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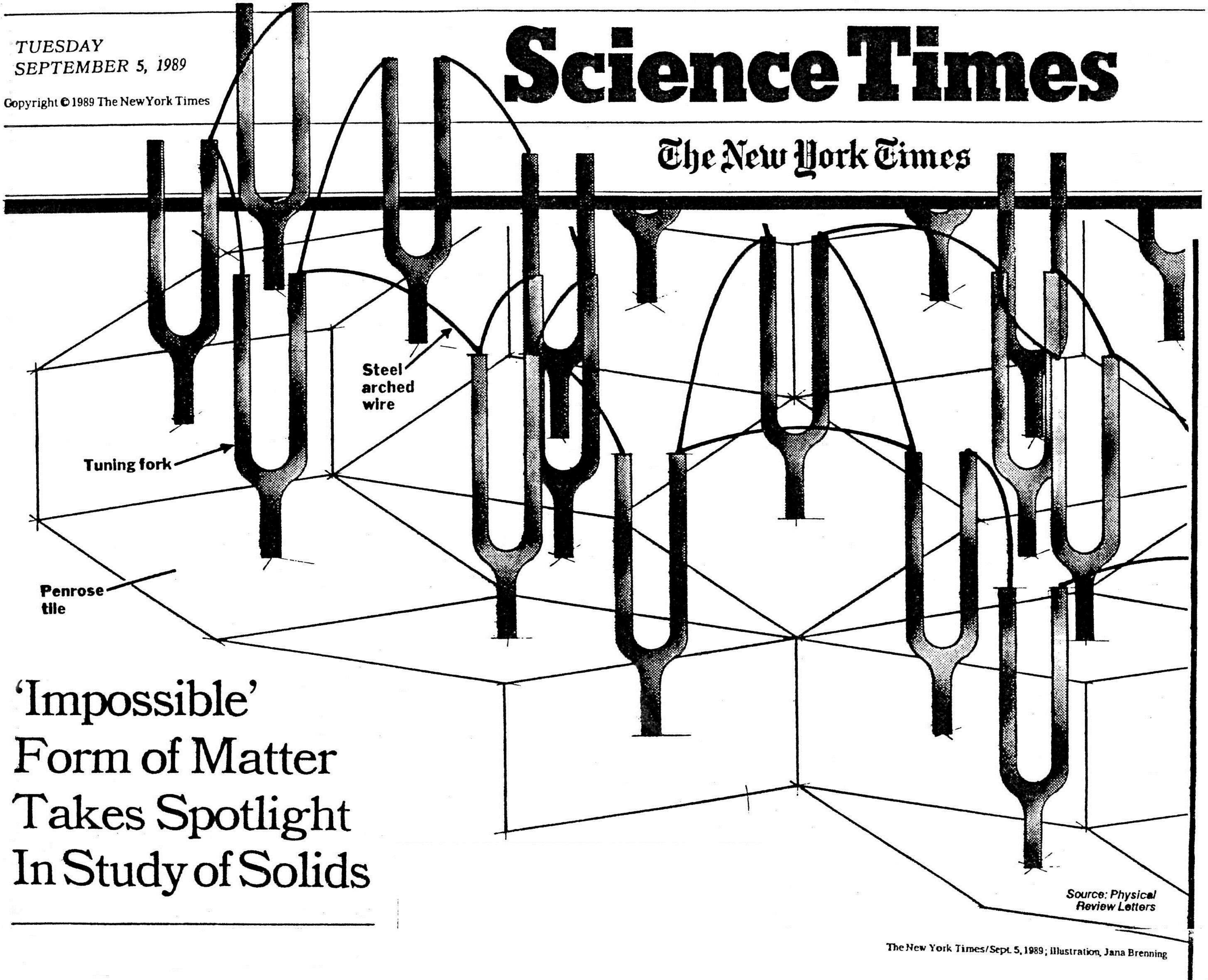
'Impossible' Form of Matter Takes Spotlight In Study of Solids

