ACCADEMIA NAZIONALE DEI LINCEI

Conference

QUASICRYSTALS: STATE OF THE ART AND OUTLOOKS

18 NOVEMBER 2022

A B S T R A C T

Organizing committee: Vincenzo AQUILANTI (Linceo, Università di Perugia), Luca BINDI (Coordinator, Linceo, Università degli Studi di Firenze), Giovanni FERRARIS (Linceo, Università di Torino), Massimo INGUSCIO (Linceo, Università Campus Biomedico di Roma), Stefano MERLINO (Linceo, Università di Pisa), Annibale MOTTANA (Linceo), Carlo SBORDONE (Linceo, Università degli Studi di Napoli "Federico II")

PROGRAMME

In the frame of the 2022 International Year of Mineralogy, we would like to propose a meeting on quasicrystals, materials which were discovered in nature about 15 years ago.
Solids are classified according to the order and rotational symmetry of their atomic arrangements. Glasses and amorphous solids have disordered arrangements with no exact rotational symmetry. Crystals have atomic structures with long range periodic order, that can be described by a single atom or atomic cluster that repeats at regular intervals. According to the well-known theorems of crystallography derived nearly two centuries ago, the rotational symmetries of crystals are highly restricted: two-, three-, four- and six-fold symmetry axes are allowed, but five-, seven- and all higher-fold symmetry axes are forbidden. Quasicrystals, short for quasiperiodic crystals, have a more subtle kind of long-range order. In a quasiperiodic structure, the atomic positions along each symmetry axis are described by a sum of two or more periodic functions whose wavelengths have an irrational ratio (inexpressible as a ratio of integers). This difference exempts quasicrystals from the crystallographic restrictions: they can exhibit all the rotational symmetries forbidden to crystals, including five-fold symmetry. The meeting will provide an excellent opportunity to present and learn the latest results in the fields of quasicrystals, complex metallic alloys and related topics. The research is highly interdisciplinary, so that the topics include mathematics, physics, chemistry, metallurgy, materials science and geoscience.

Friday, 18 November

9.00 Giorgio PARISI (Presidente della Classe di Scienze Fisiche, Matematiche e Naturali): *Welcome and Opening remarks*

9.30 Sander VAN SMAALEN (Universität Bayreuth Germania): *Aperiodic crystals and their atomic structures in superspace: An introduction*

10.10 Paul STEINHARDT (Princeton University): *Quasicrystals and beyond*

10.40 Coffee break

11.00 Marc DE BOISSIEU (CNRS - Francia): *Physics of quasicrystals: phonons and phasons*

11.30 Jean-Marie DUBOIS (Institut Jean Lamour - Francia): *Potential and marketed applications of quasicrystals*

12.00 Carlo SBORDONE (Linceo, Università degli Studi di Napoli "Federico II"): *Mathematical aspects of quasicrystals*

12.30 Discussion

12.45 Break

14.00 Emil MAKOVICKY (University of Copenhagen - Danimarca): *Quasicrystals and Art: interesting new facts*

14.30 Diederik WIERSMA (Presidente dell'istituto Nazionale di Ricerca Metrologica): *Structured photonic materials and quasicrystals*

15.00 Leonardo FALLANI (Università degli Studi di Firenze): *Quantum transport of matter waves in quasiperiodic crystals of light*

15.30 Michael WIDOM (Carnegie Mellon University - Pittsburgh, PA): *Atomistic simulation of quasicrystals*

16.00 Coffee break

16.20 Luca BINDI (Linceo, Università degli Studi di Firenze): *Natural quasicrystals and beyond*

16.50 Vincenzo STAGNO (Sapienza Università di Roma): *Quasicrystals at high pressure and high temperature*

17.20 Discussion, final remarks and outlooks

MINERALOGY 2022

Anno Internazionale della Mineralogia

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https://www.lincei.it/it/manifestazioni/quasicrystals-state-art-and-outlooks-conference

Nel rispetto delle limitazioni imposte per l'emergenza Covid-19, il numero dei posti in sala sarà limitato (vedi: https://www.lincei.it/it/news/misure-fronteggiare-lemergenza-epidemiologica).
Si prega di segnalare la presenza alla segreteria del convegno
Fino alle ore 10 è possibile l'accesso anche da Lungotevere della Farnesina, 10
I lavori potranno essere seguiti dal pubblico anche in streaming

Aperiodic crystals and their atomic structures in superspace: An introduction

Sander VAN SMAALEN (Universität Bayreuth Germania)

