

# "Experimental measurement of the photonic properties of icosahedral quasicrystals"

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## 1. *What are the most important/significant/exciting results?*

There are two real breakthroughs in this work.

a) **Scientifically**, we have made the first measurements of the photonic properties of a three-dimensional icosahedral 'photonic quasicrystal' – both its gap structure and effective Brillouin zone. The quasicrystal itself is a physical structure synthesized from two or more different materials that are quasiperiodically distributed with an icosahedral symmetry that is impossible for ordinary crystals. The gap structure and Brillouin characterize the frequencies and directions for which incoming light is trapped by the structure. These properties are important, not only because of their use in photonics, but also because they are closely related to the electronic properties of quasicrystalline solids, a subject of considerable debate and speculation since the solids were first discovered in the 1980s. Electrical conductivity, optical properties, maybe even hardness and stickiness depend on the bands, gaps and their arrangement. The lack of periodicity combined with the unconventional symmetry limited the ability to compute these properties by hand or by computer..

Our experiment effectively gives the answer through direct empirical measurement. We find that the trapped scattering directions lie along planes that enclose an almost spherically shaped polyhedron, a thirty faced, triacontahedron, which forms the effective Brillouin zone. The triacontahedron, with the same symmetries as an icosahedron, has the highest symmetry in three dimensions and implies that the gaps can be found for fixed wavevector in almost every direction.

b) **Technologically**, these scientific results mean that the icosahedral quasicrystal is the foremost candidate structure for making a complete photonic bandgap and hence trapping light. Consider a structure which completely reflects or diffracts a particular color of light independent of the incident direction. If the light were placed inside a material with that structure it could never get out. The search for such a structure, with a gap forbidding the passage of light in all directions, has fascinated physicist and engineers for the past two decades. Trapped light is controlled light, and controlled light can be directed, switched, processed like electrons in an electronic circuit. Such photonic devices have many applications in research, computation and communication. Our discovery that there are few sizable gaps in quasicrystals, that the positions of the gaps can be understood and controlled and that the gaps structure is almost spherically symmetric (much more so than competing crystalline structures) makes them the most desirable for photonics.

## 2. *What experimental/theoretical advances made this possible?*

## 3. *Can you simply describe how you obtained your results?*

What broke the Gordian Knot was the idea of experimentally determining the photonic structure rather than waiting for a numerical calculation. The real space coordinates for icosahedral quasicrystals are known. Instead of making an atomic scale model and probing it with electrons, or a micron scale model and using visible light ( probably the ultimate goal), we built a cm scale

model and used microwaves. Fortunately, the same physics operates on all (these) length scales. A commercial stereolithography machine was used to “write” the designed structure by photopolymerization and the facilities of the Princeton Physics Cosmic Microwave Background group were used to measure transmission as a function of wavelength and orientation.

A further novel feature was in the analysis/presentation of the data where we found a novel way of visualizing the three-dimensional gap structure (Brillouin zone) which shows unambiguously that the gaps lie along the flat faces of the rhombic triacontahedron (a famous geometrical shape corresponding to the projection of a six-dimensional cube on three dimensions).

4. *What implications do you foresee as a result of this work?*

Our results point to a new direction for photonics – the utilization of quasicrystals of various symmetries for technological applications – and new directions in the scientific study of quasicrystals – the use of direct photonic measurements alongside computation as a method of exploring their electronic properties.

5. *What are the next stages in your investigations?*

Our research is already proceeding along three important directions: First, we are already exploring alternative techniques for constructing a miniature version of our photonic quasicrystals (using laser tweezers) whose bandgaps are at optical (visible) wavelengths. Working with Professor David Grier and his group at New York University, a sample with 250 spheres has already been assembled into a 3d icosahedral quasicrystal structure. We plan to continue to pursue this and other methods (such as two-photon polymerization).

Second, we are exploring how to optimize the design of the photonic quasicrystal. Our first investigations have used structures composed of rods, but a combination of rods, spheres and surfaces is probably optimal, based on analogous studies of photonic crystals. We are developing a computational algorithm to find the optimal configuration for photonic applications.

Third, we are exploring different types of photonic, electronic and even acoustic applications.

For illustrations and more information, see <http://www.physics.princeton.edu/~steinh/quasiphoton> or email Paul Steinhardt at [steinh@princeton.edu](mailto:steinh@princeton.edu)