

A LONG-RANGING LOOK AT ORDER AND APERIODICITY

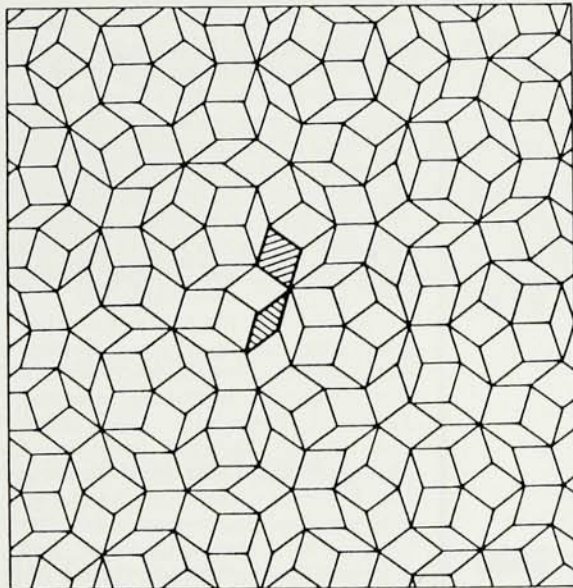
Introduction to Quasicrystals

Edited by Marko V. Jaric
Academic, San Diego, 1988.
285 pp. \$49.50 hc
ISBN 0-12-040601-1

Reviewed by David R. Nelson

When Paul Steinhardt and I began to study icosahedral order in undercooled liquids in 1981, we were astonished to find the icosahedral point group dismissed in the well-known group-theory text by Morton Hamermesh (1964 edition) as having "no physical interest." Hamermesh is in good company, for the classic quantum mechanics text by Lev D. Landau and Ilya M. Lifshitz (1965 edition) also insists that the icosahedral "groups are of no physical interest, since they do not occur in Nature." The prevalence of icosahedral atomic clusters in undercooled liquids had in fact been suggested by Charles Frank in 1952, and in 1958 Frank and John Kasper went on to explain why the icosahedron was an important and natural structural motif in complex intermetallic compounds. *Exact* icosahedral symmetries are, moreover, clearly possible in isolated molecules (for example, dodecahedrane) or in clusters of atoms in molecular beams.

The dogmatic views of most physicists on this subject arose because rigorous mathematical theorems appeared to forbid the appearance of icosahedral symmetry in large assemblies of atoms: A crystal with a single periodically repeating icosahedral unit cell is certainly impossible. It is impossible to tile the plane using only regular pentagons for similar reasons. These prejudices about *long-*



A Penrose tiling of the plane generated by the appropriate stacking of "fat" and "skinny" rhombuses. (Drawing from *Introduction to Quasicrystals*.)

range icosahedral order were shattered in 1984 when Dany Shechtman, Ilan Blech, Denis Gratias and John W. Cahn announced the discovery of a metastable alloy of aluminum and manganese with very sharp Bragg diffraction peaks arranged with a manifestly icosahedral symmetry. Almost immediately, Dov Levine and Steinhardt proposed that the experiments could be understood in terms of "quasiperiodic" arrangements of two distinct unit cells closely related to five-fold symmetric tilings of the plane invented by Roger Penrose in 1974. These results (to some extent anticipated in theoretical work by Alan MacKay and by Peter Kramer and R. Neri) led to an extraordinary fusion of physics and materials science, similar to what is now taking place in high-temperature superconductivity. Physicists learned to respect the careful work of materials scientists on complex materials, while materials scientists developed an appreciation of the sophisticated theoretical and experimental tools available to physicists.

The book *Introduction to Quasicrys-*

tals, edited by Marko V. Jaric, is a review of recent developments in this area by leaders in the field. The six theorists and five experimentalists assembled here provide an excellent introduction to the results up until 1988. For scientists and librarians who can afford the cost of approximately 17.5 cents per page, this book is well worth owning.

As the first two chapters make clear, the exciting results of Shechtman and coworkers did not emerge into a complete vacuum. David and Clara Shoemaker review the icosahedral coordination in the large-unit-cell metallic alloys we now know as Frank-Kasper phases. The Shoemakers played a key role in the elucidation of these structures, which began in the 1950s, and their article allows readers to benefit from their 35 years of research on this subject. Many quasicrystals (particularly the most stable ones) are closely related to Frank-Kasper phases.

