Physicists discover new laws governing the 'developmental biology of materials'

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When one atom first meets another, the precise nature of that interaction can determine much about what kinds of physical properties and behaviours will emerge.

In a paper published today in *Nature Physics*, a team led by U of T physicist Joseph Thywissen reported their discovery of a new set of rules related to one particular type of atomic-pair interaction. The researchers study interactions between atoms that have been cooled close to absolute zero.

"Ultracold atoms are the stem cells of materials science," says Thywissen, a Professor of Physics at the University of Toronto and also a Fellow of the Quantum Materials program at the Canadian Institute for Advanced Research. "Just as a stem cell can become a fingernail or a heart cell depending on its context, ultracold atoms can become metals, insulators, superfluids or other types of materials."

In collaboration with theorists Shizhong Zhang of Hong Kong University and Zhenhua Yu of Tsinghua University, the Toronto experimentalists have been studying "p-wave interactions." The term "p-wave" refers to the degree to which two atoms twirl around one another - a phenomenon physicists refer to as "angular momentum."

Researchers study these interactions in a highly controlled environment, coaxing a few hundred thousand gas atoms into a "trap," and cooling them to about -273 Celsius.

If two atoms hit head-on and bounce straight back from one another, it means they have no angular momentum. This interaction is called an s-wave. But if a pair of atoms ricochet off one another with a single unit of angular momentum, the resulting interaction is known as a p-wave.

P-waves, s-waves and other types of atom-pair interactions correlate with many types of emergent physical properties. Some rules that govern these relationships are well understood, but those related to p-waves have traditionally defied explanation.

"P-wave interactions fascinate scientists because they endow materials with unusual properties and puzzling behaviours," says Thywissen. "But the conventional wisdom was that gases with p-wave interactions had losses that were too strong to allow you see anything interesting."

Thywissen's team employed a method called dynamical spectroscopy to prepare and probe atoms faster than had been done in the past.

"Our observations took less than a millisecond," he says. "Previous studies were searching for properties that required longer observation. It allowed us to see something before the losses became too significant."

Their orthodoxy-challenging experiments resulted more from serendipity than a conviction that there was a problem with conventional wisdom.

"We ended up looking at this because a junior graduate student working in our lab didn't know to avoid the p-wave resonances. He took spectroscopy data on them," Thywissen says. "Nature surprised us. There was a beautiful spectroscopic signal of a new kind of pressure that was due to p-wave interactions."

Their subsequent observations sparked a flurry of activity among theoretical physicists, resulting in several new papers that attempted to explain this pressure. If correct, this theoretical work provides a new set of guidelines outlining how to understand any state of matter that emerges from p-wave interactions.

This work can help scientists better understand the fundamental question of where material properties come from. It can also make it possible to create and work with new materials that have highly unusual - and potentially very valuable - properties.

P-waves, for instance, correlate with unusual forms of superconductivity and superfluidity, in which particles flow without resistance. Such materials have vexed scientists for years.

"When made up of p-wave pairs, superconductors and superfluids should also have something called an edge current - but we know from observation that these edge currents are absent or extremely weak. We don't understand this," says Thywissen. "We hope the new relations we've discovered will help us figure out why."

Thywissen and his collaborators are already designing new experiments designed to tune and tweak the environment, creating an ever more sophisticated understanding of how material properties emerge.

"Even though this experiment looks complex now, we will continue to work to push the limits of what can be done in the lab," Thywissen says, "We never know what we're going to find, but we always have hope of discovering something like this. It is truly thrilling."

The discovery is explained fully in the the study "Evidence for universal relations describing a gas with p-wave interactions" published today in *Nature Physics*. In addition to Yu, Zhang and Thywissen, the research team includes U of T PhD candidates Christopher Luciuk and Scott Smale, and postdoctoral fellow Stefan Trotzky.

More information: Christopher Luciuk et al. Evidence for universal relations describing a gas with p-wave interactions, *Nature Physics* (2016). DOI: 10.1038/nphys3670

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