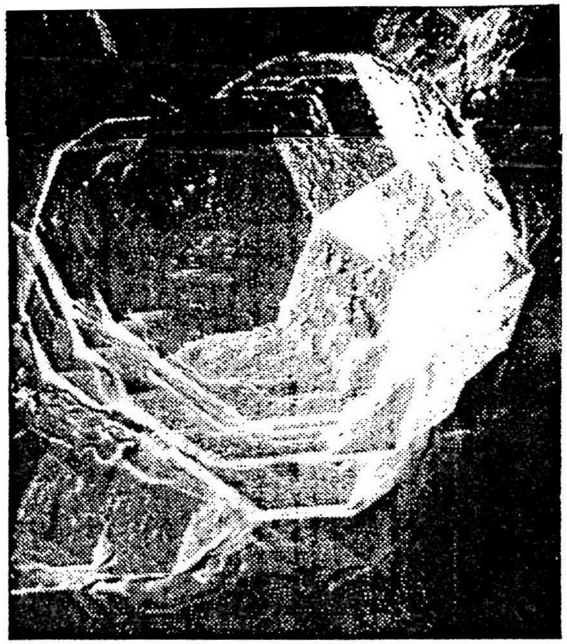


Source: Physical Review Letters

The New York Times/Sept. 5, 1989; Illustration, Jana Brenning

Theorists seek clues to nature of quasicrystals, curious alloys that may find special uses.

By MALCOLM W. BROWNE



Pechiney Research Center, France

This microscopic view of one unit of a quasicrystalline alloy shows crystal faces shaped like the rhombuses mathematicians had expected to find.

QUASICRYSTALS, a puzzling form of solid matter regarded as impossible until five years ago, have now moved to center stage in a worldwide investigation into the nature of solid matter.

Theorists and experimenters meeting at an international quasicrystal conference in Greece this week will seek to interpret some remarkable recent discoveries, including a new family of quasicrystalline metal alloys that are the most perfect quasicrystals yet developed. Scientists believe some of these new materials will have peculiar properties likely to find uses in electronics and other technologies. Quasicrystals, for example, might permit special-purpose computer components to respond to magnetic fields in ways not possible with conventional semiconductors.

"This is a great intellectual adventure for physicists and mathematicians," said David R. Nelson, a Harvard University theorist. "Quasicrystals are a delightful new toy for us, and part of the fascination stems from the fact that quasicrystals can evidently assume an infinite number of types."

Quasicrystalline matter is a category intermediate between the two types of solids traditionally recognized by physicists: the crystals and the glasses. Quasicrystal is a shortened form of the more technical term quasi-periodic crystals.

According to classical theory, which until 1984 had remained unchallenged for nearly two centuries, all solids were believed to consist either of crystals or glass. Crystals are three-dimensional frameworks of atoms bound together by electrons in such a way that the same patterns of atoms are identically repeated throughout an entire crystal.

Typical crystals are those of table salt, in which sodium and chlorine atoms alternate in a perfectly regular cubic lattice, a kind of three-dimensional chessboard, with one atom at each corner of every square. In the solids known as glasses, which include special forms of metal and other minerals as well as common window glass, there is no ordered structure; atoms are jumbled together in chaotic disorder.

By contrast with true crystals and glasses, quasicrystals contain atoms in ordered arrays, but the patterns they assume are subtle and do not recur at precisely regular intervals. Crystallographers were astonished to discover that quasicrystals exhibit a quality called "fivefold symmetry." This means that if a quasicrystal is rotated in an X-ray beam, symmetrical X-ray scattering patterns recur five times with each complete rotation. This had been considered impossible.

To create a solid exhibiting fivefold symmetry is equivalent to using five-sided tiles — regular pentagons — to cover a floor. Unlike rectangles, triangles and hexagons, regular pentagons cannot be fitted together to cover a floor without leaving gaps. By analogy, it was believed, a perfectly filled crystal could never be made using icosahedral (20-sided) clusters of atoms exhibiting fivefold symmetry.

But in 1984, theorists and experimenters, working independently, exploded this assumption.

At the National Bureau of Standards, now the National Institute of Standards and Technology, in Gaithersburg, Md., Dr. Dany Schechtman, a visiting Israeli scientist, stunned colleagues when he discovered that an alloy of aluminum and manganese exhibited the supposedly impossible fivefold symmetry.

At almost the same time, Paul J. Steinhardt, a theorist at the University of Pennsylvania, and his collaborators, discovered a scheme by which just such a crystal might be assembled. The plan was based on the mathematics of "tiling," the fitting together of regular geometric forms to cover a surface.

