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Sonia Fernandez

Of Spins, Entanglements and Spooky Actions

To UC Santa Barbara theoretical physicist Leon Balents, a magnet is far more than the thing you stick on a refrigerator, or that odd mineral that attracts metal. What many of us perceive as just another way of displaying kids' artwork in the kitchen is to him a fascinating interplay of strong and weak atomic forces, gravity and of course, electromagnetism — the fundamental forces of the universe.

Balents shared his fascination with a rapt crowd during his recent talk, "Magical Magnetism & Other Strange Stuff," the inaugural lecture of his appointment to the Pat and Joe Yzurdiaga Endowed Chair in Theoretical Physics. He is the second UCSB faculty member to hold the position named for longtime campus supporters Joe and Pat Yzurdiaga. Balents follows in the footsteps of prominent string theorist and UCSB Professor Emeritus Joe Polchinski.

"I am deeply grateful to Joe and Pat Yzurdiaga for their visionary and generous gift to establish this endowed chair, which we are honored to have bear their name," said Chancellor Henry T. Yang. "We are so fortunate to be able to bestow this honor on our distinguished colleague and leading theoretical physicist Professor Leon Balents. His inaugural lecture captured the attention and interest of everyone in attendance, and ignited our intellectual curiosity about magnetism, quantum entanglement and other mysteries of our universe."

In his opening remarks, KITP Director Lars Bildsten noted the lasting impact of Professor Balents mentoring of young scientists — both UCSB physics graduate students and KITP postdoctoral fellows: “There is always someone in Leon’s office!”

“I love magnetism,” Balents told the audience of family and friends, colleagues and supporters at his lecture. “Everyone has probably played with magnets as a kid; you can feel that mysterious force between them — it’s like you can feel magic with your own hands.”

The “magic” that we see and feel on the macroscopic level — ferromagnetism — is attributable to the collective behavior of electrons in the material, he explained, whose angular momentum, or “spin” causes each electron to behave like a magnet, with a positive and negative end.

“An electron is like a little bar magnet. You can think of it as a little spinning charge,” Balents said, “and physicists know that a spinning charge makes a magnetic field, like a tiny electromagnet.” Enough of these spins aligned in the same direction and you have a material that can call other, unpaired electrons of opposite alignment (typically from metals such as iron or copper) to themselves, or conversely, repel electrons of the same alignment.

Based on that fundamental electron spin behavior, one may expect more materials to be magnetic. In fact, said Balents, the mystery isn’t so much why are only *some* things magnetic, but why isn’t *everything* magnetic?

It turns out, he said, that while there are other, nonmagnetic materials that have electron spins, they don’t create magnetic fields because their spins cancel each other out. Case in point: the antiferromagnet, whose existence was proven as recently in 1949.

“Antiferromagnets actually come in a variety of forms; it’s not just the simple up-down-up-down pattern,” Balents said, describing the “up” or “down” state physicists use to characterize the spin of a subatomic particle. “There are all sorts of other patterns, and understanding what occurs in nature and how it occurs is kind of a tempting problem for theorists like myself.”

Balents and colleagues are currently working on one such problem, in which applying a magnetic field to a certain crystal at different angles results in a peculiar “domain wall” — an area where the spins in one area of the crystal rotate from one direction to another. The net effect is still antiferromagnetic.

Diving deeper, things get spooky. In the subatomic quantum world, electron spins not only dictate the presence or absence of magnetism — they can connect so strongly that separating the electrons and keeping them at a distance does not affect their spins' correlations.

"That's a phenomenon that goes to the heart of quantum mechanics that's called entanglement," Balents said. "This separated pair of spins is called an Einstein-Podolsky-Rosen pair. What's weird about this is the state of either spin is completely undetermined." In fact, direct observation of spin states would actually collapse the system. However, whatever one electron's spin is — and in the simplest models it could be up, down or a superposition of both up *and* down — the other entangled electron's measurement will instantly correlate with it.

"You can ask the question Einstein did at the time: Where is this information stored, physically? It's not stored with either electron," Balents said. "It's stored somewhere completely different.

"It's called quantum nonlocality — information about the state of the physical system is not anywhere in a specific point in space," he said. "Einstein didn't really like this; he called it 'spukhafte Fernwirkung' — spooky action at a distance."

And yet, said Balents, quantum entanglement is far more common than one might suspect; nature actually forms these Einstein-Podalsky-Rosen pairs commonly between atoms and molecules. Some, including minerals called herbertsmithite and bismuth selenide, may look fairly mundane on the surface but in fact are massively entangled on the quantum level, he pointed out.

"So, we can imagine there are whole families of these strange states of matter," Balents said. And where entanglement exists, quasiparticles are usually not far away. Rather than being microscopically discrete particles, quasiparticles are states resulting from the collective interactions of particles such as electrons, which do a variety of things — including producing artificial light and creating magnetism — that physicists are still just beginning to explore.

According to Balents, the infinitesimal electron may one day provide clues to one of physics' biggest mysteries: gravity. While typically in the purview of astrophysicists — including many at KITP — who study enormous and exotic objects such as colliding black holes and neutron stars, gravity is expected to become a topic for those who study quantum systems as well.

"Two years ago, Alexei Kitaev suggested that studying a particular system of electrons — the quantum dot — exerting strong forces on one another, might lead to gravity," Balents said. It wouldn't be the gravity we experience in our three-dimensional space, he added, but the Caltech physicist's idea — recently outlined in a talk at KITP — has gained momentum at the institute and worldwide, charging hopes that understanding this type of quantum gravity might lead to insight on gravity in our reality.

"It's actually through the online access to this talk that most of the work following up on Kitaev's brilliant idea has occurred — it's probably one of the most accessed videos in KITP's massive archive of scientific talks," Balents said. "The field has grown so much that there will be an entire KITP program on the physics emerging from this idea for all of 2018."

Leon Balents is a theoretical physicist researching the quantum physics of materials. He received bachelor's degrees in physics and mathematics from MIT in 1989 and a Ph.D. in physics from Harvard in 1994. First coming to UCSB as a postdoctoral fellow in 1994, he returned in 1999 as a professor in the Department of Physics. Balents became a permanent member of KITP in 2008.

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