Dense random packings of hard spheres, now a widely accepted model of metallic glasses and undercooled liquids, were shown to have many

David R. Nelson is a professor of physics at Harvard University. His research interests include the structure and statistical mechanics of metallic glasses, the physics of polymerized membranes and flux-line entanglement in high-temperature superconductors.

OPTICAL RAY TRACERS

for IBM PC, XT, AT,
& PS/2 computers

BEAM TWO \$89

- for students & educators
- traces coaxial systems
- lenses, mirrors, irises
- exact 3-D monochromatic trace
- 2-D on-screen layouts
- diagnostic ray plots
- least squares optimizer
- Monte Carlo ray generator

BEAM THREE \$289

- for advanced applications
- BEAM TWO functions, plus:
- 3-D optics placement
- tilts and decenters
- cylinders and torics
- polynomial surfaces
- 3-D layout views
- glass tables

BEAM FOUR \$889

- for professional applications
- BEAM THREE functions, plus
- full CAD support: DXF, HPG, PCX, and PS files
- twelve graphics drivers
- PSF, LSF, and MTF
- wavefront display too
- powerful scrolling editor

EVERY PACKAGE INCLUDES
8087 & NON8087 VERSIONS,
MANUAL, AND SAMPLE FILES

WRITE, PHONE, OR FAX US
FOR FURTHER INFORMATION



STELLAR SOFTWARE

P.O. BOX 10183
BERKELEY, CA 94709
PHONE (415) 845-8405
FAX (415) 845-2139

Circle number 31 on Reader Service Card

fragments of icosahedra (for example, Voronoi cells with five-fold faces) by John D. Bernal in the early sixties. The first quasicrystals were made by the same melting-spinning process used to produce metallic glasses—the short-range icosahedral order in both materials may be related. A mean-field picture of dense random packing based on an idealized icosahedral crystal (consisting of atoms at the vertices of a four-dimensional Platonic solid called polytope {3,3,5}) was put forward by the mathematician H. S. M. Coxeter as early as 1958. Michael Widom presents an elegant review of the modern development of these ideas, which occurred in the early 1980s. He shows, in particular, how the Frank-Kasper phases, metallic glasses and quasicrystals arise naturally from alternative methods of flattening polytope {3,3,5} by the introduction of wedge disclinations. Widom's article (which also discusses icosahedral order in atomic clusters) is very clear, and I recommend it particularly to experimentalists.

The metallurgical *tour de force* that arose after the discovery of Shechtman and coworkers is described in a nice article by Robert J. Schaefer and Leonid A. Bendersky. These scientists at the National Institute of Standards and Technology (formerly the National Bureau of Standards) describe key discoveries about the composition, thermodynamics and microstructure of quasicrystals. Although the article is excellent, the authors, in my view, overemphasize the differences between metallic glasses and quasicrystals. Their point that metallic glasses usually form at eutectic points, away from the compositions of most quasicrystals, is a parochial one, based on cooling rates currently obtainable in the laboratory. There is now excellent evidence that liquid mixtures at compositions conducive to formation of Frank-Kasper phases and quasicrystals form perfectly good metallic glasses when cooled at the very rapid rates available in computer simulations. The resulting glass has many icosahedral fragments—only the *range* of icosahedral order differs from the nearby crystalline phases. The presence of icosahedral fragments in the melt would account for the astonishingly high quasicrystal nucleation rates described in this article. Such nucleation would not be expected near a eutectic point, where compositional frustration inhibits icosahedral crystals, but not necessarily short-range icosahedral order in the melt.

If one sets aside the microscopic origins of quasicrystals, a useful phe-

nomenological understanding can be obtained through Landau theory and ideas borrowed from the theory of conventional incommensurate crystals. This phenomenological approach is the subject of the remaining three articles. Per Bak and Alan Goldman show that many basic features of "quasicrystallography" can be understood by postulating large Fourier components of the density at a "star" of reciprocal lattice vectors pointing to, say, the vertices of an icosahedron. The incommensurability of these vectors leads to harmonics that are arbitrarily close together in reciprocal space. These authors show that a natural indexing scheme for reciprocal lattice peaks arises by viewing this star as the projection of a regular six-dimensional cubic lattice into the three-dimensional physical space.

