Scientists Demonstrate Microscale System to Study Frustration in Buckled Monolayers of Microspheres

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(PhysOrg.com) -- A team of University of Pennsylvania physicists has demonstrated a simple system based on micron-sized spheres in water to study and control geometric frustration. Their research, published today in the journal *Nature*, elucidates open questions about frustration and frustration relief and provides a new tool for scientists grappling with these issues in a variety of fields from magnetism to basic statistical mechanics.

Frustration is a feeling known to anyone who has had to choose one course of action from a range of imperfect options. Similar situations arise in nature, and scientific ideas about frustration have been explored to understand materials as varied as water, ceramics, magnets and superconductors.

"Our experimental situation is somewhat akin to the situation faced by a party host aiming to arrange dinner seating so that men are fully surrounded by women and women are fully surrounded by men," Arjun Yodh, professor in the Department of Physics and Astronomy at Penn, said. "If the host chooses tables with odd numbers of seats, then the seating goal cannot be achieved, and some people will be frustrated. If the host chooses square tables, then all of the men can have two female neighbors and all of the women can have two male neighbors, and everyone is happy.

"We created a similar sort of packing frustration by arranging spherical particles in water on a flat triangular lattice, while permitting the particles to freely move small distances out of plane, that is, up or down," Yodh said. "The frustrated material is formed because neighboring particles prefer to move away from one another. Thus, if a particle is in the down position, its neighbors will want to move to the up position. In our case, the microspheres pack on the corners of each triangle, and the lattice is said to be geometrically frustrated. For every triangle, there is always at least one pair of energetically unfavorable neighbors that are both up or both down."

This multiplicity of imperfect choices leads to frustrated materials with many "lowest energy" states in which small perturbations can introduce giant fluctuations with peculiar dynamics. Traditionally, these phenomena have been explored in magnetism, wherein spins on each atom experience frustration as a result of their anti-ferromagnetic near-neighbor interactions and the lattice on which they sit. But it is difficult to observe individual spins directly.

"We use microscopy to directly visualize the configurations and dynamics of all the 'spins' in the sample," said Yilong Han, a member of the Penn team and currently an assistant professor of physics at Hong Kong University of Science and Technology. "This is a major advance over previous experimental work, and, furthermore, we can use small changes in temperature to change the strength of the inter-particle interactions."

The ability to control inter-particle interactions enabled the Penn scientists to control the degree of frustration in the sample and concurrently probe material responses. The team found that the lattice deforms to relieve frustration as the material becomes more strongly frustrated.

"At high compaction or interaction strength, the in-plane lattice deformed into stripes and zigzags so that the microspheres were able to pack more efficiently," Tom Lubensky, professor and chair of the physics and astronomy department at Penn, said. "We were able to understand theoretically why these particular configurations relieved system frustration using a simple geometrical model tiling the plane with isosceles triangles."

"The slow sample dynamics also offer insights into the interplay between frustration relaxation and order," Yair Shokef, a post-doctoral Fellow and theorist with the team, said. "Deep connections between frustrated materials and glasses might exist, and we are now in a position to explore these possible connections."

Since the experimental scenario emulates classic models of spin frustration, the research builds a novel connection between two very different fields of physics: soft matter and frustrated magnetism. In the near future, novel energy landscapes can be created for the microspheres using laser tweezers and enabling experimenters to directly probe the role of lattice deformability on the dynamics and creation of structure. Similarly, optical and magnetic traps can be used to "flip" and move individual particles, experiments impossible with traditional magnetic materials.

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