For many years, the crystalline state of matter has been considered to be a solid with a periodic arrangement of its atoms. This idea has emerged from the great successes of crystallography in the nineteenth century, with the development of Bravais lattices and space groups and culminating in the ultimate "proof" of periodicity: the first x-ray diffraction experiment by von Laue and coworkers in 1912. Indeed, many materials possess periodic crystal structures. Periodicity can explain the anisotropy of properties of crystalline materials, the faceting of mineral crystals and Bragg reflections in the x-ray diffraction of these materials. During the twentieth century it was slowly realized that long-range order of the atomic structures is the key for explaining crystalline properties of materials. Long-range order can be achieved in ways different from periodic arrangements of the atoms. These so-called aperiodic crystals comprise incommensurately modulated structures, incommensurate composite crystals and quasicrystals. The atomic positions are obtained according to "recipes" involving four to six periodicities hidden in the crystal structures. The crystallography of aperiodic crystals started during the 1970s with the development of the superspace theory by Pim de Wolff, Aloysio Janner & Ted Janssen, culminating in a publication in 1981 about the symmetry of four-dimensional incommensurately modulated crystals. Soon afterwards, in 1982, quasicrystals were discovered by Dan Shechtman. Here I will present the principal structural features of aperiodic crystals and I will introduce the superspace concept. Uses of the superspace theory will be illustrated by visualisations of crystal structures through Fourier maps in superspace, and by crystal chemical analysis in superspace via t-plots of interatomic distances.

Quasicrystals and beyond

Paul STEINHARDT (Princeton University)

When the concept of quasicrystals was first introduced in the 1980s [1], the goal was to challenge the conventional view of what kinds of order solid matter can possess. According to that view, the atomic arrangement in matter exhibits either regular (periodic) translational order and an exact rotational symmetry belonging to one of the 14 Bravais lattices and 230 space groups – that is, a crystalline structure – or the atomic arrangement is randomly ordered and exhibits no exact rotational symmetries – as in amorphous or glassy structures. The discovery of quasicrystals [1,2] shattered this conventional view: they exhibit quasiperiodic translation order (an aperiodic pattern described by two or more repeating intervals whose ratio is irrational) and rotational symmetries that are forbidden to crystals (such as five-, eight-, and twelve-fold symmetries). Finding solids with unconventional types of order is profoundly important because these result in novel physical properties of both theoretical and practical interest.

But have all the possibilities been identified? Are there yet other kinds of order that matter can possess? In this talk, we will show 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. In this world, conventional translational order is generalized to disordered hyperuniformity [3} and conventional rotational symmetry is generalized to on-average bond orientational order [4[. Although each has been discussed individually, the merging of these two properties using concepts borrowed from the study of quasicrystals has only just begun to be studied [5]. The talk will introduce the basic principles and some illustrative examples.

{1] D. Levine and P.J.Steinhardt, Phys. Rev. Lett. 53, 2477 (1984).
[2] D. Shechtman, I. Blech, and D. Gratias, J. W. Cahn, Phys. Rev. Lett. 53, 1951 (1984).
[3] S. Torquato and F. H. Stillinger. Phys. Rev. E, 68:041113 (2003).
[4] P. J. Steinhardt, D. R. Nelson, and M. Ronchetti, Phys. Rev. Lett. 47, 1297 (1981).
[5] A. Zentner, P.J. Steinhardt and S. Torquato, in preparation.

Potential and marketed applications of quasicrystals

Jean-Marie DUBOIS (Institut Jean Lamour - Francia)

The discovery of quasicrystals by Shechtman et al. in 1982-84 has revolutionised our understanding of crystals and order in solids. Shechtman was awarded a Nobel Prize in Chemistry in 2011 to recognize the importance of this breakthrough. Soon after the initial publication [1], a patent was filed by the author to secure the potential application of these new materials to the fabrication of low-stick surfaces adapted to the industrial production of cooking utensils [2]. Quite a few more patents followed, covering several areas of technological relevance such as low friction, thermal insulation, solar light absorption, etc.
The first application failed, although it reached market. Few others never developed to this stage, but also a (very) small number can now be considered as commercially successful. This is especially the case of polymers reinforced with a quasicrystal powder that are especially adapted to additive manufacturing or 3D printing [3]. Also very advanced is the use of a blend of quasicrystalline and complex intermetallics powders to mark and authenticate an object in a way that cannot be counterfeit [4]. The talk will review the state of the art and address few technological breakthroughs that are based on quasicrystalline alloys in the areas of mechanical engineering, catalysis, and solid-solid adhesion.

[1] D. Shechtman et al., Phys. Rev. Lett. 53-20 (1984) 1951-54.
[2] J.M. Dubois and P. Weinland, French Patent n°2635117, dated 04 Aug. 1988.
[3] S. Kenzari et al., Sci. Technol. Adv. Mater. 15 (2014) 024802 (9pp).
[4] S. Kenzari and V. Fournée, European Patent EP 3 652 526 B1, dated 11 July 2018.

