combines aspects of crystals (and quasicrystals) and glass but corresponds to neither.

Marc De Boissieu delved into the physics of quasicrystals by explaining the concept of phonons, phasons and atomic dynamics in general in these materials. He also explained that in the framework of the hydrodynamic theory, long-wavelength phason modes are characteristic of quasicrystals and are diffusive modes.

Jean-Marie Dubois presented the potential and marketed applications of quasicrystals by discussing that properties change dramatically with lattice complexity and turn the behavior of crystalline materials into a far more complex behavior. He also reviewed the state of the art and addressed few technological breakthroughs that are based on quasicrystalline alloys in the areas of mechanical engineering, catalysis, and solid–solid adhesion.

Carlo Sbordone delved into the mathematics of quasicrystals retracing the history of the geometry of Penrose tessellations and discussed the unreasonable effectiveness of irrational numbers.

Emil Makovicky touched the fascinating, strict link between quasicrystals and art presenting wonderful examples of the quasiperiodic (octagonal and dodecagonal) ornamental patterns of western Islam in Spanish Andalusia and in Morocco (Makovicky 2017, 2021, 2023).

Diederik Wiersma introduced the concept of structured photonic materials and quasicrystals discussing disordered, bio-inspired and smart photonic materials, and how complex media interact with light, but also on how light can be used to manufacture new materials and design their functionalities.

Leonardo Fallani presented how quantum transport of matter waves works in quasiperiodic structures by studying the Anderson localization of a non-interacting Bose–Einstein condensate in a quasiperiodic crystal of light. The way this system can be used to investigate the role of interactions on transport and the connections with other topics of quantum physics where quasiperiodicity emerges were also examined.

Michael Widom introduced the complex world of atomic modeling of quasicrystal structures, including testing interatomic potentials of intermetallic alloys, ab initio total energy calculations utilizing density functional theory, and possible atomic configurations of decagonal quasicrystals generated by Monte Carlo simulations.

Luca Bindi retraced the magnificent and adventurous story culminating in the discovery of the first natural quasicrystal of extraterrestrial origin. The author accompanied the audience on a cosmic-scale excursion going from presolar materials, through nuclear tests debris to recently formed fulgurites.

Vincenzo Stagno reviewed the effect of pressure and temperature on the stability of quasicrystalline materials with examples of experiments going to conditions typically occurring in planetary interiors and making speculations on the possible presence of these phases in Earth's core.

The conference was a great occasion to discuss how these exotic materials have and have had strong implications for many disciplines, particularly materials science, chemistry, geochemistry, condensed matter physics, mineralogy, and crystallography. We now know that quasicrystals can survive for billions of years and may prove to be among the most ubiquitous minerals found in the Universe.

Research on quasicrystals has determined new scientific certainties, refined and redefined previous ones, and opened incredible developments for future progress. We also think that they are a wonderful example about how sometimes being too uncritical of conventional wisdom may hinder research and progress in understanding the marvels of this world and beyond.

Acknowledgements The Authors wish to thank Vincenzo Aquilanti, Editor in Chief of the journal, for the insightful suggestions that contribute to improve the quality of the manuscript. Thanks are also due to Marjorie Senechal for the reading of the manuscript.

Funding Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement.

Data availability All the topic mentioned or examined are publicly accessible.

Declarations

Conflict of interest The authors declare no competing interests.

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