Since then, both theoretical and experimental research have put quasicrystals on a solid scientific foot-

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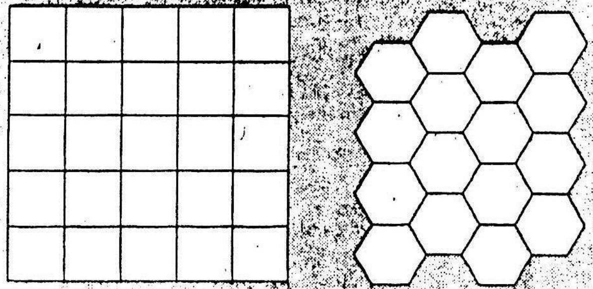
Using Acoustics to Measure Electronic Properties

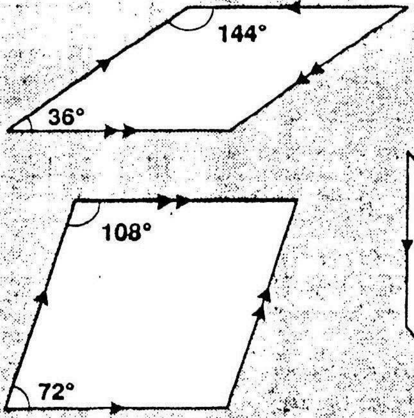
To penetrate the mysteries of quasicrystals, scientists inscribed an aluminum plate with a pattern of rhombuses analogous to the arrays of atoms in a quasicrystal. They mounted a tuning fork in the center of each rhombus and welded steel wires connecting each tine of each fork to two neighboring tines, linking the whole network. An oscillating electromagnet forced one of the tuning-fork tines to vibrate, causing resonance throughout the system. The resonance changed as the frequency of the electromagnet changed. The resulting spectrum of sound and silence might prove useful in predicting the electronic characteristics of real quasicrystals.

‘Impossible’ Matter Takes Spotlight

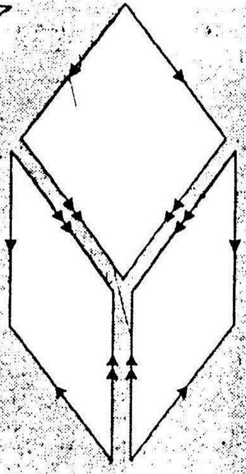
The Building Blocks of Normal Crystals and Quasicrystals

In conventional crystals, atoms are arranged in regular, repetitive patterns analogous to those formed by tiles covering a floor. Rectangular or hexagonal tiles, like those at the right, can easily form regular patterns leaving no gaps. In quasicrystals, however, groups of atoms form patterns that never exactly repeat themselves.

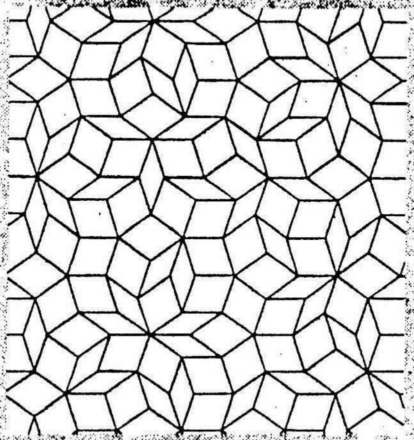




The mathematician Roger Penrose discovered two rhombuses, shown above, that can be laid out by special rules to “tile” any surface completely, with no repeating patterns.



Penrose tiles must be laid with matching edges, marked above with single or double arrows. Real quasicrystal edges may not match perfectly.



A typical Penrose tiling pattern, above, made up of two basic rhombuses. Although similarities are visible, patterns never exactly repeat. Quasicrystals are believed to embody similar arrays of atoms.

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ing. The first quasicrystalline alloy discovered by Dr. Schechtman, which was named "schechtmanite" in his honor, proved to be only the first such alloy in a long series.

Mixtures of aluminum with copper, iron, lithium and ruthenium have produced quasicrystalline alloys with even more interesting properties than schechtmanite. A gallium-based group of quasicrystalline alloys containing magnesium and zinc that exhibit particularly striking quasicrystalline characteristics is under study at Harvard.

According to David P. Vincenzo, a physicist at I.B.M., an aluminum-copper-iron alloy with the formula $Al_{65}Cu_{20}Fe_{15}$ recently discovered at I.B.M. by Peter A. Bancel appears to be a "perfect" quasicrystal — that is, its atomic irregularities, if any, cannot be detected by standard X-ray techniques.

One study involved electric guitar pickups, tuning forks and the golden mean.

The first quasicrystalline alloy was created by chilling a molten mixture of aluminum and manganese very rapidly. But it has since been found that much better quasicrystals can be made by cooling molten mixtures extremely slowly, thereby giving their constituent atoms time to find appropriate positions in the lattice structure.