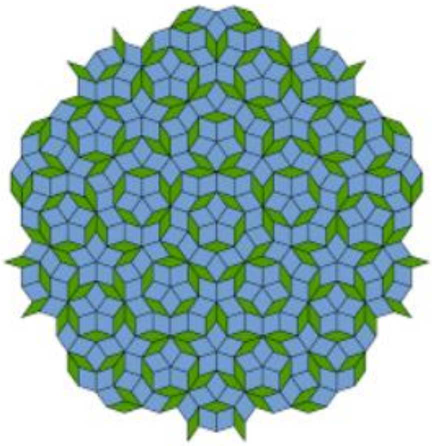
Mathematical aspects of quasicrystals

Carlo SBORDONE (Linceo, Università degli Studi di Napoli “Federico II”)

A two-dimensional model of quasicrystal is the Penrose tiling (1974): an aperiodic “disjoint” covering in the plane, generated by two rhombi R_{36° and R_{72° with the same side lenght.
Aperiodic means that these two shapes allow only non-periodic coverings of $\mathbb{R}^2$. (Shifting a tiling never gives consistent tiling).
Important : the area's quotient is irrational

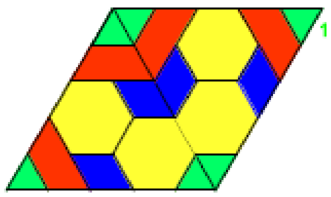
$$\alpha = \frac{area\ R_{72^\circ}}{area\ R_{36^\circ}} = \frac{1+\sqrt{5}}{2} \quad (golden\ ratio) \quad (\alpha^2 - \alpha - 1 = 0)$$

and local five-fold symmetry, forbidden to crystals, is revealed.

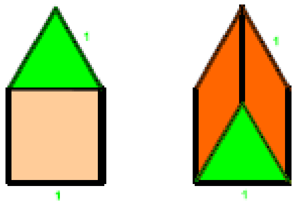


Penrose tiling

Fat and thin rhombi are coupled also in the following elementary situation where



a R_{60° rhombus (made without unit square and thin rhombus) can never be made in a different way, using unit squares and thin rhombi (which have rational area while areas of equilateral triangle, exhagones, trapezoid are rational multiples of $\sqrt{3}$).
(The unreasonable effectiveness of irrational numbers).



$$area\ R_{30°} = \frac{1}{2} area\ Q = \frac{1}{2}$$

Recent advance on "Wang tiles", that is square tiles that cover the plane but cannot do it in a periodic fashion, are due to Jeandel and Rao, giving a definitive answer to the problem raised by Hao Wang in 1961.

References

[1] L. Bindi, P. J. Steinhardt, N. Yao, and P. J. Lu, *Natural Quasicrystals*, Science, 5 June 2009 vol.324, pp. 1306–1309.

[2] E. Jeandel and M. Rao, *An aperiodic set of 11 Wang tiles*, Advances in Combinatorics, 2021, pp. 1–37.

Quasicrystals and Art: interesting new facts

Emil Makovicky (University of Copenhagen – Danimarca):

Quasiperiodic ornamental patterns represent only a small percentage when they are compared with the entire body of periodic patterns. Decagonal pattern is known from 12th century Iran and 14th century western Islam (Andalusia and Morocco), rich spectrum of octagonal patterns exists at the latter localities (14th century and later) and a sole example of a dodecagonal pattern comes from Morocco. Later copies exist in all these regions.
My most recent studies were concentrated upon the Andalusian and Moroccan regions, in which the 14th century (and later) wall mosaics occur as uninterrupted coatings of entire walls so that the individual motif panels have to be adjusted to secure continuity of their underlying bar-and-band structure. In Andalusia, the tetragonal structure of the panels and their complexes was locally adjusted to become octagonal quasiperiodic. The coloring accentuates the resulting symmetry but hides its derivation. Only two geometric types of such octagrids were derived in Andalusia, in agreement with rarity of quasiperiodic ornaments in general. In Morocco, before the panel substructure became heavily masked by overflow of rosettes of several sizes, the mosaic panel was built on octagonal quasiperiodic grid and ornamental rosettes were placed into it in form of concentric octagons. As a prominent example, the octagonal motif of the Nejjarine Fountain resembles the older mosaics from Meknes, what makes me believe that they are contemporaneous and the fountain was plastered over by ornamentation for which it is famous only at a later date.

Natural quasicrystals and beyond

Luca BINDI (Linceo, Università degli Studi di Firenze)

Until 2009, the only known quasicrystals were synthetic, having been formed exclusively in highly controlled laboratory experiments. Plausibly, the only quasicrystals in the Milky Way Galaxy or perhaps even in the Universe, are the ones manufactured by humans, or so it seemed. Then came the report that an icosahedral quasicrystal had been discovered inside a small rock fragment from a remote stream in far eastern Russia. Later studies proved the rock to be extraterrestrial, a piece of a rare CV3 carbonaceous chondrite meteorite (known as Khatyrka). At present, the only known examples of natural quasicrystals are from the Khatyrka meteorite. Does that mean that these exotic materials must be extremely rare in the Universe? During this talk, the author will accompany the audience on a cosmic-scale excursion going from presolar materials, through nuclear tests debris to recently formed fulgurites. Several reasons will be presented indicating that quasicrystals may prove to be among the most ubiquitous minerals found in the Universe. The author will also discuss how quasicrystals are an example of how sometimes being too uncritical of conventional wisdom may hinder research and progress in understanding the marvels of this world and beyond.