Condensed matter physics

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Triple jump forward

This month, we publish three articles reporting breakthroughs in different areas of quasicrystal research.

The year 1984 will, for many, ring a literary bell. But crystallographers will associate the year with the first report of quasicrystals, initiating a complete rethink of the very concept of a crystal. The landmark publication, by Daniel Shechtman and colleagues[1], presented electron diffraction patterns of a rapidly cooled aluminium alloy displaying 10-fold rotational symmetry — incompatible with 3D translational periodicity. This aperiodicity was explained soon after by Dov Levine and Paul Steinhardt[2], who also coined the term 'quasicrystal', as similar to that seen in 2D aperiodic tilings. The rest, it is tempting to say, is history. But what sort of history?

Quasicrystals are certainly actively researched today. Nevertheless, looking, for example, at the topics we publish in *Nature Physics*, they are much less present than other condensed matter areas, such as superconductors or 2D materials. Regarding the latter, the early days of graphene research bear similarities to the emergence of quasicrystals 20 years earlier. Graphene also called for a reassessment of our thinking about condensed matter — stand-alone 2D materials were seen as hypothetical constructs at the time —and caused puzzlement: didn't the Mermin–Wagner theorem prevent single atomic layers from being thermodynamically stable? Yet, 2D materials took the world by storm, and research output on the topic became vast.

Several factors have contributed to the quick and enduring success of graphene[3]. It can be easily mechanically exfoliated (adhesive tape!), it can be characterized by means of optical microscopy, and it is stable. Importantly, it also has remarkable physical properties, many of which were appreciated early on. Compelling physics and interesting properties always stimulate further research as well as explorations of applications — and, of course, research funding.

Quasicrystals, in contrast, have not enjoyed such a prosperous ride. In fact, in many ways, quasicrystals are tough: their synthesis is non-trivial, describing and characterizing them is complicated, their physical properties may be hard to lay hold of, and applications are relatively scarce. But now, in this issue of *Nature Physics*, three papers[4–6] report results that we believe signify important milestones in quasicrystal research.

Yan Gao and collaborators[4] address the problematic availability of samples. Natural specimens are rare; lab-made quasicrystals are the way to go. (Though the story behind the discovery of icosahedrite, the first known quasicrystal to occur in nature, makes for fascinating reading[7].) Despite computational prediction efforts, only several hundred synthetic quasicrystals have been reported so far, mostly metal alloys. The bottleneck is that candidate structures often turn out to be metastable, competing in the energy landscape with stable crystalline states.

Colloids offer a way forward here. Indeed, over the past decades, experiments with colloidal particles have provided many insights into various aspects of crystallization, including quasicrystallinity. Several tens of colloidal quasicrystals have been realized to date, offering platforms for studying quasicrystal growth and stability. Gao and colleagues were able to drive a system of colloids from a hexagonal crystalline state into a stable dodecagonal quasicrystalline state and back by means of coupled electric and magnetic fields. As Martin Dulle writes in the accompanying News & Views[8], the reported level of control is unprecedented, as is the fact that the authors' colloidal system has just one type of particle.

Another difficulty is how to deal with quasicrystals computationally. The absence of 3D periodicity makes it impossible to use theoretical approaches relying on the concept of a unit cell. A case in point is density functional theory, a method routinely used for computing a system's lowest-energy state. The question of whether a quasicrystalline structure corresponds to such a thermodynamic ground state or not is highly pertinent but cannot be answered by means of conventional density functional theory.

This issue has now been overcome by Woohyeon Baek and colleagues[5]. They considered clusters of increasing size of icosahedral alloys and performed density functional theory calculations for the clusters placed in vacuum. The clusters' structures were based on experimental data of two known quasicrystalline binary metal alloys. By extrapolating the numerically obtained formation energies and comparing them with candidate crystalline structures, they confirmed the ground-state character of the quasicrystals. In a News & Views[9] discussing these findings, Peter Brommer is hopeful that the computational proof of the thermodynamic stability of known quasicrystalline phases will lead to improved quasicrystal synthesis and, ultimately, to more applications.

Finally, Ryuji Tamura and colleagues touch on structure–property relationships in quasicrystals[6]. They demonstrated the existence of long-range antiferromagnetic order in a ternary-metal icosahedral quasicrystal using neutron diffraction. The result follows earlier discoveries of ferromagnetic order in quasicrystals, which is less surprising as 3D translational invariance is not a requirement for ferromagnetism. An interesting conclusion is that the observed antiferromagnetic order is the first instance of a quasiperiodic order parameter different from the nuclear sites (or the electron densities) within a quasicrystal — an intriguing starting point for further studies.

It is nice to witness steps forward like these, and we hope that they will be embraced far beyond the quasicrystal community.

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