Theorists speculate that because of the patterns of electron bonds holding them together, some quasicrystals may become superconductors at very low temperatures. Their lattice structures, expected to be more rigid than those of ordinary crysals, make it probable that many quasicrystals will prove to be harder than steel, and potentially useful for making superhard tools. But for the present, scientists are mainly concerned with understanding the electronic characteristics that may result from quasiperiodic arrays of atoms.

The mathematical tiling theory underlying the latest research in quasi crystals developed rapidly in the 1970's because of the work of Roger Penrose, a renowned mathematician at Oxford University in England. Dr. Penrose showed that by laying two types of rhombus-shaped tiles according to certain rules, a floor could be completely covered, leaving no gaps or overlapping tiles, and creating patterns that never exactly repeat themselves. Such patterns are called quasi-periodic.

Physicists at Harvard University, the I.B.M. Thomas J. Watson Research Center at Yorktown Heights, N.Y., the University of Pennsylvania and other institutions have discovered various theoretical patterns by which nature may mimic Penrose tiling schemes in real crystals.

The "tiles" (or geometric units) discovered by Dr. Penrose are of two types, "skinny" and "fat" rhombuses, which are used in combination to form patterns. All four sides of both types have identical lengths, but the corners form different angles; the corner angles within a fat rhombus must be 72 degrees and 108 degrees, while those of a skinny rhombus are 36 and 144 degrees. The sides of the two types of rhombus may be joined only by certain rules.

Link to 'Golden Mean'

Penrose tiling has another characteristic that fascinates mathematicians and architects: it exhibits a feature known to the ancient Greeks as the "golden mean," a ratio that has been used in paintings, sculpture and architecture through the ages.

The golden mean governs the proportions of the Parthenon and many other classical buildings. The ratio, as applied to artistic shapes and structures, is roughly equal to the ratio of lengths of the human body as divided at the navel, and is regarded as particularly pleasing to the eye. Scientists recently discovered that the golden mean also describes important characteristics of quasicrystals.

The golden mean can be approximated by dividing a straight line into two parts, one larger than the other. The ratio of the shorter part to the longer part must exactly equal the ratio of the longer part to the entire line, and in both cases, this ratio is approximately 1 to 1.618034..., an "irrational number" whose decimals extend to infinite length without repeating.

One property of a mathematical Penrose tiling scheme is that it incorporates fat and skinny rhombuses in exactly the ratio expressed by the golden mean. Scientists have discovered that this mathematical relationship probably has profound effects on the properties of real quasicrystals.

Julian D. Maynard of Pennsylvania State University and his graduate student, Shanjin He, recently succeeded in simulating the electronic properties of quasicrystals using an array of 150 musical tuning forks.

Tuning-Fork Experiment

The scientists, whose achievement was recently reported in the journal Physical Review Letters, first built a base, made of aluminum, and inscribed on it a typical Penrose tiling pattern of "fat" and "skinny" rhombuses. At the center of each rhombus they mounted a tuning fork with a frequency (440 hertz) corresponding to the note A above Middle C. Steel wire was then welded to the tuning forks in such a way that each tine was linked to two tines of neighboring tuning forks. This acoustically linked all the tuning forks in the system.

The investigators then placed an electromagnet next to one tine to set the tine vibrating at a succession of different frequencies. Electric guitar pickups were positioned randomly next to four other tines in the array, to sense the intensity and pitch of the sounds the tines emitted. The apparatus was thus able to measure the acoustical resonances and interactions of the entire tuning fork system, in much the same way that electronic sensors would measure the electronic resonances of a quasicrystal.

Dr. Maynard found that certain frequencies created by the electromagnet resulted in collective resonances in all the tuning forks, while other frequencies produced no resonances. By plotting a graph of these resonances over a wide range of frequencies, he found that the width of gaps between resonating frequencies occurred in ratios exactly corresponding to the golden mean.

"The effect we saw was acoustical," he said, "but it is analagous to the spectral structures you would see for electrons in quasicrystals. Our technique may have potential in predicting electronic characteristics of yet-to-be-created quasicrystals that might be useful as electronic components."

Some theorists believe such properties may exhibit "fractal" behavior, in which basic patterns are infinitely repeated at all scales, from the infinitely small to the infinitely large. For example, Dr. DiVincenzo of I.B.M. said in an interview, the resistance of a quasicrystal to an electrical current might change in fractal steps when the crystal is exposed to a magnetic field of changing intensity.

"The truth is," Dr. DiVincenzo said, "we're not sure what we'll find as we go along, and the prospect of encountering surprises is what makes quasicrystals so attractive these days."