The energy of a quasicrystal relative to a nearby liquid state can, in principle, be expanded in the Fourier components discussed above. The resulting Landau theory approach to quasicrystals is discussed in the article by Ofer Biham, David Mukamel, and Shmul Shtrikman. Although minimizing various truncations of the Landau expansion has provided an endless source of amusement for theorists, there are as yet few practical results of this program. This is because, like most three-dimensional solids, quasicrystals are separated from the liquid by a sizable first-order transition. Hundreds of terms in the expansion must be kept to obtain reliable results. Nevertheless, Biham, Mukamel and Shtrikman show that the Landau approach provides important information about the symmetry of quasicrystalline phases. Particularly interesting is their analysis of symmetry-breaking deformations out of the quasicrystalline state.

In the final chapter, Tom Lubensky gives a very thorough and readable account of the elasticity and hydrodynamics of quasicrystals, a subject which is also discussed in the article by Bak and Goldman. The incommensurability of the icosahedral crystals leads in principle to "phason" as well as phonon low-energy excitations. The phasons appear to be pinned and have no known dynamical consequences. They can be used to model distortions in diffraction patterns, however, which are then attributed to "phason strain." As Lubensky points out, phason elasticity theory is still poorly understood, and some authors have questioned the validity of a hydrodynamic expansion. Dislocations can be defined in both the phonon and phason vari-

ables; It is unclear if these defects have dynamical consequences, such as the plastic flow mediated by dislocations in small unit cell conventional crystals. Quasicrystals are usually quite brittle, suggesting that these defects are immobile.

In part because most of these articles were written in 1987, there are some important omissions. I would have liked to see a discussion of the efforts of Veit Elser, Christopher Henley and others to model the microscopic structure of quasicrystals. There are important new ideas about the entropic stabilization of quasicrystals, due to the many nearly degenerate rearrangements of the two Penrose building blocks. We are beginning to learn how quasicrystals grow. Experimentalists have now discovered Al_6CuLi_3 , $\text{Ga}_{21}\text{Mg}_{38}\text{Zn}_{41}$, and $\text{Cu}_{20}\text{Al}_{65}\text{Fe}_{15}$, which form stable quasicrystalline phases from which it is possible to grow large single crystals.

This book inaugurates a series of volumes on the general subject of "Aperiodicity and Order." A future book on the mathematics of quasicrystals is already underway. High-quality reviews, similar to those in this book, on the topics mentioned above in a subsequent volume would be most welcome.

Atomic Nuclei and Their Particles

E. J. Burge

Clarendon (Oxford U.P.),
New York, 1988. Second
edition. 208 pp.

\$42.50 hc ISBN 0-19-851872-2;

\$19.95 pb ISBN 0-19-851856-0

Atomic Nuclei and Their Particles by E. J. Burge, professor emeritus of the University of London, is a brief introduction to nuclear and particle physics. Burge emphasizes the historical development of the subject, beginning with the discovery of radioactivity and concluding with electroweak unification and even, briefly, string theory. Two chapters deal with accelerators and particle detectors. Early material, including Rutherford scattering, is developed in fair detail. Burge devotes less space to events of more recent decades, such as models of the nucleus and particle resonances. The most recent developments, including heavy-quark phenomena, are treated superficially.

There is need for text material that provides an accurate overview of 20th-century physics for both undergraduate majors and those who study physics for only a year or two. Burge's text, part of the Oxford Phys-

UNIVERSITY OF
ROCHESTER

Summer Course Series 1990 The Institute of Optics

University of Rochester
June 18-29

I. Contemporary Optics

June 18-29

Tuition fee: \$1,600

II. Nonlinear Optics

June 18-22

Tuition fee: \$950

III. Thin Films

June 25-29

Tuition fee: \$950

Enrollment forms or inquiries about enrollment should be addressed to:

Jule Reiter

The Institute of Optics
University of Rochester
Rochester, New York 14627
(716) 275-4800

For information and reservation packets for accommodations and meals, write or call:

University Conference and Events Office
Box 34 Administration Building
University of Rochester
Rochester, New York 14627
(716) 275-8370

The University of Rochester provides equal opportunity in admissions and student aid regardless of sex, age, race, color, creed, handicap, sexual orientation, and national or ethnic origin. Further, the University complies with all applicable nondiscrimination laws.